A representation theory for spatial feature based Spatial Information Systems
A figurative re-interpretation of Piaget’s theory of cognitive systems

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Abstract

The current conceptual model for data representation in spatial information systems (SISystems) has been challenged by various problems. In this thesis, a new theory of representation is presented based on the study on how spatial features are represented in the human mind in order to meet those representation requirements. It follows the idea of a spatial feature based representation. Spatial features are defined as the natural units of substances in the world and the basic building blocks of the environment.

Specifically, the biological principle is followed in understanding the representation of spatial features in mind. A situation based Ontology of the world will be introduced to provide a figurative re-interpretation of Piaget’s operative account of cognitive development. That is, based on this idea of situations and Piaget’s theory of cognitive development, four levels of cognitive systems and four stages of conceptual systems are distinguished. Thus, Piaget’s abstract structure d’ ensemble can be re-defined with part-whole relations on the one hand, a system of domains or a system of ontological-kinds of spatial features on the other hand. Regarding the representation of spatial features, conceptions are explicitly differentiated into four inclusive levels for the states, individuals, specific categories, and the ontological-kinds. Four kinds of causal relations are also emphasised as the constraints for the development of domain specific representation and knowledge. With the new theory, constraints of core-domains on representation in cognitive literature in terms of ontological-kinds of identities and causal knowledge of different kinds will be explained in an unified account. The constraint of ontological-kinds on representation of spatial features can be differentiated in terms of whether the ontological distinctions can be supported or not and what forms of representation can be given. The factors on different models of spatial features can be understood in terms of ontological-kinds, basic level categories of core-domains, details of category systems (of different kinds) of core-domains, and forms from interpretations of attributes of different kinds.

This understanding of the structural constraints on the representation of identities is ultimately for developing a new information architecture of SISystems to adaptively handle the different models for spatial features (of different ontological natures) and the representation of the environmental situations in general (including maps). The emphasis of the constraints on the representation of spatial features necessarily separates this thesis from other representation theories in SIScience which focus on the forms of representation with attributes directly.
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Chapter 1

Introduction

This thesis investigates a new conceptual model for a spatial-feature based general-purpose spatial information system (SISystem). A new theory on how spatial features in the environment are represented in the human mind is presented, which is a figurative re-interpretation of Piaget’s theory on cognitive systems and development.

1.1 Research topic

Current studies in SIScience \(^1\) cover a range of research topics. The one presented in this thesis targets the representation theory behind the design of data models for a general purpose SISystem. The possibility of a new conceptual model for SISystems will be explored and the new theoretical proposal will focus on how to represent spatial features.

A theoretical investigation on the conceptual models for SIS is a fundamental issue (Goodchild, 1992)\(^2\). In software engineering, a conceptual model is understood as the result of analysis of the problem domain. It is about the specification of concepts and their relations for data modelling (Booch, 1994). However, the concepts and relations should not just form a loose collection, but a coherent system with a principle which can unify these concepts and relations (Goodchild, 2004). Thus, for SISystems, a conceptual model should be based on a proposal of a representation theory of the environment.

\(^1\)As may be noted, the domain in the literature is called GIScience, but in this thesis, it is called SIScience. The change is to match the call to extend the areas of applications of GIS since the 1990s (Raper, 1989; Wright and Goodchild, 1997). Traditionally, the scale of space studied is the large scale physical and social environment where humans live, which is often termed ‘geoscale’. However, the new general purpose SISystems shall allow the representation beyond the spatial entities or phenomena in the geoscales. The change from the letter G to the letter S is to reflect the intended wider range of application domains. Here, S is for space, rather than shapes or geometric forms.

\(^2\)The exact phrase used in Goodchild (1992, 2006) is “data models and theories of spatial data”.
Indeed, a conceptual model for SISystems is directly contingent upon the adoption of a representation theory of the environment. In present state-of-the-art SISystems, the conceptual model is based on a *map* or *image* based representation of the environment (Worboys, 1995; Worboys and Duckham, 2004). Indeed, maps play a crucial role in representation of the environment and communication of such knowledge of the environment. However, there are various theoretical and practical problems (Goodchild et al., 1999; Mark, 2003). Even in the early days of GIS development, it was noted that the rigid data model with a focus on cartographic representation of the environment constrained the expression of various conceptions of space (Chrisman, 1978). Practically, there are application requirements that present SISystems cannot satisfy appropriately. For example, there are the needs of three dimensional representation (3D GIS), representation of changes over time (temporal GIS), the representation of spatial features with indeterminate boundaries, and integration of knowledge for categories of spatial features. All these can be traced to the inadequacy of the map-based conceptual model. A reconciling of data models for SISystems with different conceptions of space and the different ways to represent the environment has become necessary. This was called for in the past and has remained an active topic of research ever since (Mark, 2003; Goodchild, 2006; Schuurman, 2006).

A study of the representation theories for the environment has become one of the most important issues for a new general purpose SISystem since the adoption of a representation theory of the environment can fundamentally influence the conceptual model for SISystems. Regarding a representation theory, two specifications shall be made explicit. One is *what to represent*. The other is *how to represent*. Indeed, representation theories for SISystems can be differentiated based on their differences in understanding about *what to represent* and *how to represent*. Different understandings on *what to represent* can lead to different conceptual models. Most researchers of SISciences believe that the representation in SISystems is about data modelling of the environment. However, there are fundamental differences. In current SISystems, the environmental representation starts with either the maps or images for the large scale environment. In this thesis, a different theory is adopted. Namely, the environmental representations should start with the representation of *spatial features*, which are the basic building blocks for the representation of the environment. The environmental representation can be constructed with the representation of spatial features and their relations. A SISystem which is constructed with the focus on representation of *spatial features* as the basic units will be called a spatial feature based SISystem (SF-SISystem).
1.2 Scope of the study

A SF-SISSystem is not a new proposal (see (Usery, 1993; Tang et al., 1996; Mennis and Peuquet, 2000)). Nevertheless, the author believes the principle of a SF-SISSystem design requires new research. This is because the current approaches in understanding the representation of spatial features in SISystems and in the new proposals for the representation of categories and concepts are both dissatisfying. Traditionally, in SISystems, spatial features are embedded in maps and images, rather than treated as distinctive representation units themselves. In the proposals of spatial feature based SISystem (Usery, 1993; Tang et al., 1996), the representation has been focused on the representation of categories of spatial-features. However, not only are there different theories for category representation to be considered (Hampton, 1993), but also distinctive demands for the representation of spatial-features in the large scale environment which are considered as distinctive ontological kinds (Mark et al., 2001; Smith and Mark, 2001).

The study on the representation of spatial-features can be related to a currently active research area of “ontologies”. The term ontologies is used either in studies of “ontologies for” GIS (Goodchild, 2006; Mark, 2003; Mark et al., 2004; Schuurman, 2006; Tomai and Kavouras, 2004; Winter, 2001) or “an ontology-driven” GIS (Fonseca et al., 2002a,b; Frank, 2003, 2001). For ontology-driven SISystems, the specification of a set of ontological kinds or a conceptual model is required. However, such a specification often reflects the ontological and epistemological positions of a researcher (Peuquet et al., 1998) and the theories and conceptual models themselves sometimes can be questioned directly (Smith, 1995). Regarding the ontological presumptions, different aspects of the environment are taken into considerations. Some are more general and with a potential wider range of applications (Grenon and Smith, 2004). Others are rather restricted to specific concepts, such as relations (Egenhofer, 1992), activities (Kuhn, 2001), and events (Hornsby and Egenhofer, 1997, 2000).

However, regarding the epistemological commitment, the descriptionist’s understanding of concepts (Millikan, 1998a) is generally adopted in these studies of ontologies. Indeed, in the domain of knowledge representation (also in cognitive literature), the study of representation of categories and concepts is deeply influenced by the tradition of Wittgenstein (1963). The representations in a language or logical-mathematical systems are the starting points. Categories

\[^3\text{Since the term SISystems is preferred over GIS in this thesis, hereafter, the corresponding term will be changed into ontologies for SISystems or ontology-driven SISystems.}\]
CHAPTER 1. INTRODUCTION

and concepts are defined or described. The school which proposes such an understanding of categories and concepts is called the descriptionism (Putnam, 1975; Millikan, 1998a). While these symbolic representations are the basis for the models of identities in digital systems, there are concerns with such an approach. Theoretically, there are problems of symbol grounding (Harnad, 1990; Glenberg, 1997) and belief fixations (Fodor, 1983; Putnam, 1983). Practically, not only are there different proposals on how to represent concepts or categories (Smith and Medin, 1981; Pothos, 2005; Ashby, 2005), there are also the changes of representation and knowledge for concepts or categories (Litowitz, 1977; Vygotsky, 1986). Categories of spatial-features are also of different ontological natures (Keil, 1989a; Smith and Mark, 1998; Smith, 2001) and should be represented differently.

While this thesis has committed to the understanding that the environment is defined by spatial-features in relations and processes, this thesis is limited to a study on how the identities of spatial-features are represented in mind. The initiation of this approach to study cognitive theories of representation is driven by one of the research directions in SIScience regarding the cognitive theories of environmental representation, which were identified by the Varenius project (Goodchild et al., 1999; Mark et al., 1999). However, two realisations have pushed the study forward. Firstly, it is a fact that the human brain can handle the representation of the environment competently. Thus, an understanding of representation in the mind shall provide the most useful insights on this subject. Secondly, there was the (later) realisation that the development of representation in the mind may begin from a single mental structure for the category of substance (Piaget, 1954; Piaget and Inhelder, 1956; Piaget, 1962; Bickhard, 1998; Millikan, 1998a). In terms of extensions, the category of substances is essentially the same as what are called spatial-features, which refer to the distinctive parts of the environment. The representation of the (large scale) environment can be defined with the configuration of spatial features as the building blocks. If such a position is taken, then, in principle, the possibility of finding a cognitive theory of representation for identities of spatial features is high.

The realisation of the possibility of an appropriate theory for representation and the explicit statement of such a theory are two different matters. A new cognitive theory will be developed in this thesis based on a principled and systematic investigation into cognitive theories which are relevant to the representation of the environment. This defines the scope of the study in this thesis.
1.3 Research method

The research method in this thesis may be categorised as conceptual analysis, a term borrowed from the classic work of Heider (1958) in his studies of interpersonal relations. Conceptual analysis is based on an intensive and critical review of literature.

In discussing the research methodology, it should be noted that different domains may favour different methodologies for doing research. However, because of the topic and scope of this thesis, the adopted method is different from the research method in knowledge representation in computer and information science and the representation of spatial knowledge in SISystems on the one hand, the research method in the cognitive and developmental psychology on the other hand.

In the studies of “ontologies”, logical specifications and implemented systems are emphasised\(^4\). Usually, a set of concepts which are deemed to be ontologically prior are chosen by an expert depending on the expert’s view of Ontology of the world. Then the logical definitions for the ontological kinds are also given by experts. They are taken as the axioms to produce the definitions for more complex concepts. However, the research in this thesis is on searching for such a system of concepts themselves in order to obtain a sound representation theory. The topic is sufficiently complex to warrant a PhD study in its own right. It not only requires an interdisciplinary study which goes beyond the current studies in SIScience, but also determines the thesis is quite close to a philosophical study.

The distinctive topic determines that the adopted research method is distinctive in comparison to other works from information science. In this thesis, cognitive theories of representation in cognitive and developmental literature will be thoroughly investigated in order to understand how the representations of spatial features as 4D units may be handled and realised in the human mind. While cognitive literature is examined, the thesis does not follow the empirical traditions of cognitive and developmental psychology in terms of the research method either. Rather, the thesis will examine the cognitive theories themselves. Those examined theories themselves are studied in the cognitive literature and they are often backed up by their corresponding empir-

\(^4\) See the works from Frank and associates (Frank, 2001, 2003), from Mark and Smith (Mark et al., 1999, 2001; Mark, 2003; Mark et al., 2004; Smith and Mark, 1998, 1999, 2001; Smith, 2001), and from Egenhofer and associates (Fonseca et al., 2002a, 2003; Rodriguez et al., 1999; Rodríguez and Egenhofer, 2003) on their studies of ontologies. A similar statement can be made about the studies on formal ontology (Gruber, 1993, 1995; Guarino, 1994, 1995, 1998; Guarino and Welty, 2000; Sowa, 1995, 2000).
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1.4 Contribution of a representation theory

The main contribution of this thesis is a new theory on how spatial-features are represented in the mind, which is a figurative re-interpretation of Piaget’s theory of cognitive systems. Thus, the various kinds of structural and formal constraints on the representation of spatial-features can be clarified, which bear direct implications on modelling. The details can be viewed from three aspects:

Firstly, the new theory adopts explicitly the biological principle in understanding representation. Regarding the representation in mind, this thesis will present a systematic account of this biological principle. Following Millikan (1998a), the theory emphasises the representation for spatial-features as natural-units of the world. The functional and structural principles are also followed in the development of the representation in mind. The systematic adoption of these three positions distinguishes this thesis from other cognitive theories of representation.

Secondly, the thesis will introduce an ontological view of the world with the conceptual construct of situations. Situations are defined as spatio-temporally framed 4D units of substances of the world. With this idea of situations, there are a few more theoretical positions:

1. A figurative re-interpretation of Piaget’s operative theory of the development of cognitive systems will be given.

2. The two concepts in cognitive literature, core domains and ontological kinds can be defined robustly. As special cases of situations, they are both contexts for identities in the world and constraints on the representation of identities in mind.

3. This re-interpretation of cognitive and conceptual development can also allow the solid explanations of Piaget’s abstract idea of structure-d-ensemble for cognitive structure in terms of parts, wholes, and part-whole relations.

4. To define the development of representation in conceptual structure, the vertical (i.e. conceptions on different inclusive levels) and horizontal (i.e. the system of causal knowledge
of different kinds) dimensions as the general constraints are also systematically clarified.

Thirdly, this situation-based theory will explain further the development of conceptual systems and the forms of representation of identities of core-domains. With this situation-based theory, a framework is provided to integrate a range of current cognitive and developmental theories on representation of categories. Specifically, the thesis will provide two systematic accounts:

- A systematic account of domain specialisations for the environment, the development of representation and knowledge of core domains, structure and contents for domain knowledge, and domain constraints on the representations of identities.

- A systematic account on the inherent constraints from the ontological-kinds of identities on their representations in mind (which are directly relevant on their models in logical-mathematical systems). Regarding the representation of identities, the new theory will explain systematically the different factors on the forms of representation for identities. They are the factor of ontological kinds on the representation from sensorimotor experiences, the factor levels of conceptions and the development of basic level categories on the representation of individual identities, the factor of details for domain representation and knowledge as reflected in the states of the four kinds of category systems and the representation of individuals, and the factor of forms from the formal interpretations of the attributes in representation.

1.5 Thesis organisation

Apart from this introduction, there are eight chapters in this thesis. In Chapter 2, the biological principle is argued for understanding representation in mind. This biological principle emphasises that the representation in mind is about the “natural-units” of substances. Further, the functional and structural principles are called for understanding how the representation of substance is realised in mind.

Chapter 3 will firstly introduce the conceptual construct of situations as four-dimensional (4D) units of substances in the environment and the situation-based ontological view of the world. Then, based on the idea of situations, Piaget’s four developmental periods will be figuratively re-interpreted where the development of cognitive systems and the development of
CHAPTER 1. INTRODUCTION

contextual systems will be treated separately. Four-levels of cognitive systems are differenti-
ated from the perspective of what kinds of situations in the world can be represented. Four-
stages of conceptual systems are differentiated because of the changed forms of representation
of identities.

Chapter 4 will outline the structural constraints on the representation of identities from the
situation-based perspective. Firstly, spaces and situations in the environment as the contexts for
identities will be differentiated. The definitions of a few important kinds of situations as the
contexts of spatial-features, e.g. immediate situations, core domains, learning, and application
situations, will also be given. Secondly, the general view of Piaget’s identity rules and the three
levels of organisation for the representation of identities will be clarified. The structure-of-the-
whole of a cognitive system in Piaget’s theory will be re-defined with part-whole structure.
Thirdly, for the representation of identities in the development of a conceptual system, the
vertical constraint from the conceptions on four inclusive levels and the horizontal constraint
from the causal knowledge of different kinds will be emphasised. The development of basic-
level-categories from conceptual re-organisations of a core-domain as the structural constraint
will also be explained.

Chapter 5 will explain how the situation-based theory can explain the specialisation of core-
domains and the development of the system of domains for the environmental studies. Firstly,
the meaning of domains for environmental studies is clarified. Secondly, the system of domains
which are relevant for the study of the environment will be discussed, including core-domains
for identities in the common-sense-space and in small and large spaces and the application-
oriented-domains for the repeated simple or complex situations in the environment. Thirdly,
the situation-based view on the mechanisms to develop the representation for any specified
situations in the environment will also be explained.

Chapter 6 will continue to study core-domains but will focus on the development of repre-
sentation and knowledge of core-domains. The state of a core-domain is defined by the state of
the development of causal knowledge of different kinds and the representation of identities of a
distinctive ontological nature. Given the development of identities are constrained by the states
of their core-domains, this chapter also provides a systematic account on how the situation-
based theory can assimilate the different theories in cognitive literature which emphasise the
constraints on representation.

Chapter 7 will explore the ontological-kinds of identities from the situation-based perspec-
The nature of ontological-kinds for identities will be clarified, which refers to the distinctive existences in the world. The cognitive criteria for the ontological distinctions of identities will be explained, which are in terms of their distinctive existences and functional roles to the concern of a person and other objects interested by a person. The system of ontological-kinds of spatial-features supported by the fourth level cognitive structure will also be given.

Chapter 8 will continue issues with ontological nature of identities with focus on their constraints on the representation of identities. The formal schemata for the representation of identities are ultimately determined by their ontological existence. However, the knowledge of identities is constrained by the development of conceptual structure and the states of their core-domains. The rules for boundary conditions of classes on different levels of conceptions and the knowledge of such boundary conditions will be covered. The factors of ontological kinds, levels, and details on the formal schemata of identities with selections of attributes will be further explained. The factor of forms in terms of attribute natures and the different forms of interpretation will also be discussed.

Chapter 9 concludes the thesis with a summary of the major theoretical points and contributions to the understanding of representation in cognitive systems, SIScience, and SISystems.
Chapter 2

The biological principle on representation in mind

2.1 Introduction

This chapter covers presumptions about the new representation theory in mind. Specifically, the biological perspective is taken for understanding what the representation in mind is about (i.e. the category of substance) and how the representation of identities can be realised (i.e. the functional and structural principle in understanding the representation). There are three major sections:

Section 2.2 will clarify that the representation in mind is about the “natural units” of substances in the world. This presumption extends the realist’s position of Millikan (1998a). Such a position is sensible when representation is seen from the biological perspective, since it is the substances in the world which are fundamentally relevant to an organism.

Section 2.3 will discuss the functional principle of representation. Following Millikan (1998a), the primary function of the representation is to re-identify the “natural-units” of substances when they are re-encountered. This is facilitated by the accumulation of information about the identities when they are encountered. The fundamental implications of this functional principle on the realisation of representation and the different aspects of the functional principle on the representation system in mind will also be discussed.

Section 2.4 will explain the structural principle of representation. While Piaget’s general idea of structuralism shall be followed, a figurative understanding of structure will be needed. The distinction between the brains, cognitive systems, and conceptual systems as the representation system will be discussed. Different understandings of the term structure for representation will be given. The two aspects of structure versus contents for a representation system will be emphasised.
2.2 The representation for the category of substances

This thesis presumes that the cognitive representation in mind begins with the representation of the category of substances. Here, the category of substances refers to the “natural units” in the world as defined in Millikan (1998a). This presumption follows the biological principle because it is the category of substances in the environment which is relevant for an organism, given they are the food, drink, mates, and danger. It is the different natural-units of substances which are biologically relevant. Thus, the representation in the brain and the mind should be about them. The natural-units are also called the identities of spatial-features in this thesis. Here, spatial-features are the examples of the category of substances.

This presumption is inspired by and extends the realist thesis of Millikan (1998a), who argued, there is a common structure in mind for the representation of stuff (e.g. milk), individuals (e.g. Mum), and real kinds (e.g. people). However, different from cognitive theories, Millikan (1998a) has defined the concept of the concept as referring to the capability to point and perceptually track natural-units. This “common structure” in mind means two aspects. One is about the accumulations of properties about the natural units. The other aspect is about the associations of properties which can allow an organism or a person to re-identify the natural units reliably. According to Millikan (1998a), a “natural unit” (which may be denoted by a lexical name, e.g. Mum) can be understood in terms of their properties. The properties of a natural-unit can be picked up when the natural-unit is encountered. However, the properties are not for the definition of categories or concepts, but for the re-identification of those relevant “natural-units”. The properties may change in different encounters. However, the goal of a concept with the collection of properties is to make sure the particular natural-unit should be “pointed at” in different encounters.

2.2.1 On representation of natural units of substances

A crucial distinction of two families of representation theories should be made. One emphasises the representation of identities as “natural-units” in the world (such as the theory in (Millikan, 1998a), Piaget’s theory (Elkind, 1969)\(^1\), and the theory in this thesis). It emphasises the central

\(^1\)Piaget’s theory also emphasised the representation of individual identities. His identity rules implies the representation of within-thing variations (Elkind, 1969), i.e. identities as individuals. The identity rules in Piaget’s theory will be synthesised in Section 4.4.
issue of representation is about representation of identities and the purpose of representation is for re-identification.

The other family of theories, which is common in the cognitive literature\footnote{Such as the theories of (Bruner et al., 1956; Rosch, 1978; Smith and Medin, 1981; Markman, 1989; Hampton and Daniéle, 1993).}, emphasises category representation. In these cognitive theories, representation of categories is treated either implicitly or explicitly. In the tradition of functionalism and behaviourism, the issue of representation has been treated implicitly in that it is implied in the function of categorisation, i.e. the ability to classify an identity into a category (Bruner et al., 1956; Markman, 1989). The process of categorisation is often considered as implying category representation. The learning is about learning such relations of properties-to-categories of patterns. These are commonly called rules and such rules of categorisation are either implicit in enhanced associations or explicit where the perceptual cues are tested for their effectiveness of being such categorisation rules. In the other tradition of structuralism (Rosch, 1978; Smith and Medin, 1981; Hampton and Daniéle, 1993), the representation of a category is about a set of examples which share certain similarities or bear family resemblance to each other. The categorisation is based on similarity to the examples or a prototype.

The concept and conceptions of substances

Cognitive theories of representation are strongly influenced by the philosophy on concepts and word meanings (Wittgenstein, 1953). Following the descriptionist’s tradition in studying the meanings of concepts\footnote{That is, either the theories of category representation, or the semantics for word meaning and concepts.}, words are labels for categories or concepts. The meaning of a word is defined in terms of a list of features. Learning is about the representation of a category or a concept, which is further understood in terms of searching for properties which are shared by the members and which help to differentiate one group of things from others.

However, Millikan’s thesis is a considerable departure from the majority of cognitive and developmental theories\footnote{According to Millikan, her main purpose is to challenge “the theoretical assumption that the extensions of concepts (the set of things that fall under the concept) are determined by descriptions” (Millikan, 1998a, p.55). Also see critics from Putnam (1975) on descriptionism for semantic theories.}. Millikan’s study of the concept does not follow this descriptionist’s tradition since Wittgenstein (1953)\footnote{According to her, she has proposed “a thesis about the nature of one and only one kind of concept, namely,}. Her use of the term concept is also markedly different
from the common use of the same term by other philosophers and cognitive scientists. The idea of the concept in Millikan is associated with the capability of pointing and perceptually tracking of natural-units in the world. The term the concept is reserved “for abilities to recognize these substances and to know something of their potential for inductive use” (Millikan, 1998b, p.91). She thinks most of the use of this term in cognitive studies is about “conception.” (Millikan, 1998b), that is about an idea of something. “Without conceptions, no substances would be conceived of; “conception” is one of the things that “meaning” means” (Millikan, 1998b, p.90). According to her:

“The conception one has of a substance is the ways one knows to identify that substance plus the disposition to project certain kinds of invariances rather than others from ones experiences with it. I take it that what psychologists have typically studied is “conceptions” in this sense the conceptions that people have of substances and this is exactly what they should be studying (Millikan, 1998b, p.90)”.

On conceptions and descriptions for identities of substances

However, the conception of “natural-units” as ideas is crucial for modelling them, and thus to be studied. According to Millikan (1998a), for natural units in the world, there are properties picked up by the perceptual organs. However, the properties are not for classification, but for the functional purpose of re-identifications of the corresponding natural units in the world. The selected properties are evaluated and enhanced for their reliability in re-identifications. Representation is needed where the continuous perceptual tracking of the same identity is impossible, but re-identification is still needed. However, these properties do not classify the “natural unit” in the world, nor define the meaning of a category.

According to Millikan (1998b), conceptions for natural units are a different matter. They are rather results of conceptual tracking. The conceptions include the accumulated information of those “natural units” in the world. The conceptions can also change over experiences and different people can have different conceptions of the same thing:

6This distinction of a concept and a conception is largely followed in this thesis.

7Millikan considered that the conceptions for the natural units result from conceptual tracking. However, the meaning of conceptual tracking was rather unclear in Millikan (1998a,b).
“There is no such thing as “the” conception of a substance nor is there “the” conception that corresponds to a public language term for a substance. Different people competently speaking the same language may have quite different indeed, nonoverlapping conceptions corresponding to the same substance term, and a single person may have quite different conceptions corresponding to the same substance at different times.” (Millikan, 1998b, p.90-91)

There are always different kinds of information which can be picked up by the perceptual experiences and involved in the descriptions for the natural-units. A distinction should be clear regarding the two senses of the term descriptions. One refers to the representation of identities as “natural units” in the world, where properties and contexts of various kinds are associated with the identities. The other refers to the descriptions of categories or individuals in language. The two are clearly related. The descriptions in language terms are based on the conceptions in mind. However, language descriptions also depend on the development of language skills.

Millikan (1998a)’s understanding of a concept as a capability and representation for re-identification presents a significant advance and a research gap between her theory and the theories in current literature in perception, cognition, and development where the same term concepts means representation of categories (Müller and Sokol, 1998; Murphy, 1998). As was summarised by Gopnik (1998):

“…the meaning of a particular word or the content of a particular concept is what relates that concept at that time to a specific aspect of the world. Notice that this is not the way that external objects enter into psychological theorizing in perception. Instead the relation is much more indirect; the external world plays a crucial role in fixing the mechanisms that allow us to form certain representations rather than others, given particular inputs” (Gopnik, 1998, p.73).

“Somehow our interactions with the external world lead us to form one set

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8Millikan’s functional based common mental structure of an identity is also general in terms of what can be included in the set of information picked up by the perceptual organs. It can involve either the properties which belong to the identity, or the contextual information of the identity, or both. However, these properties are associated with identities either implicitly or explicitly. Indeed, the distinction of Millikan’s mental structures for substances and conceptions overlaps with the studies on implicit versus explicit memories (Graf and Schacter, 1985; Schacter, 1992; Schacter et al., 2000) and perception versus cognitive representation (Goldstone, 1998; Keil, 1998).
of ontological convictions, one theory, rather than another. Even if knowing our theories is all we need to explain our current psychological functioning, we may well need to invoke relations to the external world to explain why we have those theories rather than others. These learning processes have been almost completely neglected in cognitive psychology” (Gopnik, 1998, p.74)

“If Millikan’s externalism forces us to solve the problem of how our interactions with the world lead to conceptual change, she will have provided an important service to psychology as well as philosophy” (Gopnik, 1998, p.74).

2.2.2 On differentiating the common structure for representation

This thesis will follow Millikan (1998a) to study the representation of “natural units”, i.e. the identities of spatial-features as individuals, in a mind. However, the issues raised by Gopnik (1998) and others have to be addressed. In the rest of this subsection, there are other theoretical issues which should be covered in order to reveal why current cognitive theories of representation cannot be followed directly and where Millikan’s theory has to be further developed.

Firstly, the current cognitive theories of representation will be briefly reviewed and challenges faced by these theories have to be addressed. Secondly, the distinction of a category and a concept in current descriptionist’s theories is clarified. The essence of this distinction will be kept when a representation theory of spatial features in mind is to be developed. Thirdly, a few specific criticisms of Millikan’s theory will be discussed. For a new representation theory, these criticisms should be addressed or can be potentially addressed.

On cognitive theories of representation of categories

In cognitive literature, in the past several decades, there are several major trends in the studies on representations. Depending on which school is followed the issue of representation is dealt with differently. Two families and three major groups of cognitive theories of representation should be differentiated.

The first family of theories concerns representation with contents. This family of theories can be further differentiated into two main groups. One is commonly called the rule-based systems (Bruner et al., 1956) where representation is often treated implicitly. There are asso-
ciations of attributes with categories and the attributes function as the cues for indicating the corresponding categories. The rule-based family of theories can be differentiated based on different understanding of the mechanisms in learning and reasoning (Ashby, 2005). For example, the learning is treated either in terms of associations (Estes, 1972, 1986; Anderson and Bower, 1980), or there are different strategies which can be followed by a person (Bruner, 1957). There are also different models regarding how the rules are learned and applied, such as Bayesian models or decision trees. The Bayesian model is applied to the process of learning and decision making directly (McCloskey and Glucksberg, 1979; Fischhoff and Beyth-Marom, 1983; McKenzie, 1994). In the decision tree model (Hunt et al., 1966; Quinlan, 1986), the heuristic nature of rules are emphasized, as are the complex relations of rules beyond the simple conjunctive tendency as observed by Bruner et al. (1956) in their studies of category attainment with artificial concepts. By the 1970s, the probabilistic view was dominant over the classical view (i.e. the tradition of classic logical definition with necessary and sufficient attributes) in understanding the representation of categories with attributes. The properties for a category can be characteristic or typical, rather than definitional for the category.

The second group of theories, which are essentially in the same family, refers to examples and prototype-based theories (Medin and Schaffer, 1978; Rosch, 1978; Nosofsky et al., 1989; Nosofsky, 1991). The classic work came from the studies of Rosch (1978). She emphasised the complex internal structure for natural semantic categories. In this group of theories, the idea of similarity plays the most important role in various cognitive processes, including categorisation. However, regarding the examples or prototype based theories, there are two major problems associated with them. One major issue is related to how to interpret the representation of examples or prototypes. As argued by Rosch (1978), the natural categories are associated with complex structures. For example, there are distinctive parts, functions, physical properties, and overall shapes. These different properties bear complex relations to each other to define an example or a prototype. In the interpretation of examples or prototype, however, the complex relations of properties were not handled properly. In most cases, these properties are still treated in a list. Thus, such an interpretation of the representation of examples or properties is not much different from the rule based systems in terms of representation (Gleitman et al., 1983)10. Another major problem with this group of theories is the key concept of similarity. Specifically, the

10 However, the representation of examples and prototypes can take into consideration the complex internal structure of the examples in the world. See Section 8.4 on such a potential of the theory in this thesis.
notion of similarity is too unconstrained to give an account of conceptual coherence (Murphy and Medin, 1985; Medin, 1989).

A new family and the third group of theories challenged the unconstrained use of similarity directly. These new theories, which appear in cognitive literature since the 1980s and still dominate the current cognitive literature, emphasise the contexts and domain specificity as constraints on representation. Medin (1989) calls this change of idea on concepts as from being organized by similarity to being organized around theories. Rather than dealing with representation directly, such theories proposed the constraints on representation. Depending on researchers, the contexts (Medin and Schaffer, 1978; Murphy and Medin, 1985), theories (Carey, 1985; Gopnik, 1996), domains and ontological kinds (Gelman and Markman, 1986; Keil, 1989a), deep similarity or neo-essential tendency (Medin, 1989; Gelman, 2004), or uses or general applications (Ross, 1999; Markman and Ross, 2003) were studied as such important constraints on the representation of categories.

However, there are two other challenges to these cognitive theories in general. Firstly, the diverse theories of representation and of constraints on representation bring the challenge to integrate them. For one thing, the two families of theories on representation and on constraints of representations are to be unified (Medin, 1989). For another, while the constraints on representation were studied, e.g. domain specificities and context effects, the different theories which emphasise the constraints on representation are to be accounted systematically. However, this depends on the precise understanding of the nature of these different constraints. While rule-based theories and example/prototypes theories are often contrasted (Pothos, 2005), they are to be accounted in one developmental framework (Neimark, 1983).

Secondly, there is the challenge to the current descriptionists’ approach in general from the realists’ theory such as the one from Millikan (1998a). Millikan criticised these cognitive theories for putting too much emphasis on descriptions for representation. Following the tradition of Kripke and Putnam, Millikan also proposed that the meaning of words (at least for the concrete nouns) lie in the “natural units” in the world themselves. She further defines that a concept means the capability to allow an organism or a person to perceptually track an object in the world. In this very sense, she argued that there is a “common structure” for the category of substances.

For a new representation focusing on the representation of spatial features as natural-units...
in the world, all these general and specific challenges are to be taken into consideration\footnote{In the new theory of this thesis, a Piagetian structuralist’s theoretical framework is provided to unify these theories. Chapters 6 and 7 are specifically devoted to the study of various kinds of constraints in the second family of theories.}

**On categories and concepts for natural units of substances**

As mentioned earlier, in cognitive literature, the idea of representation is often equivalent with the idea of representation of *categories* or *concepts*. While some researchers may have used the term a *category* or a *concept* interchangeably (Smith and Medin, 1981), other studies have made the distinction of categories and concepts (Hampton, 1993; Sutcliffe, 1993; Soloman et al., 1999). According to them, *categories* are about the *extensions*. A category is closely related to the collection and the generalisation of a set of examples as *extensions*. A concept is about *intension* and definition, such as specifying a concept with necessary and sufficient properties. However, in either case, the representation of a category or a concept is understood in descriptions. There is the generalisation of properties shared by the group of identities. The list of properties has made up the representation for a category or a concept, and can be expressed in language.

Regarding the representation theories in current cognitive literature, there are two points worth noting. Firstly, the terms *category* and *concept* can have different implications. While a *category* or an understanding of a category often requires the references in the world, the term a *concept* does not need a concrete reference unit which can unify the properties. For studying concept acquisition, the artificial categories can be designed (Bruner et al., 1956). There can be no “internal structures” in the sense as discussed by Rosch (1978) (e.g. wings and beaks are often go with birds) for these categories. Nevertheless, a concept for the category of substances is fundamentally different from those arbitrary ones. It requires references in the world, even though it does not matter whether the solid touchable references may exist (e.g. the ordinary objects) or not (e.g. unicorns).

Secondly, when the term *concept* is used in a strict sense, it refers to the rule-style definition
only (Sutcliffe, 1993). Piaget adopted this strict sense for concepts in his discussion on the formal operational period (Sigel, 1983). The capability of forming such an intensional concept is achieved, according to Piaget, only in the formal period of development. However, they are for sorting identities into classes (Neimark, 1983; Sigel, 1983). If this strict sense of a concept is followed, the probability rules and descriptions with characteristic properties for examples or prototypes may not be called concepts, but pre-concepts in Piaget’s term (Sigel, 1983) or representations of categories only. For a study on conceptual capability, it does not matter whether the intensional definitions with necessary and sufficient properties for a concept exist or not.

The essence of this distinction of a category and a concept (Hampton, 1993)\(^\text{12}\) will be kept in the study of representation of spatial features in this thesis\(^\text{13}\). While the theory of categories and a theory of concepts may be differentiated, for representation of natural-units in the world, they may also be integrated from a developmental perspective. In this thesis, a category refers to a set of identities in the world. The representation of a category can be about the generalisation of similar cases. While a category is about a set of cases in the world, the representation for such a category (i.e. the understanding of it) may be in terms of the examples in the world, the descriptions for examples and prototypes (Rosch, 1978; Smith and Medin, 1981), or in terms of rules (Bruner et al., 1956; Smith and Medin, 1981) for sorting them into groups (Vygotsky, 1986). There is a developmental change from the examples and prototype based representation into the rule based representation (Rosch, 1983; Neimark, 1983; Vygotsky, 1986).

The representation of a category or of a concept will be understood from the functional perspective. Both the representation of categories and concepts are relevant to the study of conceptions for natural units of substances, but these two are associated with different cognitive functions. That is, the main function of a category representation is to support the re-identification and inferences (Millikan, 1998a; Gelman and Markman, 1986). In example and prototype based theories, representation is in terms of descriptions involving the shared features of all examples. The main function of a concept is for sorting an identity into one group other than the alternatives. A concept can be associated with a set of properties for classifications, such as in rule-based theories. That is, these properties are used for making differentiations.

\(^{12}\)That is, for extensions and intensions respectively

\(^{13}\)The distinction is directly relevant in the distinction of representation and knowledge of identities in core domains. See Section 6.3 for detailed discussions.
CHAPTER 2. THE BIOLOGICAL PRINCIPLE ON REPRESENTATION IN MIND

However, the rule-based theories are closely related to the studies of concepts with intensional definitions, they can be differentiated from the traditional theory of concepts in that rules may neither be necessary nor sufficient, but with a certain degree of probability only.

**On development of conceptions and language descriptions for natural units**

Millikan’s realist’s thesis also has its critics. Three major concerns have been raised by the psychologists on the conceptions of identities, the development of conceptions, and language descriptions for representation of identities.

*On conceptions:* Millikan (1998a)’s “common structure” can be related to a sort of representation, but it is not about conceptions. Millikan discussed the “common structure” as related to perceptual tracking where properties of the identities are picked up by an organism directly. The picked up properties are then evaluated and used to support the function of re-identification. The representation from perceptual tracking is essentially about an identity as an individual, in particular, the states and changing states of it. However, the representation is not just about perceptual differentiation, but about the conceptions for the natural-units as individuals. Although Millikan (1998b) mentioned the role of conceptual tracking for the development of conceptions of identities, there is not much explanation on conceptual tracking.

*On development:* While Millikan (1998b) mentioned that the conceptions of substances can be multiple, however, there was little concern regarding the changes of representation for an identity (either qualitative or quantitative changes). The developmental change of conceptions of identities is an important issue (Gopnik, 1998; Keil, 1998; Perner, 1998). For example, Boyer (1998) pointed at that while identifying objects activates domain specific processes, which include the tracking of different kinds of substances in different manners, there may be no functional need to incur a general tracking capacity of the kind described by Millikan. Bloom (1998) also pointed out that the differentiated representation for the so called stuffs, individuals and real kinds appear to exist in the mind of a child at a very early age. The issues raised have been centred on the further development of this “common mental structure” for the representation of identities.

The development of representation is a complex subject. There are at least three aspects to be studied. Firstly, the conceptions are about the individuals as well as the categories. The developmental distinction of individuals and categories is an earlier achievement (Bloom, 1998),
but the representation of categories of identities is excluded from the discussion of Millikan (1998a). There are two further concerns. One is that an individual as an independent existence (e.g. in Millikan’s theory) is different from treating it as a member of a category (e.g. in example or prototype based theory). A theory emphasising the representation of identities should separate the representation of a “natural unit” as an independent existence in its own right from the representation of it as a member of a category. The other concern is that an individual can be classified into different categories in different circumstances (e.g. a chair can be a dining chair and a piece of furniture) (Brown, 1976). The fact that an identity can belong to variously defined categories should be addressed.

Secondly, different ontological kinds of identities are perceptually tracked in different manners (Boyer, 1998). The development of representation is not about simple accumulation of properties for identities, but about making different “templates” for representing different kinds. The brain structure supports the differentiated representations of physical objects, animals, and people as domain specific (Keil, 1989b; Boyer, 1998; Gopnik, 1998; Xu et al., 1998). In cognitive literature, there are other ontological distinctions of identities, such as natural objects versus artefacts (Keil, 1989b) and simple objects versus environmental settings (Tversky and Hemenway, 1983). There are differentiated patterns of representation of different ontological kinds in the brain of a person (Humphreys and Riddoch, 2000).

Thirdly, the development of representation of identities also involves issues such as the nature of conceptual organisations and the constraints on representation. Both were also omitted in Millikan (1998a,b). The issue of organisation of conceptual representations in terms of the traditional hierarchy of categories was only mentioned in Millikan (1998b). However, the study of such a category system is irrelevant for her main thesis on the common structure for all sorts of substances. The traditional account in cognitive literature explained such a hierarchical system in functional terms, namely economic in representation and efficient in the retrieval of information when the representation in mind is in use (Rosch, 1978). However, from a Piagetian structuralist’s perspective (Piaget, 1971), the issue of conceptual organisations and re-organisations is much more complicated than a simple hierarchy of categories. In this thesis, the development of conceptions of an identity is correlated with and constrained by the development of the overall cognitive and conceptual structure. The issue of organisations is also related to domain specialisations and the development of domain knowledge14.

14See Sections 4.3, 4.4, and 6.3 for the issues of conceptual organisations and hierarchies of category systems.
On relations to language: Millikan (1998a) did not discuss the relations between conceptions and language based descriptions for representation of identities (Franks and Braisby, 1998; Gauker, 1998; Gendler, 1998). Essentially, the issues concern the nature of language, the relations between conceptual systems and language systems, and the relations between conceptions of identities and language descriptions. The capability to understand language descriptions is important for learning in a child. For the purpose of modelling in digital systems, the understanding of language based descriptions for identities is also crucially relevant since language based descriptions and other symbolic based representation are direct sources for models in digital systems. However, regarding language descriptions provided by people, they are constrained by not only the language skills, specific applications, but the state of conceptions in development. For the development of language descriptions, the issues of conceptions, development, and organisations are all crucial and to be understood properly. This development of conceptions has supported the language systems of representation and can assimilate knowledge expressed in language descriptions and other forms of symbolic representation.

According to Millikan (1998b), these issues are to be studied by cognitive psychologists and cognitive scientists. However the satisfactory answer to this concern is remaining to be found in cognitive literature. This thesis will have to devote to the task of presenting a theory on how the representation of “natural-units” can be realised in mind.

15 In this thesis, for the nature of language, the realist position of Kripke (1972) and Putnam (1975) will be followed. For the relations between cognitive systems and language systems, Piaget’s position (Sinclair-de Zwart, 1969) will be followed, which agrees with the realist’s theory on language. However, a cognitive and conceptual system will be distinguished (in Section 2.4). A comprehensive discussion on the relations of conceptual systems and languages is beyond what is required for this thesis.

16 For modelling identities in computer systems, language descriptions are an important issue. However, to be studied in detail, the subject requires a separate thesis. There is the inherent relations between the conceptual system and the language system of representation as believed in Fodor (1975); Chomsky (1957, 1980). However, it is not about the direct mapping of representation of categories or concepts in mind and language descriptions. This thesis will study cognitive representation of identities, which are constraints related to understanding language descriptions. Although no direct mappings, there are inherent relations between conceptions of identities and the descriptions of identities. Chomsky’s deep structure of a language lies in the Piagetian cognitive and conceptual structure in mind.
2.3 The functional principle on representation of identities

The biological perspective in this thesis means the functional principle is taken in understanding the representation and development of representation in mind. This section will explain what this functional principle means. Specifically, the three issues will be discussed. Firstly, it emphasises the essence of the biological representation is to fulfil certain functional expectations rather than to seek the truth values. Secondly, the direct implication of the functional principle in understanding how to realise the representation of identities will be explained. Thirdly, the other areas where the functional principle is applied will also be analysed.

2.3.1 On representation for the function of re-identifications

Representation in mind has functions to support. Different theories take different positions regarding what functions the representation should support (Soloman et al., 1999). The most emphasised one is perhaps categorisation (Bruner et al., 1956; Rosch, 1978; Smith and Medin, 1981) and inferences (Gelman and Markman, 1987; Markman, 1989). However, Millikan (1998a) argued, from a biological perspective, that the key function of representation is to support re-identification of the “natural-units” which are biologically relevant and may be encountered at different times. Upon re-identification, the proper actions or reactions can be applied to them or inferences can be made. The properties picked up by the perceptual systems were evaluated against their reliabilities in the task of re-identification.

From the biological perspective, re-identification is the most fundamental requirement and must be satisfied by the representation in all higher organisms at least. This functional principle has direct implications in understanding the nature of representation in mind and how representation can be evaluated, which will be further explained below in this subsection.

The psychological representation for cognitive functions

According to Millikan (1998a), the information included in the representation does not define, but facilitates the re-identification of natural-units in the world. Regarding the nature of representation of identities, this is one of the most fundamentally important positions, which is in strict contrast with the current theories in cognitive science. These cognitive theories adopt the philosophical position which emphasises truth value for the evaluation of representation, theories, and knowledge (Fodor, 1975, 2000).
In Millikan (1998a)’s discussion, the representation of an identity can include properties which are accumulated for an identity during perceptual tracking. Different properties can be picked up while an identity may remain in a position or move locations in space-time. The identity is to be perceived and recognised, and the perceptions and conceptions for the identity can be developed. Here, according to Millikan (1998a, p.61), “…the core of a substance concept is a (necessarily fallible) capacity to recognize what is objectively the same substance again as the same, despite wide variation in the faces it shows to the senses”. She argued that an identity exists in the world which renders the conceptions of an identity meaningful: “…the extent of the concept, its “meaning” in the most fundamental sense, might be directly fixed by the extent of a natural unit in nature, reference remaining the same while conceptions change” (Millikan, 1998a, p.61). “The extension of one’s concept is then determined, not by one’s fallible dispositions to recognize portions of its extent, but by the real extent of the substance that has governed the development of these dispositions” (Millikan, 1998a, p.61).

Following Millikan, there is an explicit distinction between the existence of identities in the world and their appearance to a person who perceives, understands, and acts upon these existences. This contrast of an identity versus the appearance of it is a general philosophical position. The representation in a biological system is about the biological representation and psychological apprehension of the reality. The term psychological identity refers to the fact that the representation of an identity is via how the identity may appear and is perceptually explored and cognitively understood by a person. Such an idea is about the nature of the descriptions with properties for identities. It is a theoretical position free of belief-fixation problem (Putnam, 1983). The appearance of an identity and descriptions of it can change at different times, but the identity can stay the same.

The distinction between the natural-unit in the world and its representation which involves the properties for the purpose of re-identification is a crucial one. However, this general sense of an identity versus its appearance is to be differentiated from the specific understanding of this so called contrast of reality versus appearance in the literature of cognitive development (Flavell et al., 1983, 1986; Flavell and Miller, 1998). In these studies, the researchers often make some items which look like one kind, but are not in reality. For example, a sponge is painted and made into the shape of a rock. They then test children to see how they judge the items. The younger children (≤ 4 years) who make judgement based on appearance may state it as a rock. The older children will give the right answer based on the nature of the material.
CHAPTER 2. THE BIOLOGICAL PRINCIPLE ON REPRESENTATION IN MIND

This specific sense of appearance versus reality should not be confused with the general sense of the reality versus appearances in the realist’s thesis.

**Functional evaluations of different strategies of representation**

While a psychological representation is for functional purposes, different strategies can be adopted for realising the representation of identities where the same functional expectation such as re-identification can be satisfied. The functional principle of representation implies the way the representation can be evaluated. That is, the *rule of evaluation* is functional, which is based on whether the functional expectations in general from such a representation can be satisfied and how well they have been satisfied.

Regarding the basic functional need of re-identification, some organisms may adopt the approach where a distinctive feature of the identity of interest is recognised. Others may require more comprehensive representation involving attributes of different kinds. It seems studies in evolutionary biology have provided data for the claim that different strategies indeed had been adopted by different organisms to realise the representation of identities. For example, in insects, recognition of mates and predators is often based on distinctive colours (Parker, 2006). Mammals are capable of re-identification based on *smells* and *shapes*. In humans, the strategies involved can be more complex.

The results of natural evolution have provided evidence that different strategies had been selected for the functional need of re-identification. The different strategies may imply two factors in the choices of the nature. Firstly, to an organism, it may consider that only the relevant portion of the environment needs to be represented. For example, one is to make the distinctions of identities which are relevant specifically (e.g., recognising specific *predators* in birds (Allen, 1998)). However, the other strategy may have aimed at representing identities beyond those immediately visible, including the representation of the large scale environment and the representation of the identities which may not be directly relevant. Secondly, different strategies also imply that the evolved representation systems can support the representation of the environment with different degree of accuracies. Some allowed the pursuit of the increasingly accurate representation of the environment (e.g., in mammals and primates). Other strategies traded-off accuracy with fast processing and quick responses. The selected strategy is either for

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17 See Parker (2006) on the role played by distinctive colours in re-identification and identification in insects. However, systematic studies are needed on this topic, which is beyond the scope of this thesis.
fast responses or the most accurate representation of those identities in the environment.

Over the evolution of the human brain, however, there are also increasing numbers and different sorts of functional needs, which are directly related to the development of cognitive and conceptual systems. A person uses the representation not only to re-identify the identities in the environment, but to classify, to infer, and to make a suitable decision on what to do and to reason about what actions are to be taken in order to reach certain goals. While the basic functional needs from the representation of “natural units” of substances can be realised by different strategies, the adoption of a particular strategy has consequences for further development of representation to satisfy other potential functional needs. However, the possibilities that these functional needs can be raised and satisfied are contingent upon the earlier selection of strategies in making representations.

In order to satisfy the functional need of re-identification, apart from the fast responses to dangerous situations, the human mind has evolved with the capability to develop the representation of the environment going beyond the immediate surroundings. The strategy which has resulted in the human brain has prepared the brain becoming capable of representing the increasingly complex situations in the environment with sufficient accuracy.

2.3.2 The implications of the functional principle on representation

The functional principle has direct implications in understanding how the representation of identities can be realised in mind. This subsection will clarify three issues. Firstly, Piaget’s action-based theory is adopted for the development of representation and knowledge (Phillips, 1981). In other words, representation is not about codes and coding. Secondly, figuratively, the representation of an identity is defined by the representation of other identities. That is, the conception of an identity can be defined in terms of its similarities and differences from other identities. Thirdly, for understanding nature’s design of representation in mind, i.e. for understanding how the representation in brain and in mind can be and may be realised, the principle of second order isomorphism proposed by Shepard and Chipman (1970); Shepard (1981, 1987, 2001) will be the general guide.
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Representation in biology is not about coding

Regarding the representation in mind, it is important to differentiate two schools of cognitive theories. One is the school which follows the information processing theory. This school, involving most cognitive studies, often emphasises or implies codes and coding for representation. The information processing theory has a profound influence on the study of representation and memory in mind. Indeed, the study of memories follows the metaphor of the brain as a computer rather closely. In earlier days, following information processing theories, there are the differentiations of memory into short-term memory, long-term memory (Craik and Lockhart, 1972), and working memory (Baddeley, 1986). The meanings of these terms come from the way information is processed in a computer18.

The other school proposed interactive theories (Bickhard, 1998, 1999, 2001; Glenberg, 1997). Piaget’s action-based theory of representation is one of them. According to the in-

18While the earlier studies may tend to associate the term memory with a single entity, the current understanding associates it with multiple entities in mind (Tulving, 1985, 2002; Tulving and Craik, 2005; Foster and Jelicic, 1999). Different types of memory systems are involved in these studies. Indeed, the literature is filled with proposals of different kinds of memory systems (Foster and Jelicic, 1999; Tulving and Craik, 2000, 2005). The contrasting memory systems include the distinctions between, for example, episodic and semantic memory (Tulving, 1972), implicit and explicit memory (Graf and Schacter, 1985), taxon and locale memory (O’Keefe and Nadel, 1978), habit memory and cognitive memory (Mishkin and Petri, 1984), declarative and non-declarative (Squire, 1992) or procedural memory (Cohen and Squire, 1980; Cohen and Eichenbaum, 1993), controlled versus automatic, conscious versus unconscious, intentional versus unintentional. Roediger III et al. (1999) commented: the different memory systems are identified with “different criteria, different names, and have different approaches to the whole issue. . . . With this cacophony of opinion from supporters, one hardly needs critics” (Roediger III et al., 1999, p.35). Similar criticism of such proliferates of memory theories can also be found in Watkins (1990).

In current literature on memory, memory is about the imprints of experience in the brain and the memory studies become closely associated with neuroscience studies, which look at the functions of different brain structures. It is also commonly taken that different types of memories are associated with different brain areas, which support different cognitive functions. For example, semantic memory is considered to rely heavily on posterior cortical regions, episodic memory on hippocampal regions, and working memory on prefrontal cortical regions (Munakata, 2004). However, the clarification of the Ontological commitment of different memories (i.e. what experiences the memories are representing) shall be crucially important for understanding the diverse proposals of memories.

In cognitive literature, the information processing theory is also taken for granted. There are two different understandings on how the representations in mind are coded. The debate is on whether the representation is in spatial codes (Kosslyn et al., 1996) or propositional forms (Pylyshyn, 2002). However, this debate is irrelevant, given they are more about expressions of the representation in different forms.
interactive theories, representation develops from the interaction between the organism and the environment. The actions and interactions with the environment are emphasised as the foundations for representation. According to Piaget, representation is implied in the actions towards the identities in the world (Phillips, 1981; Chapman, 1988). Different actions upon the identities mean the differentiations of them. However, Piaget’s theory also allows the development of symbolic systems of representation and conceptual systems of representation in mind.

The thesis follows the interactivist’s position. Indeed, the two understandings of the representation system in biology, the coding or interactive theory of representation, can be evaluated functionally. They can be judged based on their usefulness and efficiency in fulfilling the expected tasks, such as re-identification and the efficiency in adaptation. Functionally, an interactive theory has more advantages. While both codes and actions can be used to represent, the former emphasises the representation of categories or concepts. The latter is about the identities as natural-units in the world. The two theories are differentiable in terms of the efficiency in their corresponding evaluations of the quality of a representation. In action-based theory, the effects of actions can be evaluated straightforwardly for their effectiveness (Bickhard, 1998). The properties picked up about the identities can also be judged based on their efficiency for reliable re-identification and useful inferences (Millikan, 1998a). However, the evaluation of the truth values of concepts is a philosophical conundrum and virtually impossible. The functional evaluation should also take the criteria on how well the representation system can allow adaptations. A coding system is rigid. However, an interactive theory which emphasises actions in the environment is better suited for such a demand of adaptation. Action-based theory is more flexible, and even animals can have representation (Allen, 1998). Representation in biology is not about coding or at least does not start with symbolic codes and coding.

On conceptions of identities derived in comparisons

In Piaget’s theory, representation of identities lies in the generalised and specialised action schemes. Piaget’s understanding of identity representation emphasises the conservation of actions towards the identity (Phillips, 1981; Piaget, 1972). The explicit conception of an object is derived when it is compared with other identities in terms of generalisation and specialisations of action schemes. This point is repeatedly emphasised in Piaget’s study on children’s imitation for object learning (Piaget, 1962). This is the fundamental difference in Piaget’s theory in
comparison with the understanding of representation in most figurative theories.

From a figurative perspective, this means directly that the representation of one object is based on the similarities and differences of the objects in comparison with others. In other words, the representation of one identity can be described by the representation of another identity in terms of the conceptual distance between them. A note should be made regarding the position of Millikan (1998a) on this issue. According to her, the representation of an identity is associated with the perceptual tracking of information about the identity. If different properties are picked up by the perceptual system, there are different representations for an identity. However, the formation of a conception for an identity is a different issue. For the conceptions of identities, there is the mechanism of conceptual tracking (Millikan, 1998b). Unfortunately, she did not give a precise definition or detailed explanation of this very important idea. From a figurative perspective, this conceptual tracking should also be associated with the capability of comparison of objects for similarities and differences. However, unlike perceptual tracking, conceptual tracking can be made in both the presence/absence of the physical stimuli. That is, the representation of the substances can become the objects in thoughts (i.e. internal thinking) and in propositions (i.e. externalised expressions of thoughts).

**On representation following the principle of second order isomorphism**

This thesis follows the position that the representation of an identity is developed based on the comparison of it with other identities and defined in terms of its similarities and differences to other identities. The representation system as a whole can be realised based on the representation of similarities and differences between and among identities. This understanding of representation is in fact the essence of the representation theory of Shepard et al (Shepard and Chipman, 1970; Shepard, 1981, 1987, 2001) in terms of the second order isomorphism. The second order isomorphism means representation is about the representation of similarities and differences, rather than the true duplicates of the things in the world. This principle of second order isomorphism is followed in understanding how representation of identities in mind can be realised.

However, there is yet a theoretical issue to be answered, given concepts of different nature cannot be meaningfully compared for similarities and differences directly. Indeed, from the figurative perspective, the number one task is to explain the conceptual systems (structure and
the contents for representation of a system of identities) in mind for the representation of the environment. There are two conditions for such a theory of conceptual development and representation. For one thing, the development of the representation system has to deal with the increasing number of identities on the one hand, the differentiations of identities of different ontological natures on the other hand. For another, regarding the attributes involved in the representation of an identity, there are developmental changes (Smith, 1989b; Vygotsky, 1986), i.e. there are different attribute dimensions and against them different values are measured for distinguishing one identity from others. For example, an identity is first understood from its functions in terms of actions on them. Later, an identity is described with percepts of properties about the state of it as a figure. Then, the differentiation of the identity can be made in terms of differences in the descriptions of the contents and contexts of it. At last, they are differentiated into core-domains with different representation templates for identities from different core domains. Within their core-domains, the representation of an identity is only compared with other identities of the same core-domain for similarities and differences. Indeed, for such issues to be addressed, it requires the understanding of the states of cognitive structures over development and structural constraints on representation.

The second order isomorphism can become the foundation for studying the possibility of representation in external media, such as in digital systems\(^{19}\). However, this general principle is yet to be combined with a general understanding on the constraints on representation. In other words, for the representation of identities, the second order isomorphism can integrate the prototype theory of Rosch (1978) efficiently only when the identities studied are of the same ontological-kind. For representing an identity, the idea of reference points is the essence of the prototype theory of (Rosch, 1978, 1983). A reference point is either one example which can be learned from direct experience, or the prototype of the examples, or it is an instantiation of the generalised formal schema for an ontological kind (Rosch, 1983). There are reference points for each of the ontological kinds. The representation of a particular case which belongs to the same ontological-kind is in terms of distances to the reference points. The representation for multiple identities of the same kind in mind is realised in terms of representation of similarities and differences to reference points. A similar approach with distances-to-reference-points can be applied to the model of properties and contexts\(^{20}\).

\(^{19}\)The issue of modelling is not the focus and will not be addressed directly in this thesis.

\(^{20}\)The prototype theory can be re-interpreted from the perspective of a realist theory. The possibility is mentioned
2.3.3 The functional dimension for identities and representation

The functional principle for understanding the representation in mind is a complex issue. It is not only about the nature of representation and which identities are to be represented and can be represented, it also contributes to several other discussions. Specifically, two groups of issues will be understood from the functional perspective, which will be briefly introduced. Firstly, it is about the functional expectation to represent the environment which extends in space and time and with increasing accuracy. This functional expectation has direct implications on what properties of the environment are also to be represented in order to fulfil the functional expectations and what are the other cognitive functions the representation of identities should support. Secondly, it is about the functional properties of identities in a general sense and the role the functional understandings play in the development of conceptual systems.

The functional principle on cognitive development

The functional principle is adopted to understand cognitive development. The functional demands, rather than the development of theories as proposed in Gopnik (1996), are the causes for cognitive development. The representation and knowledge of the environment is to serve ultimately the functional expectations to understand the environment and act accordingly in the environment. The purpose is to facilitate an organism to solve real world problems of different kinds. This often involves the representation and models of different kinds of situations in the world.

Fundamentally, the development of cognitive systems is constrained by the applications and potential applications. Regarding the applications as constraints on representation, the most general sense means that the development of a cognitive system is towards the capability in (Millikan, 1998a). However, the realist interpretation requires the differentiations of ontological-kinds, not only the different ontological kinds of identities, but also the differentiation of identities from the descriptions with properties, contents, and contexts. See Sections 8.3 and 8.4 for further discussion relevant on modelling identities and attributes.

The functional principle is also applicable to understanding the development of different representation systems, such as in mind, in language, and in computer systems. There are the functional expectations behind the development of different symbolic systems of representations (Nelson, 1998, 1999). Following Piaget’s position, the development of systems of symbols for representation, such as languages, requires the development of conceptual systems for its conditions. However, the topic on the functional principle for the development of language and other symbolic systems of representation is beyond the scope of this thesis and thus excluded.
to support the representation of (any arbitrarily defined) situations in the environment. There 
are indeed two observed facts. One is that the environment which can be understood expands in 
space and time. The other is that the environmental situations can always be studied in increasing 
detail. To increase the potential of a cognitive system for the representation of various kinds 
of situations has driven the different operational styles as described by Piaget. To support these 
two fundamental expectations, there are the structural changes to the cognitive and conceptual 
systems, including the specialisation of core-domains and development of representation and 
knowledge of core-domains (see Chapters 5 and 6.).

While the development of the cognitive system and conceptual system is ultimately to support 
such demands to represent any situation in the environment accurately, there are also corresponding functional expectations from the representation system in mind in general and from the 
representation of identities specifically. For example, the functional expectations often demand not only the representation of identities of different ontological kinds, but also the representation of the transformation kind, such as processes, behaviour patterns of identities, events, and causations and causal theories. Regarding the representation of identities, while the initial function of representation is to support re-identification of identities (Millikan, 1998a), there are also other cognitive functions to be supported, such as identifying the existence of an identity and categorising an identity as a member of a kind. There are attributes of different kinds for understanding identities and environmental situations. The representation of identities also supports the inferences of properties about individuals or categories. Such inferences can determine the possible involvement of an identity in an application or support a person to make sensible responses, behaviours, and decisions of projects.

The functional constraint and properties of identities

The functional principle is also followed for understanding the development of a conceptual 
system. There is the functional constraint on identities for their representation. That is, for identities to be studied and represented, they must have a functional value. The functional 
constraint means identities should bear functional relations to an organism either directly (i.e. 
their affordances to the needs or relevancy of a person) or indirectly (i.e. they are functionally 
related to other objects which can be used directly by a person). The functional values of

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22See Section 6.2 for further discussions.
identities mean they are relevant for not only the *biological* needs, but also the *cognitive*, *social*, and *emotional* needs.

The functional constraint on what identities can be represented is to be differentiated from the functional properties of identities, although the two bear inherent relations. The functional constraint of identities is that the identities in the world need to have the functional values to be represented. The functional properties are about the understanding of identities in terms of their functions or the uses the identities can afford. While the functions of identities are determined by their own natures of existences, for *figures* in the *common-sense-world*, the functional properties of these identities are learned via direct actions upon them, i.e. the exact ways identities can be and are interacted with by a person. The functional properties are understood in terms of the *action schemes* and *exact actions* which can be applied to the identities (Piaget, 1954). The functional properties are acquired when an identity can play a particular function in an application (Piaget, 1962). For example, a needle is for sewing. Two other points can also be made. One is that an object can have multiple functions. The functional properties commonly known to an identity can be different from the exact function an identity plays in certain circumstances. Some functions of an identity can be known by a person, and a person may always find an innovative use of an identity. The other is the understanding of the functional properties of identities is an objective and subjective matter. That is, the cultural dimension also contributes to the understanding of functional properties of identities (e.g. pork is not considered food in some culture).

In cognitive literature, functional properties play the defining role in categorising artefacts (Humphreys and Forde, 2001). However, the functional properties of identities are important to classify any identities (not just the artefacts) into their categorical groups. That is, the functional dimension plays an important role in distinguishing the ontological kinds of identities and grouping identities into categories. Indeed, there are four levels of functional distinction of identities. Specifically, to the understanding of identities (as wholes), the functional properties are in terms of 1) their direct relations to the biological needs of a person (e.g. differentiations of substances as *food*), 2) the interaction and haptic manipulations applied to them by a person (e.g. functional based differentiations of *tools*), 3) their functional roles for being the *parts* or *wholes* towards other targeted *figures* in the *common-sense-space*, and 4) if they are identities in the small or large space, their functional relations to a person or other identities in the *common-sense-space*. 
Indeed, the functional dimension is crucial for the development of conceptual system i.e. conceptual organisation and re-organisation of identities. The conceptual system is developed in mental operations, i.e. the applications of representation and knowledge in mind for dealing with various demands of a person. In the operations of a cognitive system, on the one hand, identities of different ontological-natures with direct and indirect functional uses are learned and sorted into groups based on their shared functions and perceptual dimensions. On the other hand, the representation of an identity develops and can be in different forms (Vygotsky, 1986; Karmiloff-Smith, 1992). The issues of conceptual development will be studied in details in the rest of this thesis.

2.4 The structural principle for the representation in mind

The third presumption in the understanding of the representation of identities in mind is the structural principle. The structural principle is related to the understanding of the constraints on the representation of identities of spatial features. In this section, there are two main contents. Firstly, the need for a figurative re-interpretation of Piaget’s characterisation of a structure is argued since his description of a structure is abstract and cannot be adopted directly for the purpose of modelling in digital systems. The distinction between the brain systems versus cognitive systems versus conceptual systems will also be given. Secondly, the meaning of the term of structural principle as used in this thesis will be explained, which is associated with the constraints on the representation of contents in a conceptual system. Other meanings which are often associated with the term structure in cognitive studies and in the representation theory for SISystems will also be examined.

2.4.1 Towards a figurative re-interpretation of Piaget’s theory

The theory developed in this thesis is mainly based on Piaget’s grand theory of cognitive system and development\footnote{Piaget’s theoretical positions are scattered in a huge number of his own publications. There are several books which are directly relevant to this thesis. The list includes the books with empirical studies, such as his study on children’s construction of reality (Piaget, 1954), the development of representation of space (Piaget and Inhelder, 1956), the development of representation and knowledge in imitation and play (Piaget, 1962), the development of mental imagery (Piaget and Inhelder, 1971), and the development of memory (Piaget and Inhelder, 1973). It also}. As argued earlier in this chapter, Piaget’s action based theory is compatible
with a figurative theory which focuses on representation of identities, given actions are applied to substances. His \textit{non-coding} approach to representation is also a great advantage over the \textit{descriptionism}.

While Piaget’s structuralist’s position sets up the general understanding on what can be called a structuralist’s theory for cognitive systems (Beilin, 1983), however, Piaget’s definition of a \textit{structure} is worded in abstract descriptions in terms of \textit{wholeness}, \textit{transformations} and \textit{self-regulations} (Piaget, 1971):

“As a first approximation, we may say that a structure is a system of transformations. Inasmuch as it is a system and not a mere collection of elements and their properties, these transformations involve laws: the structure is preserved or enriched by the interplay of its transformation laws, which never yield results external to it. In short, the notion of structure is comprised of three key ideas: the idea of \textit{wholeness}, the idea of \textit{transformation}, and the idea of \textit{self-regulation}” (Piaget, 1971, p.5) (emphasis added)

Apart from this abstract general account of a \textit{structure}, his operative account of cognitive development and the mechanism for cognitive development has made it even harder for the direct adoption of his theory when the representation of identities in the environment is the focus. Specifically, in his account of the developmental mechanisms, the two biological functions of \textit{assimilation} and \textit{accommodation} of action schemes are used (Phillips, 1981; Piaget, 1972). In his formalisations of cognitive development, Piaget introduced his own distinctive logical system (Brainerd, 1978; Chapman, 1988) with \textit{identity rules} and \textit{reversibility rules} (Brainerd, 1978). However, because of Piaget’s distinctive understanding of \textit{identity rules} and \textit{reversible operations} (Chapman, 1988), his account was not widely accepted and his logical formalisation was criticised by the logicians (Brainerd, 1978).

\footnote{See Sections 4.3 and 4.4 on the identity rules.}
\footnote{See Section 5.4 on the figurative view of the mechanisms of cognitive development.}

includes his own summaries of cognitive structure (Piaget, 1971) (also see (Beilin, 1983)), development (Piaget, 1972), and formalisation of development (Piaget, 1977) (also see Chapter 4 in Chapman (1988)). His theoretical positions were studied in other books which synthesised his theory (Flavell, 1963; Brainerd, 1978; Phillips, 1981; Chapman, 1988) and other papers of his specific theoretical positions (e.g., (Elkind, 1969) and (Sinclair-de Zwart, 1969) on his identity rules and languages respectively). A detailed review of Piaget’s theory is not the purpose of this thesis. However, statements of his positions are referenced. For a detailed study of Piaget’s theory, these references should be consulted.
In general, Piaget’s theory itself lacks a systematic account of conceptions for identities and changes in representation (Chapman, 1988). Thus, pragmatically, a figurative interpretation of Piaget’s theory on representation is needed for the purpose of modelling\textsuperscript{26}. However, the value of a figurative re-interpretation of cognitive and conceptual structure stands in its own right.

**On brain, cognitive, and conceptual systems**

In cognitive literature, *brains, cognitive systems*, and *conceptual systems* are all studied as representation systems. The brain system is the central part of the nervous system studied from the perspective of anatomy and physiology. It is also the place to hold representations of different environments, including the representation of the physical environment, of the body parts, and of the internal milieu. The representation in the brain system is defined with neurons of different kinds and their connections into patterns of different kinds and functions.

*Cognitive system* and *conceptual systems* are both used to refer to the part of a brain system with the focus on representation of the environment outside the body. The representation of the environment in both the cognitive and conceptual system is about the differentiation and representation of identities in the world. Here, a brain system is the biological substrate for a *cognitive system* and a *conceptual system*.

However, cognitive systems and conceptual systems are distinguished. There are three points for the distinction. Firstly, the representation of the environment in cognitive systems and conceptual systems are in different manners. That is, cognitive systems and conceptual systems view the environment from different perspectives. Cognitive systems view the environment in terms of what the environment can *afford* to an organism and the *actions* and *action schemes* which can be applied upon the environment. Conceptual systems view the environment in terms of *identities*, their *relations*, and *processes*. Secondly, in a cognitive system, representation of an identity is in terms of the *action schemes* applied to the identity. The recall of actions is often activated by percepts of certain properties. In a conceptual system, the representation of an identity is in terms of its similarities or differences to other identities. Thirdly, the conceptual representations of identities are embedded in the cognitive systems of representation. That is, the state of a cognitive system constrains the state of a conceptual system. Cognitive systems exist in the brains of organisms. However, conceptual systems can be re-described with

\textsuperscript{26}This is the original purpose of the study behind this thesis.
symbolic systems and realised in media other than the brains.

In a sense, cognitive systems and conceptual systems can be understood as corresponding well with the operational theory of representation (e.g., Piaget’s theoretical account (Chapman, 1988)) and the figurative theories of representation (e.g., in this thesis and in the theories of category representation). A study of cognitive systems emphasises actions. The central concepts for the cognitive systems and development are actions, action schemes as the internalised representation of actions, control of actions which can be applied to the environment, and the evaluations of the effectiveness of the actions against the functional expectations. The control of actions refers to the planning and coordination of action schemes and implementations of the physical actions (with the body and particular body parts). The cognitive system takes input from the environment, such information is then transformed and leads to proper actions upon the environment. The information processed by the cognitive systems also covers the processing of language symbols and productions of speech.

The emphasis of a conceptual system is on the representation of identities. What makes it different from a cognitive system is that, an identity is no longer implied in action schemes which can be applied to the identity. The representation of an identity is explicit and can be defined in comparison with other identities. A conceptual system is symbolic in nature. The representation of an identity can be represented by a simple node which takes a position in space-time. The recall of this identity, even if it is hidden in the world, can be triggered by the presence of another identity in the surroundings. In Piaget’s theory, it takes a child until 10 months of age to develop this understanding that an identity is an independent existence in the world, i.e. the development of object permanency. The explicit descriptions for an identity can be in terms of the functional, physical, spatial properties (Litowitz, 1977).

The distinction of cognitive systems and conceptual systems is useful for understanding the differences of terminology used in the study of cognitive systems in Piaget’s theory from those in figurative theories of cognitive systems. Piaget’s theory used actions and action schemes as the basic units of account. In the current cognitive theories of representation, the terms schema and schemata are used as the representation units for categories or concepts (Bartlett, 1932; Neisser, 1976; Jackendoff, 1976; Talmyn, 1983; Johnson, 1987; Lakoff, 1987; Mandler, 2000a, 2004). The schema or schemata are one way of representing examples and prototypes.

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27 This difference between action schemes in Piaget’s theory and schema and schemata in other cognitive theories was noted (Skolnick, 1986). The representation of identities in the form of schemata will be further discussed in
2.4.2 The structural dimension for the representation of identities

This thesis is devoted to providing a figurative understanding of a cognitive system from the perspective of understanding the mind for the representation of identities. In this particular subsection, there are two main discussions. Firstly, the discussion will clarify that in this thesis, the structural principle is about the various kinds of constraints on the representation of identities. Secondly, a few other understandings of structures in cognitive and SIScience literature will be compared and clarified.

On structure versus contents of representation

In Piaget’s theory, there is a crucial distinction of structure versus contents. The two aspects of structure and contents for a representation system were also emphasised by other theorists (Elman et al., 1996; Johnson, 2005) and transformation. Piaget’s theory considers the qualitative changes of cognitive system and he emphasised the transformation aspect, namely, the structure of knowledge (Chapman, 1988). In Piaget’s theory, cognitive structure and contents (Brainerd, 1978; Phillips, 1981) was made. The structure emphasises the totality of the cognitive system, i.e. the structure d’ensemble or structure of the whole (Piaget, 1971). The action schemes are contents. This distinction has often been criticised as abstract and unclear (Brainerd, 1978; Phillips, 1981).

It is an observed fact that cognitive systems go through development. However, the changes in the transformation aspect are supported by the changes of the underlying representation (Piaget, 1962, 1977). From a figurative perspective, the distinction of structure versus contents can be understood from the perspective of the whole and parts. There are two dimensions to understand structure and contents. Firstly, the state of a cognitive and conceptual system for the representation as a whole shall be treated differently from the mental representation of identities as individuals or categories of spatial features or other elements (e.g., studied in Karmiloff-Smith (1992) and Vygotsky (1986)). A structure may be associated with the representation system as a whole (e.g., the primary, secondary, and meta-representation studied in the theory of Perner (1991)). The contents are closely related to the exact states of representation for identities or situations as particulars or their generalisations. Secondly, the representation in mind is about the environment which is to be assimilated by the representation structure in mind (e.g., the

Section 7.3.
mental structure of Millikan (1998a)). The *structure* and *contents* are two aspects to define the *state* of representation in mind. This state is influenced by innate factor of development and experiences in the environment. The *structure* is more often associated with the relatively stable characterisation of a cognitive and conceptual system, e.g., the general patterns of representation for a kind. If there are changes to the *structure* of a cognitive system, it is associated with the qualitative changes of the brain for representation in general (Johnson, 2005). The *contents* are about the exact states and differences in states.

The cognitive and conceptual system as a whole develops when identities of functional values are distinguished and represented. While natural-units of different kinds can be represented in mind, there is no simple one-to-one direct mapping between them in the world and the corresponding representation units in mind (Piaget, 1971). The representations of identities (which are of different core-domains) define the state of cognitive and conceptual structure, i.e. the *structure-of-the-whole*. This structure-of-the-whole will constrain further representation demand. Although the development of representation (e.g. different conceptions for an identity) and the development of structure are different issues, they are closely related to each other as two sides of the same coin. The contents define the structure, and the structure constrains the contents (Phillips, 1981; Johnson, 2005). These positions on the relations of the environment and the cognitive system as a whole for its representation and *structure* versus *contents* are hallmarks of Piaget’s structuralism. It is also the most important criteria of any theory to be called a constructionist’s understanding of representation and knowledge.

In the re-interpretation of this thesis, *structure*, the representation of identities will be emphasised. A *structure* will be understood from the perspective of understanding the constraints on the representation of identities. In this study of constraints, apart from Piaget’s theory, new data and theories in the current cognitive literature will also be incorporated. In a sense, Piaget’s theory agrees with the theory of Spelke (1994, 1998) in that the capability to represent objects in the environment is largely innate. However, Piaget’s constructivist’s position in understanding knowledge is in contrast with the innate theory of knowledge of Spelke (1994, 1998). The change of representation in Piaget’s theory is not in terms of simple accumulation of information, but involves qualitative structural changes. From the figurative perspective, development is associated with structural change in the way the mind can operate in dealing with the demand to represent the environment (Chapman, 1988). Three levels of organisation and three kinds of *organisation units* for the representation of identities will be emphasised explicitly. The unit
refers to the representation of an identity, the organisation for a set of identities, and cognitive and conceptual structure for all identities to be represented. The developmental changes can be applied to three organisation units. That is, during cognitive development, these three units have all gone through changes in the process of construction. With the organisation units are explicitly introduced into the general structure of representation, the family of theories which emphasise the context and domain specificities can be assimilated.\textsuperscript{28}

**Other understandings of structures in representation theories**

The structural constraint on representations is the main issue studied in this thesis. However, the term structure has been associated with different meanings in cognitive and SIScience literature. One use of structure is in the cognitive theory of representation (Smith and Medin, 1981) where a structure refers to the forms for the representation of categories. The term structure in these current cognitive theories of representation often means the representation of categories with attributes of different kinds. In rule-based systems, the representation of a category can involve a list of properties. However, for the representation of natural categories, Rosch (1978) argued that the internal structures of the examples are to be taken into consideration. Thus, in the example or prototype based theories, a category is represented with schemata, which can include physical properties, overall shapes and sometimes with distinctive features of a surface, internal configurations with parts, processes, behaviour patterns, functional properties, and external contexts. The context can either refer to other identities in the same spatial context, or the identities which may be interacted with at some times.

The other use of the term structure is often associated with spatial properties for spatial-features in the studies of SIScience. For example, for objects, there are shapes, boundaries with distinctive features, the configuration of parts, the configuration of objects (which define a location), and topological relations. For substances, the spatial properties can refer to the textures of the material. Sometimes, structural properties of an identity also include its spatial relations to other identities which often co-exist with the identity in the same space-time. These spatial properties can be handled by the perceptual systems directly (Gibson, 1969; van Essen et al., 1992; Norman, 2002).

The third use of the term structure is in the area of information system where models of

\textsuperscript{28}These theories were reviewed earlier in Section 2.2.
identities of different kinds are constructed in digital systems. For example, the study on how to digitally define the shapes or boundaries of spatial features and how to efficiently store spatial data which define the shapes or boundaries is about data model and data structure. A data schema, such as a frame in the frame-based system (Kuipers, 1975; Winograd, 1975), refers to the formal specifications for the representation of categories. A model of a category often involves descriptions with attributes. Usually, the data schema should allow the specifications of different kinds of attributes for modelling categories. However, for the concern of a knowledge representation system itself, two issues have to be handled properly. One is about how the specified attributes in a frame are interpreted in logical and mathematical forms. The attributes can be modelled in terms of functions, topological and geometric forms, or simple numerical values. The other is how the relations of the attributes can be handled. Usually, the attributes for natural categories are not independent to each other (Rosch, 1978). Different attributes can bear strong correlations, e.g. a beak and wings are two correlated attributes for a bird.

While formal specification of the representation of identities of different ontological kinds is not the focus of this thesis, however, the constraints on the development of formal schemata for identities of different ontological kinds, the constraint on the inclusion of attributes of different kinds in representation, and constraint related to the formal interpretations of attributes will be studied in Chapter 7.

2.5 Summary

This chapter has argued for the biological principle in understanding the representation in mind. Section 2.2 stated that the central concern of representation in an organism is for the representation of the category of substance, i.e. the “natural units” in the world, also called the identities of spatial features in this thesis. The representation theories which focus on the representation of identities as individuals should be distinguished from the representation theories which emphasise the representation of categories or concepts. Brief but critical reviews of current cognitive theories of representation and Millikan’s theory were also given.

Section 2.3 argued for the adoption of the functional principle in understanding the nature of representation. It means representation in mind is to fulfil the functional expectations from such a representation, such as to support the re-identifications of an identity. The functional nature of representation bears direct implications on how the representation can be realised and evaluated.
With this functional principle, the descriptionist’s understanding of representation in mind in terms of codes and coding is discarded. Instead, the principle of second order isomorphism is adopted. That is, the representation of an identity is in terms of its similarities or differences to other identities. Few other areas of studies where the functional principle should be applied were also covered, including the functional constraints on identities in order to be represented, other functional expectations of a representation system in mind, the meaning of functional properties and the functional dimension in the conceptual organisation of the representation system.

Section 2.4 explained the structural principle of representation. The distinctions of a brain, a cognitive system and a conceptual system as representation systems were made. The structure and contents as two aspects of a representation system were distinguished. For the purpose of modelling, the need for a figurative re-interpretation of Piaget’s abstract idea of structure and his operational account of cognitive development was argued. In the development of the new figurative theory, the section also clarified that in this thesis, structural principle is about the four distinctive levels of structural constraints on the representation of identities. Other uses of the term structure were explained.
Chapter 3

A situation based figurative interpretation of Piaget’s cognitive development

3.1 Introduction

This thesis presents a situation-based theory of cognitive and conceptual systems in minds. In this particular chapter, the two fundamental points of this new theory will be covered. Section 3.2 will introduce the conceptual construct of situations. A situation is defined as a spatio-temporally framed part of substances in the world. Section 3.3 will use the conceptual construct of situations to re-interpret Piaget’s operative classification of cognitive systems. Four levels of cognitive systems are distinguished based on what kinds of situations in the world can be represented. Four stages of conceptual systems are distinguished based on what kinds of identities can be explicitly represented and what forms of representation can be given to the identities. The general positions regarding the constraints on the representation of identities will also be covered.

3.2 The situations in the world

The idea of situations is introduced in this thesis to study the world. A situation refers to a unit of spatio-temporally framed substances in the world, i.e., a four dimensional (4D) unit of substances in the world. A situation exists as a portion of the world. It has states at different times defined in three dimensional (3D) space and transformations of states over time (1D).  

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1The ontological understanding of the environment with 3D space and 1D time is commonly accepted in SI-Science (Couclelis, 1992, 1998b). (Goodchild et al., 2007, p243) also define a geo-atom in terms of “an association between a point location in space-time and a property.” However, in this thesis, a 4D unit of substance as a situation in the world and the formal model of this are also ontologically differentiated. Different subtypes of situations also demand different formalisations. However, specifying these different subtypes, their relations, and real world
In this section, some primitive distinctions of situations in the world and general aspects for cognitive understanding of situations will be given. Specifically, with this situation-based Ontology, three points will be made. Firstly, there is the ontological distinction of the self (i.e. an organism) versus the rest of the environment (excluding the self). The environment as a whole is defined with the integration of the representation of situations in the world. Secondly, there is the ontological distinction of two basic kinds of situations, namely, situations with substances and situations with objects (Couclelis, 1992, 1998b; Goodchild et al., 2007). A few primitive subtypes for each of the ontological kinds will also be covered. Thirdly, from the cognitive perspective, there is also the function-based distinction of situations in the world. That is, situations in the environment which are relevant for an organism can be seen as the figures, the contents of figures, and contexts of figures.

3.2.1 The self in the environment

From the perspective of an organism, there are two primary distinctions of the situations in the world. One refers to the distinction of the self from the rest part of the world (hereafter the environment) excluding the self. The self and the environment are two ontological kinds. The other refers to the distinction of two kinds of environment. Specifically, the environment can be differentiated into the physical world of substances and the symbolic world. Language forms a special part of the symbolic world. So do the symbols used in logic and mathematical studies.

Indeed, the first landmark achievement of cognitive development for a human infant is the explicit differentiation of the self from the environment. To a neonate, an explicit idea of the self as the agent of actions is the first step to be developed for cognitive systems. According to Piaget’s theory, it occurs at no later than one month old at the end of the stage I of the sensorimotor period (Brainerd, 1978). Before stage I, the environment is mainly understood in terms of the non-differentiated continuity of substances\(^2\). Piaget characterised this stage as “narcissism without a Narcissus” (Piaget, 1972, p.21), given the world is contingent to the actions of an infant, the infant still has no accommodation of herself in her mind. By the end of stage I, there are the self versus the environment, and the two are understood as connected by the actions of the infant. Infants can now explore what they can do and what results these 

\(^2\)But see the review in Gibson (1988) of the studies which demonstrated the earlier competency of an infant who can differentiate the movement of the self and that of the environment
actions can bring about\(^3\).

**The primitive distinctions of the situations in the environment**

The physical environment is made of the continuity of substance in space-time. However, with the concept of situations to understand the world, there is another ontological distinction of the *world* from the *situations* as the portions of it. Situations in the world can be of different sizes and extend in different spaces. Some units of situations are smaller and can be held in hand. Some are larger and extend beyond the reach of direct visual examinations. The world as a whole is the container which contains situations as its parts. In the meanwhile, the world is represented via the representation of these situations. There is the representation for a *largest situation* in the mind of a person, which is an integration of the representations of all the situations experienced by the person in the past.

As a 4D unit of substances, a situation can be represented with the substantial contents or formally defined either with spatio-temporal coordinates for its boundary (Golledge, 1993). A situation can be distinguished by the substances inside its spatio-temporal frame. Following Piaget’s theory, the cognitive representation of a situation starts with *actions* upon it (Phillips, 1981). The representation derived from this manner is about the *substantial contents* of the environment. There is an ontological distinction between the *situations in the world* which exist objectively in their own right from the *representation of the situations in the mind of a person*, which can be *subjective* depending on the experience and the developmental stage of the person (Phillips, 1981; Johnson, 2005). To an organism, not everything in the environment

\(^3\)This sense of the *self* which is in contrast from the rest of the world is a general one. The *self* (i.e. I) as a part which contrasted with the rest of the environment and an *agent* of actions is different from the sense of the *self* (i.e. me) as one individual among others and when a child develops self-consciousness. This self can act upon situations in the environment. In Piaget’s theory, the representation of the environment is developed during the *actions* and *reactions*, which is one part among others which defines the self as a distinctive person (Phillips, 1981). Different species and different people can have qualitatively different representation of the same environment (Chapman, 1988). The actions of the self can be mechanical, biological, and emotional and always with purposes either instinctively reactive or calculatedly intentional. However, the *self* is also a *part* which is embedded in and constrained by the environment. As a part of the environment, the self is *physical object*, a *biological entity*, and a *social member* of variously defined social groups. The self as an *agent* of actions takes this into consideration. There is an *actor* as well as an *observer* who observes both the others as well as the *self* and adjusts following actions correspondingly.
can be relevant and thus be represented. The cognitive representation in an organism focuses only on the biologically relevant situations in the environment. A situation should be and will be represented if it is biologically crucial. The innately determined potentials of our cognitive systems shaped by evolutionary history are closely related to the situations our long ancestry has experienced and the choices of strategies to get them represented.

The representation of a situation can be defined in terms of its boundary in space-time. For situations on earth, the boundaries of situations can be defined in two ways, either the relative or absolute representations. The boundary in relative terms means it can be defined in terms of relations with other situations. While a situation is a portion of the world as a whole, it bears spatial-temporal relations to other situations which take different positions in space-time. The concrete environment is differentiable into variously defined situations. A situation is inside a larger situation and contains smaller situations simultaneously. The various situations as portions of the environment can be organised into two kinds of structures. On the one hand, there is a hierarchy of situations where the larger situations contain the smaller situations. On the other hand, two situations can be separate elements of a larger situation. They exist in parallel in different locations in space-time\(^4\). The boundary in an absolute representation involves Geometry and geometrical coordinates. For a situation in the environment on earth, geo-coordinates are used for spatial resolutions and extensions and Calendar time for temporal positions. However space and time are both theoretical constructs which extend infinitely. They do not exist in the physical sense. In Piaget’s theory, the capability to define the environmental situations which involves the configurations of objects is developed in the concrete operational period. The capability to define environmental situations in Euclidean Geometry and to apply Geometry for represent space-time starts to develop when a child is in the formal operational period (Piaget and Inhelder, 1956).

Mathematically, when situations are defined with geometry, the situations can be as small as can be. The value zero has different meanings when it is applied to spatial and temporal dimensions. Zero space is the theoretical limitation on how small a situation can be. While situations can be as large as large can be, there is no situation in the world which is smaller than zero. In this sense, 0 in space is absolute. The 0 point in time is relative. If zero time means the present, then the negative numbers mean the past and positive numbers the future. Here, 0 can be arbitrarily chosen based on a particular event. However, time is also defined for measuring

\(^4\)Further studies on the relations of situations and the environment can be found in Section 4.2.
the period an event can last. In such cases, 0 means no time. Different events can occur at different places in the same time. Thus, for situations studied in SISciences, when they are formally defined, they can be defined by the two parameters. That is, the formal specification of the situation in terms of spatial-temporal resolution and extension. The extension corresponds to the situation of the minimum size in space-time where the configuration of all the relevant occurrences as the components of the situation can be contained. The resolution corresponds to the spatio-temporal units (which are inside the situation) of the maximum size which are about the data supports where the properties which are relevant for the identities can be measured.

3.2.2 Situations of fields of substances versus with objects

The situations in the environment can be further differentiated based on the structural consideration. An important structural based ontological distinction of situations should be made, i.e. situations with fields of substances treated as homogeneous versus situations with objects as heterogeneous. In the latter case, there is at least one object as separated from a situation in the environment as its context. This distinction corresponds to the distinction of substances versus objects view of the world in the study of SISciences (Chrisman, 1996; Couclelis, 1992, 1998b). This development where an identity is differentiated from a situation is possible when the two kinds of identities are differentiated. One refers to the substances. The other refers to the objects with clear boundaries. The studies in perceptual development have provided convincing evidence that in Stage II infants (about 4 months old), the perception of shapes in 3D space is fairly developed (Gibson, 1988). However, the explicit representation of objects with boundaries as distinctive kind from substances in general is perhaps achieved until stage IV. In Piaget’s theory, the change in stage IV is called object permanency. Here, according to Piaget, children have developed the understanding that an object exists in the world in its own right, which relates to other objects and can be located based on its relations to other objects. However, this representation of an object in stage IV is rather restricted given the representation of locations defined in terms of configurations of objects is still under development.

The contents of a situation can either correspond to the homogeneous substances or be heterogeneous with objects contained within it. This distinction is crucially important for the development of cognitive systems. With an object distinguished from the situation, both the identity and the situation which contains it can become the contents of representation in their
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Figure 3.1: On spatial features as figures in the world

own right and supported by the cognitive structure. There is also the corresponding development of the representation system where an identity is seen as in a situation, and an identity as a part of a situation is in the same sense that a situation is a part of the environment as a whole. The two types of situations can be further differentiated. A few more subtypes for each kind will be defined below.

On formal differentiations of situations with substances

A situation, which is a part of the world, can be defined in terms of the substances contained within it. One subtype of situations can be conceived as with the continuity of substance within the spatio-temporally defined locations, i.e. situation-of-substances or situation-of-fields. However, the continuous substances inside a situation can either be homogeneous or heterogeneous\(^5\).

The situations which are filled up with continuous substances are parts of the direct or indirect environment for people. A situation of substances is one which can be acted upon

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\(^5\)These subtypes of situations will be further discussed in Section 7.3 on ontological kinds of identities which can be handled by the fourth-level cognitive system.
directly. It can be homogeneous in that the substances are largely the same basic type (e.g., a body of water). A situation of field-kind refers to the case where a situation is in the large scale environment.

A situation-of-field is largely considered being filled up by the “substances” for being the “contents” in general which is of some kind. However, internal variations of the substances (e.g. different soil types in different locations) are possible. Being heterogeneous means there are at least two types of substances contrasting with each other. There are again two subtypes of the heterogeneous fields, object like or contrasting situations (e.g., ore deposits versus coastlines). For being the environmental contexts relevant to the lives of people, these two subtypes are studied with different focuses.

A contrasting situation refers to the case where a situation can be divided into several parts of different substances (e.g., geographical features, such as coastlines). Such a situation is particularly relevant to the study of the Earth’s surface. For a study of landscape, a situation can include different substances which share boundaries, e.g., the solid material for the earth and the air above. The sudden changes of this shared surface of the Earth define the landscape of plains, mountains and valleys. The study of coastlines deals with the same kind of situations. These landscape features are important landmarks in nature. However, there are also artefacts as landmarks. The sharply changed surface features define the distinctive grounds which can be relevant for a person. Other examples include the geographical features such as coastline or river bank. To the cognitive concern of a person, the fast changing boundary between these two substances is of great interest.

A situation-of-field can also refer to a region. Regions are situations in large scale environment. They can form a hierarchy where the situation as a whole can be divided into smaller situations. For example, a country can be divided into provinces, and each province can have counties or districts. A city has different suburbs, and a suburb has blocks of buildings. There is another kind of region or geographical region, which refers to a kind of homogeneous or heterogeneous background of situations (see Figure 4.2). It is about the case where a situation is the environmental context of a person or other interesting objects. A region can refer to the background as a whole. However, regions can also be variously described based on the selections of attributes to make differentiation of the regions. That is, the same area can be studied from different scientific perspectives. When the background as a whole can be further differentiated into a distinctive feature part (i.e. a spatial feature of the object like with certain nature
and a size) and the surrounding background, a region can also refer to the distinctive feature of the background, which bears direct or indirect relations to the lives of people.

**On formal differentiations of situations with objects**

A situation in the environment of a person can have at least one distinctive spatial feature contained within it. In this case, it is a situation-of-object kind. A situation can have a single object or multiple objects identified within it (see Figure 4.2).

A simple situation refers to a situation which has a single object identified and the rest as the background within a spatio-temporal frame. The situation as a whole is defined with the object and the background are two distinctive parts. It can also be characterised by the single object or the background. When the object is the focus, both the situation as a region and the background define the contexts of it.

A situation with multiple objects identified within its spatio-temporal frame is called a complex situation. A complex situation as a whole can be defined with these identified objects and the rest of the situation as the background which excludes these objects. That is, the complex situation itself is characterised by these objects, the spatio-temporal and causal relations of these objects, the background, and the possible causal relations of the objects with the background which immediately surrounding them. For an object in such a situation, the contexts of the object can be variously defined, such as indicated by any of these other objects which function as landmarks, by the collection or configuration of them, the background, and the region as a whole.

For situations with objects, these objects can be further differentiated into those belonging to different core-domains in the common sense world (e.g. physical objects, organisms, and people (Carey, 1985; Gelman and Markman, 1986; Keil, 1989a; Wellman and Gelman, 1992, 1998)). However, for the study of the environment of a person, the matter is complicated when situations in the large space which is beyond the direct sensorimotor experience are also to be taken into consideration. For a figure as an object in a situation, depending on the nature of the situation, there are the ontological distinctions of objects versus complex kinds (e.g. natural-systems, and social-organisations).

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6The formal definition of the concept of core-domains can be found in Section 6.2. Based on the cognitive literature, Chapter 6 is devoted to a critical study the cognitive literature on core-domains and their constraints on the representation of identities.
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For studying an identity as a figure in a situation, there are not only spatial features which are defined on the same spatial-temporal scale (as the figure), but also natural-units defined over smaller or larger scales which are also relevant for the figure. Such natural-units are usually directly related to the contents or contexts of the figure. For example, there are smaller “natural-units” which correspond to parts of the figure or samples as the smaller portions of substances which support the measurements of physical properties. Thus, even when there is only a single identity within a situation, there is still the possibility to make further differentiations of situation with the “natural-units” which are relevant for defining the contents of a figure. Such natural-units can go infinitely small. The background part of the situation, which is the context of the figure, is also further influenced by the even larger situations which contain it. The situation which functions as the indirect context of the figure can go infinitely large.

3.2.3 Situations as figures, contents, and contexts

Cognitive representation of the environment starts with the sensorimotor experience of the state of the environment at a time and transformations of the states over time.

From the functional perspective, there are always three functional roles for any natural-units in the world to play, namely, the role of being the figures, contents, or contexts. For the concern of an organism at a time, the situations in the environment can also be differentiated into three kinds. First, they are the figures of interest of an organism. That is, when a situation is the focused target for the direct actions of an organism, it is a figure, also called standalone identity in this thesis. Second, they are the contents of figures. When a situation is within the boundary of a figure, it is about the contents. The contents of an object can be the structurally or functionally distinctive parts, the portions of substances, or sample points or data supports for measurements of properties which are relevant for the study of a figure. Third, they are the contexts of figures. When a situation is a large situation which is the container of an identity, it is the context of an identity. The context can be defined differently. It can refer to the boundary of the situation, a collection or configuration of other objects in the same spatio-temporal frame, or the ground part of the situation excluding the figure (See Figure 4.2). However, the context of an identity can go beyond its container. The locations studied in the environment are the distinctive parts of the world near the Earth’s surface. They are spatial features in the large scale as locations of people or other objects interested by people.
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Representing situations with contents and in contexts

A situation is a generic idea. Identities can be special situations. Both the identities within a situation and the situations themselves are contents of the cognitive system. The contents of representations in cognitive systems are either for identities which have situations as contexts or situations which are defined by identities as the elements.

The representation of an identity with situations as its contexts and the representation of a situation which has identities as its contents are closely related but also different subjects. From the data collected in cognitive literature (in particular, the studies on object permanency) (Bremner, 1985, 1998), it appears clear that the earlier representation of an identity is indexed by its locations and closely related to the representation of locations as existence in their own right. Locations are not only interesting in their own right, but also important for searching, locating, and re-identifying objects.

For an identity as a natural-unit to be studied, it is studied as a figure with its contents and within contexts. Firstly, an identity is treated as a whole. Cognitively, an identity as a “natural-unit” can be studied solely in terms of the direct actions upon it from a person. However, other properties of the figure, such as its shapes, processes, and behaviours, can also be observed. Secondly, an identity is studied for its internal contents. Depending on whether the identity is a simple or complex one, it can have one more distinguished part within it. The study of the internal content of an identity is used to explain the overall behaviours or functions of the situation to the perception of a person. Thirdly, an identity can be studied with the understanding of its external context. The contexts of an identity are those larger situations which function like the containers. The contexts are important for understanding the conditions or causal constraints for the processes or behaviours of an identity. While in the cases where identities are studied on their own, there is no objective context for it apart from the person who interacts with it and develops a sensorimotor based understanding of it. When the external contexts of a situation are examined, there are objective spatial, temporal, and causal relations to be established. Indeed, there are kinds of relations to be distinguished, such as the spatial relations (of states) of identities in space at a time, the relations of states of an identity over time (i.e. processes), causal relations of identities as individuals when they interact (i.e. causations), and temporal relations (of states) of different identities (i.e. in events) overtime. The identities and these relations are
all parts of the representation for a situation\textsuperscript{7}.

For a situation as a 4D unit of substance, it can often contain identities of spatial features as distinctive elements within it. These identities are identified within the situation and characterise the situation. Again, there are three aspects regarding the definition of a situation with the identities contained within it. Firstly, the identities which are recognised as the internal components of the situation can have states, shapes, processes, and behaviour patterns. There are boundary parts of objects which are considered functionally or structurally important. The configuration of the boundary parts shall define the overall shapes and functions of objects. Secondly, these identities which are contained within the situation can have their own internal parts and material components. The configurations of internal parts are often associated with their processes or behaviours. Thirdly, the context of an identity within a situation is about the rest part of the situation excluding the identity and beyond. When there is more than one identity in the situation, these identities bear certain spatial, temporal, and possibly causal relations to each other. However, the context of an identity is not restricted by the situation which contains it. In fact, such situations as the contexts of the identity can be infinite as long as they are containers of the identity\textsuperscript{8}.

The representation and development of representation in the cognitive system is towards a better representation of the environment. It is also for the representation of situations of different kinds in the environment. On the one hand, the representation of a known situation can be associated with increasing detail of information about it. On the other hand, the situations which can be represented extend in space and beyond current time, i.e. situations beyond here-and-now.

\textsuperscript{7}An identity has internal contents and external contexts. The study of identities with contents and within contexts are directly related to the development of core-domains and distinctive causal knowledge of the core-domains, see Chapter 6.

\textsuperscript{8}A situation can have one identity or multiple identities within its spatio-temporal frame. The view of a situation as a whole with certain aspects of it can be examined with sensorimotor modalities is closely associated with the ontological distinction of identities, see Chapter 7.
3.3 The figurative theory of cognitive and conceptual development

In Piaget’s theory, cognitive systems have been gone through four major structural changes, from sensorimotor period, to pre-operational period, to concrete operational period, and to formal operational period (Brainerd, 1978; Phillips, 1981; Skolnick, 1986; Chapman, 1988). A situation-based figurative re-interpretation of Piaget’s four periods of cognitive development is developed in this thesis. This proposal is based on the idea of situations discussed above, Piaget’s theory of cognitive development, empirical data and theoretical explanations from Piaget’s studies (Piaget, 1954; Piaget and Inhelder, 1956; Piaget, 1962), and current literature of domain specificities on representation and development (Carey, 1985; Keil, 1989a; Gelman and Markman, 1986; Karmiloff-Smith, 1992). This situation-based account examines closely the documented landmark achievements in each of Piaget’s four periods. It separates the development of representation of situations from the development of representation of identities which are within situations.

This section will present three general points about this situation-based theory. Firstly, the four levels of cognitive systems emphasise the representation of situations of different kinds which can be represented and operated (i.e. the representation and knowledge of such situations can be applied to handle new situations) upon by a person (Table 3.1). Secondly, the four stages of conceptual systems emphasise the different forms of representation of identities which are within certain kinds of situations. Thirdly, the overview of the study of structural constraints on the representation of identities will be presented.

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9Perner (1991) also presented a situation based theory of representation. However, his theory and the theory in this thesis are fundamentally different. Two points can differentiate his theory from the one presented in this thesis. Firstly, in Perner (1991), the term situation refers to the contexts in space. In this thesis, a situation is a 4D unit, and there is the dynamic dimension inherent in this concept. Secondly, the situation in Perner (1991) (i.e. the context really) has certain focus on the contexts extending in space only. In this thesis, the situation refers to any extension in space-time. It can refer to an identity of spatial feature, its contents and contexts.

10The difference in terminology should be noted. In Piaget’s developmental theory of cognitive systems, there are different periods which correspond to the different styles the mind can operate. In this thesis, however, there are different levels and stages of the representation in mind.
Table 3.1: Four level cognitive and conceptual systems

<table>
<thead>
<tr>
<th>Levels</th>
<th>Cognitive systems</th>
<th>Conceptual systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>identities</td>
<td>From implicit to explicit representation</td>
</tr>
<tr>
<td>II</td>
<td>relations</td>
<td>Means-ends coordination, spatial and temporal relations of identities. Explicit descriptions with properties.</td>
</tr>
<tr>
<td>III</td>
<td>core-domains</td>
<td>Causal relations in interactions. Sorting identities of an ontological-kind into specific categories. Understanding simple causal systems and the productions of them</td>
</tr>
<tr>
<td>IV</td>
<td>core-domains in other spaces and representing arbitrary situations</td>
<td>Intensional definition, different kinds of category systems for core-domains, and logical-mathematical systems for representation</td>
</tr>
</tbody>
</table>

3.3.1 The four levels of cognitive systems

The cognitive system in the mind of a person can be differentiated into four distinctive levels. The four levels of cognitive systems are correlated with increasingly complex kinds of situations in the world which can be perceived, explored, and represented in a mind.

The main criteria for differentiating the cognitive systems into four levels are based on the different kinds of situations which can be represented appropriately in the mind. There are two dimensions to understand the differences of the situations in the world. One dimension is about the complexity of the situations. The complexity of situations increases when they change from situations of single identities to situations with multiple identities (see Section 3.2). The other dimension is about the locations where the situations are. Regarding the locations of situations, the world as a whole can be differentiated into three spaces, called the common-sense-space (or common-sense-world), the smaller-space, and the larger-space. To the concern of a human being, the common-sense-space is the space of the right size that is crucially relevant to our lives. This is the world which is filled up with the familiar objects, people, other animals, plants, and

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11See Table 3.3.1 for Piaget’s four cognitive periods from the operative perspective and the main achievements in each period. Also see Table 3.3 for Piaget’s six stages in sensorimotor period.
### Table 3.2: Four periods of Piaget’s cognitive development

<table>
<thead>
<tr>
<th>Period</th>
<th>Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensorimotor (0-2 years)</td>
<td>Egocentric representation of the environment. The self separated from the environment (1 month); perceptual representation of shapes in 3D (4 months) (Kellman, 1984) and recognition of faces (Johnson and Morton, 1991); object permanency (10 months); and means-ends coordination in mental operation (2 years).</td>
</tr>
<tr>
<td>Preoperational (2-7 years)</td>
<td>Representation of parts of objects. Representation of the environment with objects, and objects can be ordered in terms of their spatial-temporal relations. Symbolic plays and imitations with learning objects in focus. Language learning, language terms for concrete objects can be explained in terms of functions and physical properties, however communication is largely egocentric. No transitivity, certain understanding of the relations of order and class inclusions. No reversibility in mental operations. Development of theory of mind (at 4 years of age) (Wellman and Gelman, 1998).</td>
</tr>
<tr>
<td>Concrete operational (7-12 years)</td>
<td>Representation of the large scale environment. Explicit understanding of two relations of numbers. Conservation of quantity. Transitivity. Reversibility in operations but only of one kind (reverse or inverse, but not both). Representation of physical systems (Siegler, 1976, 1978). Differentiated core-domains and domain specific causal theories (Smith et al., 1985; Carey, 1985; Keil, 1989b).</td>
</tr>
<tr>
<td>Formal operational (12 years onward)</td>
<td>Further development of logical-mathematical systems. Capable of second order relations. Can involve both kinds of reversibility (inverse and reverse) in mental operations. Intensional definition for concepts in terms of necessary and sufficient properties. Logical inferences based on class inclusions. Becoming capable of representation any given situations in spaces other than the common sense world; Making complex physical machines.</td>
</tr>
</tbody>
</table>

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The milestones listed are mainly claims from Piaget’s theory based on research by him and associates. Other achievements with references are from new empirical studies, for example, the research on theory of the mind in children around four-years-old. Depending on researchers, there are two kinds of understanding. One is the proposal that children have a sort of naive theory of actions and behaviours of people in terms of beliefs, desires and intentions (Flavell and Miller, 1998; Wellman and Gelman, 1998). The other is the proposal of earlier understanding of different representations of the same thing exist. Different people can have different representations of the same thing because the different experiences (Perner, 1991; Flavell and Miller, 1998).
<table>
<thead>
<tr>
<th>Stage</th>
<th>Age</th>
<th>Milestones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage I</td>
<td>0-1 month</td>
<td>Response with reflexes. By the end of this stage, the self is understood as separate from the world.</td>
</tr>
<tr>
<td>Stage II</td>
<td>1-4 months</td>
<td>Earlier purposeful actions. Recognition of faces, perceptually recognise 3D objects, but no searching of objects removed from sight.</td>
</tr>
<tr>
<td>Stage III</td>
<td>4-8 months</td>
<td>Turning around a bottle to meet the mouth if it is handed the wrong direction. Searching for a partially occluded object, but stop searching if it disappears from the visual field.</td>
</tr>
<tr>
<td>Stage IV</td>
<td>8-12 months</td>
<td>Searching an object, but will search the first place A even if the object is seen as being removed from A to B. Permanent object in mind.</td>
</tr>
<tr>
<td>Stage V</td>
<td>12-18 months</td>
<td>Searching an object even if it has been shifted to several positions. Tool uses and exploring various combinations of actions to produce novel effects</td>
</tr>
<tr>
<td>Stage VI</td>
<td>18-24 months</td>
<td>Searching for an object without seeing it being shifted. Symbolic representation where an object can be used to represent another object. Mental operations with means-ends coordination to reach goals before direct actions are carried out. Representation of spatial relations and spatial contexts. Representation of collections</td>
</tr>
</tbody>
</table>
buildings. It is the space we can see, touch, and explore by moving around without the needs of any instrument to aid us. The other two spaces are those which are much smaller (e.g., the smaller space for molecules, atoms, and particles studied in atomic physics) or larger (e.g., cities and regions studied in SISciences, astronomy and cosmology) than the common-sense-space. Only when the fourth level cognitive systems are developed, the situations (with their distinctive entities or phenomena) in these smaller or larger spaces can be studied by people.\textsuperscript{12}

The four levels of cognitive systems

Figuratively, there are four levels of cognitive systems and the advancing levels of cognitive systems can deal with situations with increasing complexity. The first level (Level-1) cognitive system (starting from birth or stage I of the sensorimotor period in Piaget’s theory) can explore and represent simple situations of substances only, provided the situations are at their immediate surroundings.

With Piaget’s data, the Level-1 cognitive systems may be seen with two periods. In the first period (0-1 month), there is the distinction of the self from the environment. In the second period (after 1 month roughly), there are sensorimotor-based distinction of stuffs in the environment, but no explicit distinctions of them in their own right. That is, \textit{out of sight, out of mind}. In Piaget’s theory, the change from implicit representation of identities to explicit representation happens at stage IV of the sensorimotor period (when infants are about 10 months old), which is called \textit{object permanency}.

The second level (Level-2) cognitive systems (starting from stage IV or stage V of sensorimotor period, i.e. children about 10 months or 18 month old) can represent simple-situation with single object explicitly, provided the situations are in the direct surroundings in the common-sense-space. There is the ontological distinction of objects from stuffs in general (Xu and Carey, 1996). It can also deal with slightly complex situations with two or more objects if the objects only bear spatial or temporal relations. That is, such situations can be defined with several simple-situations as the primitives and in conjunctions.

This second-level of cognitive systems is important for the development of conceptual system. For one thing, there is the major change about the way relations of objects can be represented, from implicit representation of relations embedded in the sequences of actions in

\textsuperscript{12}See Section 4.2 for more discussion on spaces and identities in situations in spaces.
sensorimotor period (Piaget, 1972) to the explicit representation of them in the pre-operational period. The relations of the identities can be represented distinctively in their own right. However, the explicit relations are either spatial relations of objects or temporal order of them. For another, identities can be represented objectively in terms of their relations to other identities in the world. Conceptually, an object can be understood in terms of its similarity or differences to others. The explicit representation of an identity either means the recall of it based on the presence of other identities as the locational cues (e.g. in Stage V of searching of hidden objects), or it means the explicit descriptions with attributes of different kinds (as shown in the studies of language development in the pre-operational children (Vygotsky, 1986)). The explicit knowledge of attributes for identities requires the attributes to be studied as domains in their own right.

The third level (Level-3) cognitive systems (starting from the end of the first stage of the pre-operational period or the end of pre-operational period, i.e. children about 4 years old or about 6 years old respectively) can support the representation of complex situations with multiple objects, provided the situations are still those in the common-sense-space. However, there are two crucial points. One is that the relations of these identities are not only spatial and temporal, but causal. The other is that the situations can be differentiated into core-domains and as representation units in their own right, such as those in physics, biology, and social domain (Wellman and Gelman, 1992, 1998).

The third-level cognitive system is about the explicit representation of certain special kind of complex situations, i.e. core domains. Core-domains are special kind of situations in that they are both the contents of representation of the cognitive systems as well as the constraints on the representation of identities as members of core-domains. The arguments in cognitive literature on the development of core-domains in this of cognitive systems are based on two other kinds of development. One is the explicit distinction of objects into different ontological-kinds (Keil, 1989a; Gelman and Markman, 1986). The ontological distinctions can be based on perceptual observations (Mandler, 2000a), such as a person or an animal can be an agent who can initiate actions. The other the development of causal theories and different core-domains which are associated with their distinctive causal theories (Smith et al., 1985; Carey, 1985; Gopnik, 1996;)

\[13\] However, both senses of explicit representation are different from the representation in language and in logical-mathematical systems.
Ahn et al., 2000).14

The development of causal relations in children has been an important area of study (White, 1988, 1990). There are empirical evidences for the perception-based understanding of the relation of cause-effect when two objects interact with each other in children of a much earlier age (Leslie, 1982, 1984; Leslie and Keeble, 1987). In Piaget’s study of stage V and VI of the sensorimotor period (see (Piaget, 1972)), relations can be explicitly embedded in the mental operations to produce plans of actions. Two sorts of causal relations may be distinguished. One is about the action-based representation of causal relations of objects evidenced by the capability to use a tool as the mean for reaching a target (in Stage V). However, such causal relations often involve the children as the causes (i.e. agents of actions) directly. The other is about the organising the chain of relations which are embedded in a plan towards the realisation of a goal explicitly (see Table 3.3). The representations which can be embedded in a plan are of various kinds, such as spatial relations (for locating targets), tool uses (which implies certain causal or functional relations), and temporal relations of events (evidenced by the capability to use a sequence of different tools in stage VI).

However, the explicit understanding of causal relations when two (or more) identities interact and explicit distinction of objects into different kinds and core-domains based on distinctive causal relations for explaining interactions are late achievement until this third level cognitive systems. It starts from understanding the different actions of the self (as a physical object, biological entity, and social member) interact with others in the environment (Harris, 1992). For the representation of core-domains, there are also distinctive patterns of development of causal knowledge of core-domains (Carey, 1985; Gopnik, 1996). However, there are not only the naive theories of core domains, but also elaborated causal knowledge of the corresponding further development scientific domains (Gopnik, 1996; Harris et al., 1996).

The Level-3 cognitive system can support the representation of certain complex situations which include objects from the same or multiple core-domains as long as they are objects in the

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14The concepts of ontological-kinds, theories, and core-domains are the key concepts in cognitive theories which emphasises on the constraints of representation and important to the development of the figurative theory in this thesis. They will be studied in detail. The concept of core-domains will be further explained and defined in Section 4.2 and Chapter 5. The criteria for domain specialisations and the development of conceptual structure for the representation of core-domain can also be found in Chapters 5 and 6. The different kinds of causal knowledge and the concept of theories will be studied in Section 4.4 and 6.2. The concept of ontological-kinds will be studied in Chapter 7.
common-sense-space and the transformations of such complex situations can be explained by the simple causations (in particular, the physical mechanism) when these objects interact with each other. The complex systems can be the man-made artefacts (simple or complex machines). They can be the natural biological organisms or social organisations of different functions. The development of domain specific causal knowledge is important for two aspects. On the one hand, they are involved directly in predicating states of complex situations over time. There is the understanding of core-domain specific situations with multiple objects involved in the chain of cause-effect relations. The results from such interactions of physical objects can be predicted, such as in the cases with Domino games. On the other hand, they are also important constraints on the development of representation of identities (Ahn et al., 2000; Gelman, 2004). For example, they are important for the understanding of the internal parts of identities (which are complex systems, natural or man-made) for their functional contribution to the behaviours of the systems as a whole and representation of categories with distinctive features and properties.

The fourth level (Level-4) cognitive systems (starting from the formal operational period, i.e. children about 12 years old) can allow the representation of any arbitrarily specified situations. The complex situations can involve identities from different core-domains and from different spaces, such as smaller particles or larger scale environment. In Piaget’s theory, there are the development of formal logical systems and mathematics (Chapman, 1988; Piaget, 1972). In particular, Euclidean Geometry can be used to represent space-time (Piaget and Inhelder, 1956).

The fourth level cognitive system is associated with the possibility and capability to represent any arbitrary situations in mental operations. This kind of change in cognitive systems is associated with the functional expectation to support the representation of the environment which extends in space and changes of states over time. However, when discussing the representation of a situation, what shall be considered is not only the possibility to represent a certain situation, but also the exact forms of representation. While the possibility to represent any situation is ultimately constrained by the state of cognitive systems, the exact form of representation of a complex situation will be determined by the forms of representation of identities and causal knowledge of the core-domains and scientific domains which are involved in defining the situation.
From implicit representation to explicit knowledge

To the concern of a cognitive system which aims at handling different situations in the environment, the matter is not only about whether certain information about the situations can be represented, but also whether useful information can be recalled or inferred so that the recalled or inferred information can be applied in new applications. The issue is not only about what kinds of situations can be represented, but also how the situations are represented.

Thus, there is a minor dimension to understand the development of representation of different kinds of situations as contents. Here, the criteria for the figurative differentiation of cognitive systems have to consider whether the representation can be recalled implicitly or explicitly. The implicit representation of an object is often associated with direct sensorimotor experiences with it. In Mandler (2000a)’s account of Piaget, the explicit representation means the recall can be made in the absence of the direct stimulations of objects in the environment. However, the recall of objects in action schemes is a different matter from the recall of properties associated with the objects in explicit descriptions.

In this figurative theory, the explicit representation of different kind of situations is emphasised as the criteria. The implicit versus explicit representation is applicable to the representation of identities, core domains, and complex situations. Within each level of cognitive systems, there is the capability to have explicit representation of certain situations. That is, the onset of a particular level is defined by the explicit representation of the corresponding kind of situations. However, the implicit representation can exist at a much earlier time. The matter can be further complicated with another distinction of representation and knowledge in Piaget’s theory (Brown, 1975; Piaget and Inhelder, 1973). The term knowledge is associated with the capability of making inferences (e.g. to infer properties of an unseen object or predict behaviours based on causal theories). The development of such a capability can extend well beyond the cognitive level where the explicit representation of a certain situation first develops.

Piaget identified the four periods of cognitive system based on the different operational styles (Chapman, 1988). However, because of the different classification criteria, the four levels of cognitive system in this thesis correspond but do not match exactly with Piaget’s four periods in terms of when they start and end. Another note is that two consequent levels of the cognitive systems can have considerable overlaps to each other in terms of what kinds of situations in the environment can be represented. What is meaningful in order to differentiate the levels of
cognitive systems is perhaps only the onset time of a new level. This is because, once a cognitive system has become capable of dealing with complex situations, it does not imply that it stops the capability to deal with simple situations. Rather, the representation of a complex situation always demands the representation of identities and their relations within it, which are simple situations in themselves.

3.3.2 The four stages of conceptual systems

In this thesis, the development of conceptual systems focuses on the representation of objects, which are in situations of different kinds. The differentiation of the four levels of a conceptual system is largely based on the different forms the representation of an identity can have, from unknown, to implicit representation of an identity in actions and action schemes, to explicit representation of the identity which can be treated as a whole in locations, to explicit representation of the identity in descriptions with attributes (Karmiloff-Smith, 1986, 1992).

On four developmental stages for objects in four levels of cognitive systems

The development of representation of objects in the common-sense-space starts with the implicit representation. This is the main form of representation of objects in the mind of children between Stage I (about one-month-old) to Stage IV (about four-month-old) in the sensorimotor period. In Piaget’s theory, before stage I, there is not permanent representation of objects, although there are different actions schemes which can be recalled for different kinds of objects (Mandler, 2000a, 1988; Mandler and McDonough, 2000) and there are mature perceptual

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15On the development of a conceptual system, the theory in this thesis has assimilated the representation re-description (RR) model of Karmiloff-Smith (1986, 1992) which emphasised the different forms of representation, from implicit to explicit and three explicit kinds of representation. However, there are significant differences. For one thing, the representation changes studied in Karmiloff-Smith (1986, 1992) are associated with different kinds of contents beyond the representation of the category of substances. For another, regarding the development of representation for natural-units of substances as identities, the exact meanings of the second and third types of explicit representation of Karmiloff-Smith (1986, 1992) are too vague for the purpose of modelling. Thirdly, the explicit representation in conceptual systems has to be clearly distinguished from the explicit representation with domain independent symbolic systems. The first and second type of explicit representation in the RR theory of (Karmiloff-Smith, 1992) can largely be taken as representation in conceptual systems (such as language). The third type of explicit representation in the RR model can be associated with representation with independent symbolic system. This thesis only focuses on the explicit representation in conceptual systems.
modalities for the representation of shapes (Kellman, 1984; Kellman and Kenneth, 1987). The development of object permanency at stage IV marks the **Stage 1** of conceptual development.

The first stage of the conceptual systems (Stage-1) is associated with explicit representation of objects. However, the representation of objects at stage IV is rather restricted in that infants fail to search a new location after a short delay when the object was shifted into a new location even in the full view of the infant (Harris, 1975; Bremner, 1985; Munakata, 1998; Thelen and Bates, 2003). There is a close tie between the *object* and its *locations*. The capability to represent different locations for the same object can become mature only by the end of the sensorimotor period.

The restricted representation of objects shall be understood from two aspects. On the one hand, the explicit distinction of *states* of an object and an object as 4D existence should be made. An object is bonded with a location. In stage V, infants can find the hidden object after a longer delay even if the object was shifted to several positions. In stage VI, searching can be successfully performed, even when the shifting of positions happened out of the sight of an infant. Here, the success in Stage VI is associated with the representation of spatial locations. A child at stage VI can be said to have a reasonably good grasp for representation of a *location* in terms of the collection or configuration of objects explicitly. On the other hand, not only is there the understanding that an object can be at different locations at different times, but also the general understanding of a location, a kind of *ground* defined in terms of the configuration of objects.

The second stage of conceptual development (Stage-2) is associated with the development of the explicit descriptions with attributes for the representation of an object (Litowitz, 1977). The explicit descriptions can include the understanding of *functions*. Sometimes, there are properties such as *shapes* and *physical material*. Since language descriptions (which are supported by the conceptual development) of this sort are rather common in children at the end of the pre-operational period (about 7-years-old), the explicit representation of an object with explicit representation of functions, physical material, shapes, and locations should be possible earlier for children at the end of the first stage of pre-operational period (at about 4 to 5 years old).

The **Level-2** cognitive development underlying this Stage-2 conceptual system is the foundation for the structural change of the representation of objects and has the fundamental impacts on later development of conceptual systems. One major change of the cognitive development is the explicit understanding of *relations* between and among identities. Unlike in the sensori-
motor period, where these relations are embedded in the actions of a child, by the end of this Stage-2 of conceptual development, there are the explicit representations of spatial relations of objects and the temporal relations of different states of the same object over time.

To understand the data from the related cognitive literature, a few distinctions should be made clear. Firstly, spatial relations of objects should be differentiated from the relations of different states of the same object as seen from different perspectives when it is held in hand. The spatial relations among objects themselves should also be differentiated from these relations established indirectly by their relations to a person (i.e. Piaget’s allocative versus egocentric representation). Secondly, the objective temporal relation of objects (e.g. parents and a child) should both be differentiated from two other kinds of temporal relations. One is the temporal relations of the same object at different locations at different time (i.e. the change of locations). These different states belong to the same individual. The other is the relations of objects which are established by a child in the sequence of actions, e.g. in Nelson (1986).

There are the representations of parts of identities and contexts of identities in their own right. In other words, there are “natural-units” of different ontological natures from functional perspective, i.e. the differentiations of “natural units” as standalone figures in common-sense-space, parts, and collections of identities. This functional dimension to differentiate “natural units” will be called the horizontal dimension, which is important for the latter development of the system of core-domains and ontological-kinds. The parts are mostly boundary parts and can be associated with functions of objects. They also define the overall shapes of objects. The contexts (for objects) can be defined in terms of configurations of objects. However, these objects (or substances in containers) are the ones which are not too big or small for the perceptual examination by a person without external aid. The representation for objects (such as house and building) or environmental settings (e.g. a hospital or a suburb) on the large scales in their own right are only started and understood with emphases of their functions. In the concrete operational period, there are also the configurations of landmarks for the representation of the large scale environment at a time, which are mainly based on the projection of schema for configuration of objects. Later, there are also representations of spatial features in the even large environmental scale, such as a city. These are closely related to the representation of space and differentiations of core-domains in larger spaces relevant for SIScience.

Relevant to the concern of conceptual development, there are two other directions to be noted. 1) Once objects are also studied for their internal parts, functions of parts, and material
components for different parts. Such a study has prepared the establishment of the core-domain of physics as distinctive and further development of physical sciences and engineering in later development. 2) For an identity in a cognitive system, it is defined in terms of its direct relations to a person who perceives, acts, recognises, and forms a cognitive representation of such an identity. For an identity in a conceptual system, an identity is defined in terms of their relations to other identities which are either in the same or different core domains in conceptual systems. There are sorting identities into categories. The representation of collections of objects as a distinctive kind is a crucial development not only for spatial representation, but for the development of categories (Nelson, 1986) and concepts (Markman, 1983).

The third stage (Stage-3) conceptual system starts at the time before the end of the pre-operational period of Piaget’s theory. From the perspective of conceptual representation, the development is associated with the explicit differentiations of identities into core-domains and studied within their core-domains (Wellman and Gelman, 1998). The explicit representation of an object can include internal parts which are seen from the functional perspective. More importantly, the representation of an object can assimilate the sequence of representations of the same object with perhaps different states (e.g. wearing different address or with different hairdo) at different locations (e.g. at home or in school). These are demonstrated well by the data from the study of 4-year-olds of their representation change at this period. For the underlying cognitive systems, there are explicit representations of functional relations of parts to the object as a whole. There are also the knowledge of causal relations of objects when they interact and explicit distinctions of causations when identities of different ontological-kinds interact. These are the foundation for the development of the core-domains in the common-sense-space, i.e. the explicitly differentiated core-domains which are associated with specific situations and further development of representation and knowledge of these special situations.

The above study has mainly examined the changes to the conceptual systems up to the third level cognitive systems, i.e. objects can be classified into their core-domains and studied within the context of core-domains. Regarding the changing form for the representation of identities in the common-sense-space in the fourth-stage, there are two empirical observations which should be taken into consideration for any theoretical account:

- There are different theories for the representation of categories (Smith and Medin, 1981). While the ontological kinds and core-domains can be the constraints on the represen-
tation of identities which are studied as figures in core-domains, the precise constraints should be spelt out. For such a concern, the representation of identities in terms of formal schemata should be distinguished from the knowledge of identities for different functional uses.

- The development and maturation of a fourth stage (Stage-4) conceptual system corresponds to the formal operational period in Piaget’s classification. At this stage, there is the possibility to provide intensional definitions to concepts (Vygotsky, 1986; Sigel, 1983) and the further development of category systems, in particular taxonomies.

On further development of conceptual systems

The above explanation of the four stages of conceptual systems is about the development of representation of objects in the common-sense-space. For understanding the further development of a conceptual system, two positions are maintained.

Firstly, while the four levels of cognitive system is often taken as the general trend for the representation of the environment, the development of conceptual system may be taken as domain specific (Karmiloff-Smith, 1992) in that, for situations of different complexity as distinctive units of representation in their own right, their representations start at different times in comparison with the starting time for the representation of objects in the immediate environment of a person. The identities in situations in the larger or smaller spaces can be explicitly represented only when the cognitive systems can start to represent explicitly such situations. Indeed, the applications of the four-stages of conceptual systems for different cognitive contents are constrained by the general development of cognitive systems.

Secondly, development of conceptual system is also domain general in that the general pattern of development may appear the same for the representations of situations of different kinds (Karmiloff-Smith, 1986, 1992). The development of the conceptual structure for the representation of objects in the common-sense-space is the foundation for learning the representation of identities in other situations. Although the first stage for different contents may appear at different times, the general sequences of development can stay. That is, for the representation of identities in other situations in different spaces, the same pattern of change of the representation forms for objects in common-sense-space will be repeated16.

16In Piaget’s theory of cognitive development, the relevant idea may be the so called vertical and horizontal
3.3.3 On representation and structural constraints

Indeed, to provide a consistent explanation of the empirical data for cognitive development is an important research in its own right. However, this re-interpretation is also intended to serve a practical purpose, i.e. for the design of new information architecture for SISystems. For such a purpose, the cognitive system and the development, as seen from the perspective of representation of identities, should be stated rigidly. While the fourth-level cognitive structure and fourth-stage conceptual structure should be modelled, further details about this structure will be needed and specified.

Following Piaget’s understanding, the representations of identities in the mind of a person are highly dependent on the development of cognitive and conceptual systems. The form of representation of identities is always correlated with the general changes of cognitive and conceptual structure. The key purpose to study the development of structural changes is to understand the constraints on the representation of an identity. However, the topic of structural constraints on the representation of identities in mind is rather complex. For such an issue, Piaget’s ideas of structure d’ensemble for the state of the cognitive and conceptual structure, his position on representational change, and his complex identity rules for the representation of identities will be proved to be crucial. While the rest of this thesis is devoted to such a discussion, a short introduction will be given below:

For understanding representation and knowledge in Piaget’s theory

Piaget’s understandings on representation from sensorimotor to representational intelligences in general (Piaget, 1962) and his complex idea of identity rules (Elkind, 1969)\(^\text{17}\) can provide a ground for developing a figurative theory of representation. Regarding the representation in mind, there are two general perspectives to study the complex picture drawn by Piaget’s theory. decalages for the development of the structure-of-the-whole. However, the two ideas are explained in Piaget’s logic of groups and rather abstracts. According to (Chapman, 1988, 149):

The fact that groups and groupings can be found at different levels of development was referred to by Piaget under the rubric “vertical decalages”. The latter may be opposed to “horizontal decalages”, referring to the fact that within a given structurally defined level, the same structure may appear at different ages with respect to different contents.

\(^{17}\)See Section 4.2 and 4.3.
Firstly, Piaget (1962) has stated the general changes in mind from sensorimotor to representational intelligences. This kind of representational change corresponds to the distinctions made in this thesis on the representation understood in a cognitive system with a focus on actions and action schemes to the representation understood in a conceptual system where the representation of an identity is definable by its similarities and differences to other identities. Another note about the representation in this kind of discussion is that the representation is about the whole. Similarly, in Piaget’s theory, there is the change of knowledge, from egocentric to allocative understanding (Bremner, 1978a). In egocentric representation, the representation of the environment and the relations in the world are established with the direct involvement of an organism as the agent. In an allocative representation, the environment is represented objectively with the relations in the world as the conceptual constructs.

Secondly, Piaget’s complex idea of identity rules (Elkind, 1969) is also important for understanding the structural changes related to the representation of identities. The representation of an identity in Piaget’s theory has gone through several changes, from sensorimotor based to conceptual representation. For example, to understand the developmental changes of representations in cognitive and conceptual systems, the idea of object permanency and its implication on representation is crucially important (Harris, 1973; Bremner, 1985). It marks the start of conceptual development where the world can be represented in its own right. However, representation and knowledge of identities should also be distinguished in Piaget’s theory. The latter requires not only recall of an absent object, but also inferences of properties which have not been observed in the past\(^\text{18}\). The idea of identity rules implied in the conservation task, sorting task, and class inclusion task (Elkind, 1969; Brainerd, 1978) is about knowledge development. While the conception of an identity is derived in comparison with others in terms of similarities and differences, the knowledge of identities develops in the application of their representations

\(^{18}\text{Regarding the representation of identities, Piaget’s position is compatible with but more complex than the representation re-description (RR) model of Karmiloff-Smith (1986, 1992) which proposed the changes from implicit to explicit representation. In Piaget’s theory, two kinds of implicit representation of identities can be identified (one before stage I and the other is about stage II to stage IV). Two kinds of explicit representation of identities as individuals were also identifiable. One is about the development of object permanency (stage IV). The other is about the development of representation with explicit attributes involved in representation (from stage IV till the end of pre-operational period). The explicit descriptions are possible only when explicit representation for the (physical, spatial, or functional) properties become possible.}\)
in mind. These positions of Piaget will be kept in this thesis\(^\text{19}\).

**On structures as the constraints on the representation of identities**

Ontologically, the structural constraint is related to the existence and the contexts of an identity in the world. The different locations in space-time can restrict the kind of direct sensorimotor examinations.

Cognitively and conceptually, the term *structural constraint* on representation is understood in association with the states of cognitive systems and the states of conceptual systems. To develop an appropriate account of the development of the representation of an identity, two kinds of structural changes should be treated separately. One is about the change of cognitive structure for the possible explicit representation of different kinds of identities. The constraint from the state of *cognitive structure* is also related to what kinds of identities and *complex situation* can be represented. The other is about the changes of the conceptual structure, which constrain the exact forms of representation (Vygotsky, 1986; Karmiloff-Smith, 1992). The constraints from the state of *conceptual structure* are related to how the representation of an identity and a *complex situation* can be realised. They are also related to the conceptual re-organisations of categories of identities within a core-domain and the development of a representation schema for a particular application where the representations of identities are often involved.

Four levels of structural constraints on the representation of identities will be studied, which are about 1) system of *core-domains* and system of *ontological-kinds*, 2) the distinctions of *different conception levels* for the representation of identities and the distinctions of *different kinds of causal knowledge*, 3) the development of representation of situations as particular and different kinds of *category systems*, and 4) the *formal schemata* for the *representation* and *knowledge* of identities and the constraint of *attributes* of different ontological-kinds\(^\text{20}\).

The state of a *cognitive system* and *structure* corresponds to the *structure-d-ensemble* in

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\(^{19}\)The development of knowledge of identities has gone through other changes, including structural distinction of *individuals* versus *categories* (Brainerd, 1978) and changes from pre-concept in descriptions to the possibility of providing definitions (Sigel, 1983). For the synthesis of Piaget’s complex idea of identity rule, see Sections 3.3 and 4.4. Further discussions can also be found in Section 6.3.

\(^{20}\)For the re-definition of cognitive structure as the-structure-of-the-whole in terms of part-whole relations, see Section 4.3. For the system of specialised *core-domains* and *application-oriented-domains* supported by the fourth level cognitive systems, see Section 5.3. For the system of ontological-kinds of identities supported by the fourth level cognitive systems, see Section 7.3.
Table 3.4: Kinds of constraints and kinds of representation

<table>
<thead>
<tr>
<th>Levels</th>
<th>Constraints</th>
<th>Representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-level</td>
<td>cognitive and conceptual structures</td>
<td>implicit versus explicit representation</td>
</tr>
<tr>
<td>Second-level</td>
<td>situations and types of applications</td>
<td>explicit descriptions of individuals versus conceptions on different inclusive levels; causal knowledge of different kinds</td>
</tr>
<tr>
<td>Third-level</td>
<td>category systems of core-domains</td>
<td>explicit conceptions in core-domains versus representation in languages, distinctive causal theories</td>
</tr>
<tr>
<td>Third-level</td>
<td>ontological-kinds of core-domains</td>
<td>representation in formal schemata versus knowledge of categories with definitions versus representation in applications</td>
</tr>
</tbody>
</table>

Piaget’s theory. The *state of cognitive system* is correlated with the support for the representation of a system of specialised domains and a system of *ontological-kinds* of identities. The identities of different core-domains bear part-whole relations to each other. The *cognitive structure* as a whole is to accommodate identities as “natural-units” in the world which are in variously defined situations. However, whether or not an identity is explicitly represented as a member of an *ontological-kind* and a *core-domain* is determined not only by nature, but also the state of a cognitive system\(^2\). This is about the first level structural constraint on representation.

The *second-level-constraint* refers to the conceptions on *different-inclusive-levels* and different kinds of *causal-knowledge*, which are called *vertical* and *horizontal* dimensions of conceptual structure. They are developed to support the representation of an arbitrarily specified *situation* in mind needed for different types of *applications*. They are also constraints on the specialisation of *core-domains* as well as the representation of identities within a *core-domain*. The exact form of representation of an identity is constrained by the state of representation and

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\(^2\)That is, the representation of an identity, e.g. an animal as an existence in its own right is different from the representation of it as a member of a biological domain, i.e. the animal as a member of a kind. For the second understanding, it requires the cognitive systems reached the third level.
knowledge of its core-domain\textsuperscript{22}.

The \textit{third-level-constraint} on the representation of identities, also called \textit{relational constraints}, is about the various constraints from core-domains. The structural constraints on representations are in terms of the development of \textit{basic level} categories (Rosch, 1978) and \textit{category systems} of different kinds (Murphy and Medin, 1985). This tendency to develop a set of basic level categories and the different kinds of category systems are applicable to all core domains, however, the exact state of representation and knowledge of a core domain is determined by the general development of cognitive and conceptual structure as well as the experience with the specific domain. The state of a core domain is closely related to the representation and knowledge of identities of a distinctive \textit{ontological-kind} (Keil, 1989a) and domain specific \textit{causal theories} (Gopnik, 1996). The intended uses or applications also constrain the representation of categories (Ross, 1997, 1999; Markman and Ross, 2003)\textsuperscript{23}.

For the representation of an identity, the \textit{fourth-level-constraint}, also called \textit{formal constraints}, is related to the development of domain specific \textit{formal schemata} and \textit{attributes} for the representation of identities. The \textit{identities} which are newly encountered can be sorted into \textit{core-domains} and classified into one of the \textit{ontological-kinds}. Identities of different \textit{ontological-kinds} are often associated with different patterns of representation, i.e. with different attributes. Attributes involved in the representation of identities are of different ontological kinds. They can be defined mathematically, but in different forms\textsuperscript{24}.

### 3.4 Summary

This chapter has presented an overview of a situation based theory of cognitive and conceptual systems. Firstly, the idea of situations as 4D framed substances was introduced. There are also different perspectives regarding the representation of such situations in mind.

Secondly, four levels of cognitive and conceptual systems are differentiated based on this idea of situations. The representation of an identity is essentially restricted by the state of a

\textsuperscript{22}For the structural constraint of four conception levels, see Sections 4.4, 6.3, and 8.3. For the structural constraint of four kinds of causal knowledge, see Sections 4.4 and 6.2.

\textsuperscript{23}For domain representation and knowledge and structural constraints from core-domains, see Sections 6.2 and 6.3.

\textsuperscript{24}For modelling the representation and knowledge of identities of different ontological-kinds, see Sections 7.3 and 8.3. For the constraints from attributes on the representation of identities, see Section 8.4.
cognitive and conceptual system. Specifically, two theoretical positions are studied from a figurative perspective. The state of cognitive structure at a time constrains the possible situations which can be handled. The stage of conceptual structure at a time constrains the possible form for representation of identities (however, the ontological natures of the identities shall also be taken into the consideration). The fourth level cognitive structure and fourth stage conceptual structure supports the specialisations of core domains in the common sense world, small space, and large spaces for identities. This situation based Ontology of the world and situation based re-interpretation of Piaget’s theory of cognitive system and development lay down the foundation for the discussion of structural and formal constraints on the representation of identities.
Chapter 4

A situation-based understanding of structural constraints on identities

4.1 Introduction

A figurative understanding of Piaget’s structure-of-the-whole and consequently the understanding of structural constraints on representation can be achieved based on the situation-based Ontology and the situation-based figurative re-interpretation of Piaget’s cognitive theory of development. The idea of situations is crucial for understanding cognitive development as well as the constraints of cognitive and conceptual structure on the representation of identities. This chapter will present an overview of the structural constraints on the representation of identities. Specifically, three issues will be covered:

Section 4.2 will present the situation-based understanding of locations and locational constraints on the representation of identities. Identities are in situations in the world, i.e. situations are contexts of identities. The understanding of situations as the locations of identities will be differentiated from the understanding of spaces as the locations of identities. Situations are important because they are cognitive contents themselves as well as the contexts of identities in the environment.

Section 4.3 will explain the structure-of-the-whole from the perspective of representation of identities. Two issues will be covered. One is about the three levels of organisations and the three organisation units for the development of representation and knowledge of identities. The other is the re-definition of Piaget’s abstract structure-of-the-whole from the perspective of the representation of identities. This is about the first level structural constraint. The structure-of-the-whole will be explicitly re-defined with identities as parts and wholes in part-whole relations.

Section 4.4 will introduce the second and third level structural constraints on the repre-
sentation of identities. The second level structural constraint is in terms of conceptions on
different inclusive levels for identities and a system of different kinds of causal knowledge for
core-domains. These are called the vertical and horizontal dimensions for the conceptual sys-
tems respectively. The third level structural constraint is about the development of basic level
categories and category systems of different kinds for core domains, which are results from con-
ceptual re-organisations of identities within core-domains. These positions are generalised from
the empirical studies on identity rules and associated cognitive processes in cognitive literature.
They will also be studied further in details in the following chapters of this thesis.

4.2 On identities-in-situations in the world and in mind

From the situation-based Ontology, identities are in situations in the space-time. Situations are
contexts and locational constraints of identities. This section will present a detailed discussion
on situations as the locational constraints of identities. Firstly, Zubin’s proposal of four spaces
for identities will be briefly reviewed. A two-level-understanding of the spaces as the locations
for identities will be explained. Secondly, a situation-based understanding of contexts will be
emphasised since situations are both locational constraints for identities as well as cognitive
contents of representation themselves. A formal distinction of spaces versus situations as the
contexts for identities in the environment will be given. A formal analysis of the formal subtypes
for the characterisations of situations as contexts of identities is given. Thirdly, a few special
situations as contexts of identities will be defined. These distinctions can allow the situation-
based definitions of immediate situations for ontological distinctions of identities, core-domain
situations, situations for learning (hereafter learning) and situations for applying the learned
representation and knowledge of identities and other kinds (hereafter applications).

4.2.1 On Zubin spaces and spatial features in Zubin Spaces

To discuss the locations of identities, a short review of Zubin’s proposal of four spaces for
spatial features in environmental studies should be given first.

In the literature of SIScience, Couclelis (1992) discussed a classification of the world into
four different spaces based on an oral presentation of Zubin in NCGIA’s initiative 2 specialist
meeting. In this presentation, Zubin presented a theory of four categories of space according
CHAPTER 4. THE STRUCTURE-OF-THE-WHOLE

to different spatial scales. These spaces are named as A-space, B-space, C-space, and D-space.
There are different categories of spatial features in each of the relevant spaces. For the first three
spaces, the scale is increasing from smaller to larger.

A-space is the space for everyday objects, which are usually smaller than human bodies. A-space is also called the table-top world. A spatial feature in this space is often small enough
to be seen from a single point of view. It is usually an object that can be manipulated by hands.
Many of them are human-made.

B-space is filled by larger objects than the ones in the A-space. These objects are too big
to be manipulated directly. They can be interacted with in different ways (e.g. a vehicle), but
they still can be sensed and perceived by direct experience. This space is called the cityscape
in Frank et al. (2001). The cognition of an object in this space is from different aspects. The
different perceived aspects are then integrated together to form a whole view of it. A building
can be such an object (Couclelis, 1992). This level is about the environmental settings where
our daily activities happen. There are landmarks and roads for this space, and these spatial
features define a city on an even larger scale where a person may navigate daily.

The C-space is the space larger than a B-space, with larger landscapes which are hardly
accessible by direct sensorimotor experience. The term geographic landscape in Frank et al.
(2001) is equivalent to things in the C-space. Spatial features in C-space “experienced only
by integration of perceptual experiences over space and time through memory and reasoning,
or through the use of small scale models such as maps” (Mark et al., 1999). This is the space
concerned by environmental studies.

The D-space is the largest space and with the highest complexity. The entities and phe-
nomena in the D-space are constructed. The formation of a spatial feature shall be based on
considerations of both spatial and other non-spatial knowledge, information, and belief. The
explanation of the D-space is, in a sense, unclear in literature. To such a D-space, the con-
tents and structures are still far beyond our understanding (Couclelis, 1992). But it is said, the
D-space is the space with the involvement of entities or phenomena which are defined with
conceptual, institutional and social dimensions of consideration.

This proposal of Zubin on four spaces for spatial features is quite influential to the study of
ontologies in SIScience. As pointed out by Couclelis (1992), the classification of the different
spaces is relevant to make the point that human experience of these spaces are not homogeneous,
but strongly scale dependent and intentional. The identities of spatial features are differentiated
into spaces of different sizes. The spaces play an important constraint on the representation of spatial features in each of the spaces.

On spaces as the locational constraints of identities

The spaces are indeed important constraints for the development of the representation of identities in mind. Both an identity and its environment (which refers to the part of the world excluding the identity) are handled simultaneously in brain with the ventral and dorsal visual pathways in the brain respectively (Norman, 2002). However, there is a concern regarding how the constraints of spaces as the locations of identities can be taken into account directly.

From the empirical data on the earlier cognitive development (see Section 3.3), however, the cognitive development in differentiating the environment as the context of an identity has gone through a few steps and with increasingly enriched understanding. In Piaget’s theory, there is the change from the egocentric to the allocative representation of the environment. A few relevant observations in cognitive literature should be noted:

1. A location is earlier defined egocentrically which is largely about the infant who acts upon the object. In later stage of development, a location is defined in allocative manner where other objects and their relations contribute to the objective definition of the location (in Stage V of the sensorimotor period) (Bremner, 1985). In other words, an identity is now in a context in the environment. The context is the location of the identity.

2. Identities can be differentiated into one of the three distinctive functional kinds as the figures, parts, and cues for locations. Correspondingly, the environment can be differentiated into three kinds of spaces, i.e. the common-sense-space for the figures, the small space for the parts, and the larger space for the locations.

3. There are further distinctions of the environment in each of the three spaces. For the further distinction of the common-sense-space, there are the distinctions of three core-domains for a figure. For the small-space, the part is studied with parts and contexts and there are increasingly differentiated small spaces. For the large environment, there are the increasingly differentiated large spaces as the contexts for spatial-features defined on different scales. The four Zubin spaces can be understood as results from the application of this repeated pattern of development to the study of locations.
Thus, it can be proposed that regarding the context for an identity, there is a two-step approach. Firstly, there is the distinction of the common-sense-space from the small-space and large-space. From the formal perspective, if there is a single point to represent the universe, the universe as a whole can be differentiated into five points with the three spaces plus two theoretical limits. That is, the original single point of the world is differentiated into five points for five spaces. The five spaces are: the theoretical limit of zero space ($0_w$), the small-space ($S_w$), the common-sense-space ($C_w$), the large-space ($L_w$), and the theoretical limit of the infinitely large-space ($U$).

![Figure 4.1: The two levels of spaces for identities](image)

Secondly, there are further distinctions of the spaces as the contexts of identities in their corresponding spaces. For the natural-units in small-space, on the one hand, they are in situations in the small-world $S_w$. On the other hand, when they are studied in their own right (i.e. they are treated as figures and can have their own contents and contexts), it can also lead to the further differentiations of the small-space into the small-space ($S_w$) which bordered directly with the common-sense-space, the smaller space ($XS_w$), the smallest space ($XXS_w$). The “natural-units” which are studied in the smaller world ($XS_w$) can be refined into smaller and smaller...
ones, down to the theoretical limitation of zero size (Figure 4.1).\footnote{These differentiated spaces for identities are important in studying the ontological-kinds of identities and core-domains for the environmental studies.}

Also on the second level, there is a similar pattern of differentiations for the large-space. The nature of identities in the large-space in the first level distinction is about being the locations or contexts. The result from this differentiation of the large-space is the large-space ($L_w$), the larger space ($XL_w$), and the largest ($XXL_w$) up to the infinitely large. This understanding bear direct relations to the four Zubin spaces (i.e. B-space, C-space, and D-space). In terms of being locations of objects or people, these spatial features in different Zubin spaces are the same functionally. However, identities in A-space can be figures which are biologically relevant directly. There are also inherent functional relations of identities from the different Zubin spaces. The universe ($U$) is the theoretical limit towards the infinitely large which can also be represented by an abstract point. However, this point for the universe ($U$) refers to a container for all the things which have been identified and will be identified within it.

Following Goodchild et al. (2007), for the relevancy of SIScience, the environment is defined by the common-sense-space, part of the small-space, and part of the large-space. The study of natural-units which are extremely small, such as atoms and molecules studied in theoretical physics and chemistry and those which are extremely large, such as stars and other objects larger than the size of the earth in cosmology are excluded. If the expected application scope of a SISystem shall be as described in Goodchild et al. (2007), the set of spatial features shall at least include substances and objects in the A-space and the smaller natural-units corresponding to the parts of objects in A-space. The four Zubin spaces are particularly relevant to understanding the different ontological-kinds of spatial-features studied in SISciences\footnote{See Section 7.3 for detailed discussion on the ontological-kinds of identities.} and are to be handled by the SISystems.

**On functional nature in the distinctions of spaces as contexts**

A crucial point should be clarified regarding the functional nature of the three spaces (i.e. the common-sense-space, small-space, and large-space). Cognitively, the three spaces are functionally defined for being the contexts for identities which are figures, parts for the contents, and locations respectively. The common-sense-space ($C_w$) is defined by being contexts of the figures which are biologically meaningful and can be acted upon by hands. The small-space...
(S_w) and large-space (L_w) are the environments which are too small and too large to be directly relevant. Later, there are the distinctions of the small and smaller-spaces and the small-space become the environmental context for studying internal parts or portions of substances of figures. The large-space is also differentiated in the large and larger-space and the large-space refers to the relevant environment which contains the locations of the figures (Figure 4.1.).

The boundaries of these three spaces are hard to drawn. The small-world (S_w) has the minimum size of zero. The maximum boundary of the small-space can be approximately defined by the sizes of the objects in the common-sense-space or the sizes of the portions of substances or stuffs (e.g. a bag of grocery (Wierzbicka, 1984)) which can be handled by the bare hands. The common-sense-space (C_w) is mainly defined by the sizes of objects in A-space and B-space. However, it can also include parts of objects in A-space and thus the minimum boundary is largely approximated by the sizes of samples as portions of substances or the parts of A-space objects. Similarly, the large space (L_w), which is generally the locational context for identities as figures in the common-sense-space (which are interested and act upon by a person), has the minimum size which allow all kinds of objects (including people) in the common-sense-space to be contained. The minimum size can correspond to the size of objects in A-space. Theoretically, it does not need a maximum size for the bottom boundary.

If the spaces are functionally defined, it implies that the identities studied in one of these three spaces are associated with an inherent functional role. The functional value is important for distinguishing these identities as well as the situations as their contexts in the same space. However, the knowledge of the absolute sizes of spaces for identities alone does not provide sufficient information as constraints on their representation. The functional roles of identities are yet to be understood on two levels, i.e. in terms of their functional relations to the concern of a person and to the concern of other identities. Regarding their functional relations to a person, when a natural-unit has one of the three functional roles as the figure, part, or locational cue, it is correspondingly studied in the common-sense-space, small-space, and large-space.

The natural-units in the small-space are often for understanding the contents of physical components for identities which are figures of study. The small-space (S_w) can correspond to the sizes of the parts for objects or the sizes of samples of substances or data supports (i.e. samples which supporting the measurement of physical properties). The study of natural-units in this small space is to understand the materials which give the visible physical properties of different substances, objects or their distinctive parts in the common-sense-space (for example,
different materials for parts of machines or cells for organisms). The *smaller space* is \((XS_w)\) with *atoms* and *molecules* in physics and chemistry which explain the differences of materials. The observation of such units directly or their actions often involve the use of certain instruments. The *smallest space* \((XXS_w)\) for the *fundamental particles* has the units of sizes further towards the theoretical limit of zero size \((0_w)\).

The *large-space* \((L_w)\) refers to the immediate context of *objects* and *substances* or *people* in A-space and B-space (e.g., buildings or small environmental settings, such as childhood centres or hospital). This space is directly relevant to *people*. The *larger space* \((XL_w)\) is about the environmental context for situations which correspond to Zubin’s B-space and C-space, which include spatial features, such as a city or a type of land use. This space is considered to include landscapes and natural systems which are characterisations of the earth surface. These characterised locations are often directly relevant to the living and the life of a person. This space is larger, but it still belongs to the observable space in the sense. They are also locations for spatial features in B-space in the sense that the identities in B-space can be the elements or parts for the spatial features in C-space. The third is the *largest space* \((XXL_w)\), which is relevant to study the *spatial patterns or regions* in C-space and D-space. To the study of SIScience, the largest space is the earth surface and its atmosphere (Goodchild et al., 2007), which is an element of the universe \((U_w)\). This world is segmented into such variously defined regions. These identities usually bear indirect relations to the concern of a person.

On the second level, the functional relations to other identities (relevant to the second level distinction of spaces) are taken into account directly. There are two cases to be considered. Firstly, the same identity may take different functional roles in different circumstances. For example, objects in A-space are usually the *figures* in that the haptic actions of a person can be applied to them directly. However, they can also function like *parts* (e.g., when used as tools) or *wholes* (e.g., they are used to indicate locations) in different application circumstances. Secondly, identities in small-space are often the *parts* for studying the contents of figures in the common-sense-space or the large-space. Identities in the large-space are the *wholes* for studying the *contexts* of identities in the common-sense-world or small-space in the general sense. However, the identities in the large-space or small-space can also be studied as figures in their core-domains. Thus, this two-levels approach to understand the functional roles of identities is necessary, since from the cognitive perspective, different functional roles can be played in different circumstances.
4.2.2 On situations as contexts of identities and locations of the environment

To explicitly account the locational constraints on the representation of identities, situations as spatio-temporal framed substances in the environment will be needed. As the locational contexts of identities, they are important since they are the components of the environment as well as the locations of identities. For developing the representation and knowledge of identities in mind, situations in the environment are also crucially important because they are locational attributes for identities as well the locations to be studied in their own right. In this subsection, firstly, a few formal subtypes to define a situation for characterising the environment and for the context of an identity will be presented. Secondly, the issue is about the locating of these cognitively significant situations for identities. A situation can be formally specified with spatio-temporal coordinates. However, as the context of an identity as well as a distinctive location of the environment in its own right, it is not arbitrarily specified. The situations which are locations of figures and distinctive features of the environment have to be studied.

On the formal subtypes for characterising situations as contexts of identities

Situations as 4D units of substances are important because they define the contexts of identities as well as being the contents of representation themselves. For an identity as a figure, there must be at least a situation in the environment which can contain the identity. The situation as the context can be formally differentiated into a few formal subtypes in terms of how they characterised the locations\(^3\).

Specifically, a situation can be defined with 1) spatio-temporal frame with geometrical coordinates; 2) regions of substances. A region may be understood the same as a partition in that they both refer to the complex environmental situations. However, partitions can be made arbitrarily, regions cannot; 3) concrete container which can refer to the part of a situation excluding the identity as the figure. It can either refer to a simple container or a further characterised ground by other identities. A geographical region is the environmental context of a person which has an inherent cause for its existence. However, such a region is more complicated than a partition; 4) landmarks or configurations of objects within the same spatial context. It includes natural

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\(^3\)These formal types are involved in the distinction of identities into ontological-kinds for the locations-kind of spatial-features in Section 7.3.
systems (e.g., those studied in geology or hydrology) or phenomena (e.g., events such as floods) which exist in the large scale environment in their own right; and 5) core-domain situations and ontological-kinds. These last two will be further discussed separately.

Figure 4.2: A situation with spatial features, context, and the background

For any kind of situation, its context can always be defined with spatio-temporal-frame. A situation as the context of an identity can be defined in Euclidean Geometry, i.e. the formal specifications of spatio-temporal coordinates for the boundary of the situation. However, the coordinates can be in global coordinate systems, i.e. the geo-coordinate systems and Calendar time used for spatial features in geo-scales, or the localised coordinate systems, such as the use of the Euclidean Geometry for studying shapes of objects in A-space. A-space is a part of the environment relevant for studying the locations of small objects.

A situation can also be defined as the substances within a spatio-temporal frame. For a portion of material as a figure within the situation, it is to characterise the concrete material as the whole within the spatio-temporal frame. A figure of a situation can refers to a distinguished part of the situation. There are two types. One is derived from the geometrical partitions of a whole, e.g., the partitions of earth surface with their distinctive characterisations (e.g. natural landscapes). The other case is associated with distinguishing a spatial entity from the background, e.g., a natural system in the environment.

For a situation with a single spatial-feature, the context of it refers to the part in a spatio-temporal frame excluding the figure identity. In this case, the context is about a concrete container, which contains the figure, but the figure is not a part of the container. However, there is a complex case with a region which refers to the part of the complex situation excluding the figure. However, this region can be defined with identities on different scales and with different
### Table 4.1: The formal subtypes for the characterisation of situations

<table>
<thead>
<tr>
<th>Formal subtypes</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-I</td>
<td>Spatio-temporal frame</td>
</tr>
<tr>
<td>Type-II</td>
<td>The whole of the concrete content</td>
</tr>
<tr>
<td>Type-III</td>
<td>The container</td>
</tr>
<tr>
<td>Type-IV-1</td>
<td>The landmark</td>
</tr>
<tr>
<td>Type-IV-2</td>
<td>The configuration or collections</td>
</tr>
<tr>
<td>Type-IV-3</td>
<td>Core-domains</td>
</tr>
</tbody>
</table>
For a situation which can have multiple identities recognised within it, the context of a figure is closely related to how the situation which contains the identity can be characterised. For the context of an object, the definition of its context can be in different ways.

- **Landmarks**: The ground can be marked by a distinctive spatial-feature (e.g., a landmark) as the locational cues. The context of an object is defined by other distinctive spatial features which can be used to indicate the locations for the figure identity. In particular, these other spatial features can bear direct causal relations to the figure identity.

- **Configurations**: The context is related to the existences of other identities on the same scale which define the location where the identity of interest can be located. Any one of the identities can bear spatial and temporal relations to other identities. In other words, these other identities can define a location for any one of the identities which is in the study focus. In such cases, the context of a figure can be restricted to the spatial context of the figure at a time. For example, a person can appear in a sequence of locations at a school, in the office, and at home at different times. The locations are defined in terms of configurations of objects, buildings, or landmarks. They are the environmental settings on a larger scale. The contexts of the person are defined in terms of sequences of locations over time.

- **The core domains**: A core-domain refers to special kind of situations or specially characterised situations with identities belonging to a distinctive ontological nature and these situations as wholes can be associated with the distinctive pattern of causal knowledge. Core-domains and ontological-kinds will be studied in later chapters.\(^4\)

**On localising situations for identities in spaces**

Spaces in Zubin’s proposal and situations in this thesis are both locations and contexts for identities. However, an important distinction of spaces and situations should be made. Both spaces and situations can be containers for identities, however, they decompose the world in different manners. The three spaces (i.e. the common-sense-space, small-space, and large-space) are

\(^4\)More discussion on these can be found in Section 5.3 on system of core-domains and Section 7.3 on the system of ontological-kinds.
independent components of the world. The small-space has a maximum size for an outside boundary (i.e. the extension). The large-space has the minimum size for an inside boundary (i.e. the resolution). Only the common-sense-space is defined with both parameters as spatio-temporal resolution and extension. They occupy different locations and their aggregations or combinations define the world as a whole. The situations, on the other hand, are defined differently. A situation always starts with zero size and extends beyond. A situation can be restricted into a single space. It can also be defined across spaces. Although two situations can be located in different spatio-temporal locations and thus they are independent of each other, a large situation always contains smaller situations within it. The representation for the largest situation in the world, which is often taken as the approximate of the world relevant to a person, is constructed based on the representations of all the smaller situations experienced directly or indirectly by the person.

Following the situation-based Ontology, an identity is in (at least) a situation in the environment. When situations are studied as locations, they can be precisely specified. However, situations are not purely mathematical construct, although they can be specified formally in geometrical frames. They are cognitive units with corresponding existences in the environment. From the cognitive perspective, situations are important because they are not only the contexts of identities, but also the contents of representation themselves which are to be handled by the cognitive systems. As distinctive characterisation of the environment, locations are distinctive situations to be studied in their own right. The representations of identities constrain what kinds of situations in the environment can be represented. The situations in the environment also constrain the development of representation of the identities which are contained within the situations.

The crucial issue relevant to understand the situations is how to locate such situations, given they are not randomly given. The localisations of such special situations in space-time are necessary. It is a crucial issue on how these special situations which are cognitive contents in their own right can be derived. The localised positions are determined by their relations to spaces as the contexts on the one hand, as the contexts of identity on the other hand. While the exact mechanism and processes are beyond the scope of this thesis, two processes are understood which can constrain the development of such situations. One is the top-down process which decomposes the environment as the whole. The other is the bottom-up process which focuses on the study of an identity which has contents and contexts in space-time. These two processes
are both recursive. However, they might stop when there is a suitable unit (defined with an identity in a situation) can be reached.

![Diagram showing the relationship between identity in the world and identity in mind, with the world and mind connected through various levels of contexts and situations.]

**Figure 4.3:** An identity in the world and the identity in mind

From the cognitive perspective, on the one hand, the idea of a situation as the context for an identity is rather flexible. The situations as the contexts of an identity can be variously defined as long as the identity is contained in the situations. The existence of a situation is not necessarily restricted in one space only. However, there is at least one situation as the context of an identity is in the space where the identity is located. On the other hand, with situations as one level of contexts of identities, there are at least three-levels in understanding the locations of an identity, namely, from an identity in the world, to an identity in a situation in a differentiated space in the world (Figure 4.3).

The identity has the situation as its context and the situation is definable with the identity within it. This unit can become stable when it can satisfy one of the two conditions or both. One is that the increasing or decreasing the size of the situation will not have significant impact on the representation of an identity. Or the representation of an identity can be sufficiently accurate to support the representation of situations where the identity is involved as an element.
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Because of the existence of the functional criteria, although both processes can be recursive, the empirical data may have suggested the temporary balanced states. The special situations which are represented in the Level-4 cognitive systems can be understood in the two-levels of decomposed spaces (as components in the environment in their own right) and two-levels of constructions of situations (as the contexts for identities).

4.2.3 On situations as contexts from the semantic perspective

To differentiate the special situations which are contexts for identities and important locations, three perspectives to study situations will be covered. Firstly, it is about the distinction of an immediate situation of an identity from any other situation as contexts of the same identity. Secondly, there is also a distinction of the learning situations (hereafter, learning) and the application situations (hereafter, applications). Learning can happen in the immediate situations and complex situations as contexts. However, these two kinds of learning are often associated with supporting different cognitive functions. Thirdly, situations for ontological-kinds, core-domain specific, and applications are defined.

Immediate situations and complex situations

A situation can be defined with the identities which can be recognised as the elements of the situation. The development of cognitive structure is correlated with the representations for the increasingly complex situations with multiple identities which extend in space and time. Regarding these situations as the contexts of identities, from the formal perspective, the situations can be differentiated into simple or complex kind. When a situation as the context of an identity has only this identity as its element, it is a simple situation. If it has more than two elements, it can be a complex situation.

There is a special case of the simple situation called immediate situation. The immediate situation for an identity refers to the situation which contains the single identity as its content and it defines the maximum extension of the identity it contains. An identity is functionally meaningful and structurally distinguishable in terms of its relations to other identities. However, the forms and functions of an identity are inherently constrained by the very existence of such an identity. This inherent locational constraint can be characterised by the location of its immediate situation. The constraints of immediate situations on the representation of identities are not just
structural in that it contains it, but also functional. The immediate situations, which are contexts for identities (hence the extensions of the identities), are in different spaces. The ontological-kind of an identity can be indicated by the nature of the space where such an immediate situation is located.

When an identity is studied in the contexts of variously defined situations which include not only the identity of interest, but other identities defined on the same scale\(^5\), these situations are called complex situations and are contexts for the identity of interest. However, two types of these complex situations should be differentiated. One refers to the situation where the other identities in the situation belong to the same ontological-kind. Such situations define a core-domain. The other refers to the situation which is general in that the other identities in the situation can belong to either the same or different ontological groups. For identities in the same space, they can belong to the same or different ontological groups. However, for identities in situations in different Zubin spaces, they are often considered as belonging to different ontological kinds. An identity can be relevant to an application which extends beyond the space for the extension of a core-domain for the identity\(^6\).

**Learning and application situations of identities**

Regarding the situations as contexts of identities, from functional perspective, these situations can be differentiated into those for learning the representation of identities and those for applying the learned representation of identities for problem solving.

The representation of an identity is learned in different circumstances. An identity can be examined as a whole. This often happens in the simple situations as the contexts of the identity. An identity as a figure can have different states at different times. A state can be defined with distinctive features or the overall shape. It can also have distinctive patterns of transformations, e.g. self-initiation of actions or processes. The internal content of an identity can also be learned when its parts or components of materials can be examined. This often happens when an object can be cut through physically or seen through with X-ray machines. The context of an identity can also be learned when the identity as a figure is examined in a large and complex situation which involves multiple other identities. These other identities can define the spatial contexts,

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\(^5\)That is, all the situations as the contexts of the identity excluding the immediate situation of the identity.

\(^6\)For example, a person which is an object in the common sense world, can contributes to a census tract, which is a data support for studying demographical patterns defined on the large space.
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temporal constraints, and possible causal relations to the figure.

The representation and knowledge of an identity is often learned to support the functional role it plays. There are two functional roles for an identity in applications, namely, they are either the *wholes* or *parts*. An identity can be the whole in its own right and the container for other smaller natural-units. For being a whole, an identity either plays the role of being the whole of a situation or the container (i.e. as the complex object). When an identity plays the role of being the part, it contributes to other wholes. It is either a part belonging to another identity defined on a larger scale. Or it is one of the elements that is configured with others to define a location. An identity as an element of the environment can be located in variously defined larger situations in the environment.

There is a unit for the representation of an identity and the unit is defined with an identity which has content and in context. In these situations of learning, an identity can be associated with three components of information about the figure, its parts, or the contexts of it. When the increasingly detailed components for the internal content can be examined with smaller and smaller particles, the identities are complex objects. The unit of an identity with content and in context can become stabilised in terms of the representation. The stabilised knowledge about an identity means the representation can support the use of it to study other situations in the environment. That is, the understanding of the internal structure can be sufficient for understanding and predicting the behaviour patterns of the identity as a whole on the one hand, the changes in states when it interacts with other identities in certain situations on the other hand. Such situations are core-domain situations for the identity and representation and knowledge of them define a core-domain.

However, both the internal contents and the situations as contexts of an identity can go beyond the scope of the core-domain of the identity. This happens when there are increasingly detailed contents and contexts of the identity are to be studied. The state of knowledge of an identity is indeed determined by the learning of identities and the applying the representation and knowledge of identities in various situations. When the learning of an identity is in its immediate situation, the learning is often associated with the purposes of re-identification and categorisation. Anyway, the learning can involve the examination of the smaller natural-units which is far smaller than those necessarily to differentiate the identity within its core-domain. The applying situations (i.e. applications) are when identities are involved and play certain functional roles. They can be core-domain specific situations. However, an application situation
can involve identities of different core-domains (of the same or even different spaces).

**Ontological-kinds, core-domains, and applications**

The view that identities are in situations is developed to understand the constraints on representation in current cognitive literature. The ideas of *ontological-kinds, core-domains, and applications* as the constraints on the representation of identities are the main points in current cognitive theories. The theories emphasise domain specificities (Smith et al., 1985; Carey, 1985; Gelman and Markman, 1986; Keil, 1989a; Gopnik, 1996) and the effects of contexts on representation (Murphy and Medin, 1985; Medin and Ortony, 1989; Ross, 1999; Markman and Ross, 2003). However, these different kinds of constraints themselves are rather unclear and have to be defined. As the first step towards such a purpose of clarification, the two dimensions to understand these situations have been discussed above. *Ontological-kinds, core-domains, and applications* are all special cases of situations.

The *ontological distinctions* of identities are based on the distinctive functional roles of the identities to the concern of a person and their functional relations to other identities. For studying identities, the representations and functions of identities are learned in the sensorimotor examinations. The distinction of *ontological-kinds* for identities of spatial-features takes consideration the locations of the *immediate-situations* of identities. That is, the spaces where the *immediate-situations* for identities are located. The spaces are good cues for understanding the possible functions of identities. Identities in different Zubin spaces are generally considered as of different ontological-kinds. The structural differentiations of the *immediate-situations* can also be useful for ontological distinctions. Within the *immediate-situations*, there are either *complex objects* (for figures in the common-sense-space) or *complex situations* (for locations in large-space). For the ontological distinctions of identities, it requires identities to be *functional* and *structural* distinctive.

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7For the further study (with detailed discussion of the cognitive theories in literature) of core-domains, system of domains for the environment, the states of representation and knowledge of core-domains, and their constraints on the representation and knowledge of identities, see Chapters 5 & 6. For the further study of ontological kinds, their natures, cognitive criteria of distinctions, and their constraints on the formal schemata for the models of identities, see Chapters 7 & 8. For the constraint of applications on the specialisations of core-domains, see Section 5.4. For the constraints of applications on the states of representation and knowledge of core-domains, see Sections 6.2 and 6.3.
The ontological-kinds and core-domains sometimes even used interchangeably in cognitive literature. However, in the situation-based theory, the two can be differentiated. Core-domains as special situations in the environment are also contexts of identities. However, core-domain situations can include multiple identities of the same ontological-kind. Core-domains are distinctive from each other. The distinctiveness of core-domain is either because the situations of different core-domains are in different spaces or they are in the same space but associated with different kinds of causal knowledge. Identities in the common-sense-space can be differentiated into core-domains of physical objects, animates, or people.

The applications are situations where an identity is involved. However, the applications can be the newly encountered situations in the world or an identity is involved in new uses. When the increasingly comprehensive contextual information about the identity can be included, there are the complex situations for the identity. The application situation is a context of an identity which can extends in space-time. It can include multiple equivalent or larger sized natural-units. In an application, an identity contributes to the content of the larger situations or a larger identity. It can play the role of being the element, part, or particle. These three cases shall be differentiated. Firstly, it can be an element. The configuration of this element with others can define the internal structure of a large identity. However, there are either the collections/spatial configurations of these elements, or the collection/configurations stay in their own right. Secondly, there are not only spatial relations of these elements and their configurations, but also inherent functional relations of this part with other parts and to the whole defined by them. These multiple parts can define the complex systems which are the wholes as identities on the large scale. There are inherent functional connections of these elements which can explain the overall behaviours of the configurations. The example of such wholes can include natural systems or complex machines. Thirdly, it can neither be the element nor a part. Rather, it may be considered as a particle, which is an even smaller natural-unit. This particle is relevant for defining the substances of the part or components or contributes to the data supports which define the larger identity (e.g. people in the demographical studies).

4.3 On representation in structure d’ensemble

The state of the cognitive systems is a structure-of-the-whole in Piaget’s theory (Chapman, 1988). From the figurative perspective of representing identities, the structure-of-the-whole can
be defined with identities as parts and wholes which bear part-whole relations. The representations of identities define the state as the structure-of-the-whole. This structure-of-the-whole also constrains further representation.

In this section, the structure-of-the-whole will be studied and there are two issues. Firstly, three levels of organisation and three kinds of organisation-units for the representation and knowledge of identities in mind will be clarified. The structure-of-the-whole can contain not only the representation of identities, but also the representation of identities-in-situations (i.e. core-domains) and situations-with-identities (i.e. applications) are organisation units for identities. Secondly, with the specialisation of core-domains for identities, the part-whole relations can be differentiated into those between and among identities in different core-domains and those within a core-domain. That is, there are discussions on part-whole relations for two cases. One is the part-whole relations of identities which are from different core-domains. The other is the part-whole relations in the study of identities as figures in a core-domain and in an application.

4.3.1 The three levels of organisation for identities

In Piaget’s theory, identity representation starts with actions and internalised action schemes in mind. The specialisation and generalisation of actions schemes are for different objects. There are not only the assimilation and accommodation of the action schemes to the environment, but the assimilation and accommodations of the action schemes among themselves and them to the structure of the whole (Piaget, 1972). The latter is about organisation and re-organisation of the cognitive systems in Piaget’s theory (Phillips, 1981).

Apparently, for the purpose of modelling, a much more solid sense should be made about the identity representation and conceptual re-organisations. In this subsection, three levels of organised will be discussed. Firstly, it is about the representation of identities in themselves in cognitive systems. Two crucial views in understanding the complex identity rules in Piaget’s theory will be clarified. One is about the two senses of the identification processes of an individual. The other is about the distinction of representation and knowledge of an identity.

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8 According to Brainerd (1978), the structure d'ensemble in Piaget’s theory is about the general understanding of part-whole structure for cognitive systems. However, Piaget’s theory did not explain the form of cognitive and conceptual structure in terms of part-whole relations. Rather, he focused on the operative characterisation of cognitive systems (Chapman, 1988).
Secondly, a figurative understanding of the organisation of representation is given. That is, the representation of situations is explicitly included for the representation of identities in mind. The core-domains as contexts of identities are emphasised. The core-domain for an identity is explicitly differentiated from any other situations which can contain it. Thirdly, the development of cognitive and conceptual structure as a whole is discussed, which is differentiable from the representation of a particular identity in situations.

**On representation and knowledge of identities**

For understanding the representation of identities in mind, the idea of identity rules in Piaget’s theory is followed. However, there are difficulties. Specifically, the idea of identity rules in Piaget’s theory is implied in a range of cognitive tasks, including preservations of actions and object permanency, action based imageries, the conservation task (e.g. of physical measurements), sorting task, and the class inclusions task. According to Elkind (1969), the representation of an identity is defined in terms of “invariance” in transformation in Piaget’s theory. The meaning of a concept in sorting and class inclusion tasks is commonly understood as related to the capability to develop criteria of sorting items into groups, other interpretations of the identity rules in Piaget’s theory has focused on identities of individuals (i.e. the same amount) and identities of categories (Elkind, 1969; Brainerd, 1978). However, these interpretations are rather limited.

To clarify the meaning of the identity rules in Piaget’s theory, as a first step, three different perspectives of an identity should be taken into an account directly. Namely, the three kinds of existences, an identity as a natural-unit in the world, the representation of the identity, and the knowledge of the identity, should be explicitly differentiated. An identity is a natural-unit in the world. This existence is recognised and represented in the mind. In Piaget’s theory, the representation of an object comes to exist in the cognitive system when there is the object permanency in mind (Harris, 1975; Bremner, 1985; Thelen et al., 2001). By then, an object is understood as independent existence in the world in its own right. The representation in mind exists when the explicit recall of an identity in its absence from the environment has become possible. Infants can start the searching of the absent object.

Regarding the cognition of the existence of an identity, the two senses of the process of identification should be distinguished. In the most general sense, the process of identification
is related to the understanding of an identity as an existence in the environment which can be perceived and conceived as distinctive from its background. There is the cause for the identity to exist and the psychological rule for the discrimination and recognition. However, the cognitive process is also related to identify a natural-unit and establish of the existence as a particular one. As a particular individual, it has certain characterisation and can be differentiated from other individuals. This specific sense of identification is closely related to the re-identification of an individual in the study of Millikan (1998a).

Thus, for a matured cognitive system, the representation of an individual can also have two senses. The general sense of it is about the existence of an individual in its own right. Such an existence can be recognised and explored. The exact representation of it can be explored by the sensorimotor modalities. The identity rule in Piaget’s theory, which refers to the invariant in transformation (Elkind, 1969), is about this general sense of identification of an individual. The specific sense of it is a particular existence, which is often an example of a kind, such as an instance of an ontological-kind or a member of variously defined categories. This specific sense of the identification of an individual and the representation of it as distinguishable from others is inherently constrained by the development of a conceptual system.

The third issue in studying the identity rules is about the distinction of representation versus knowledge of identities. The knowledge of an identity is about it as a particular 4D individual which exists in a particular location at a time. The knowledge of an identity is also about what kinds of properties it can have and thus it is possible to reason on what possible uses the identity can be involved. While the knowledge of an identity is developed based on the representation, it emphasises the functional expectations from the representation. The knowledge of identities is associated with the functions on how the identities can be re-identified. The recall of information of the identities is from the perspective of its relevancy for the uses of identities. A more specific sense with the term knowledge is often restricted to the inferred information from reasoning. In Piaget’s design of class inclusion task, children have to understand the logical relation of super-ordinate and subordinate categories in the taxonomy in order to be said as passing the task. That is, the answer that a super-category always has more number of examples in comparison with the number of examples in its sub-category. This knowledge is not based on the counting of the numbers of examples, but on the logical understanding.
On core-domains and applications for identities in conceptual systems

The second issue with Piaget’s theory is about the conceptual organisation and re-organisation, which is also important for understanding the structural constraints on the representation of identities. In cognitive theories, the issue is studied in relations with the development of category systems, in particular taxonomies (Rosch, 1978) and events (Nelson, 1986). From the perspective of the situation-based theory, apart from the representation and knowledge of identities as single units, there are two kinds of organisation units, namely, the core-domains and any applications which are about situations in the environment.

The specialisations of core-domains as distinctive units of representation and knowledge in mind are important. Consequently, the identities are sorted into their core-domains and the further development of representation and knowledge of identities happens in the context of their core-domain. The representation and knowledge of an identity in a core-domain is constrained by the representation and knowledge of other identities of the same core-domain and there are further conceptual re-organisations which can result in changing the set of categories for sorting identities in the core-domains because of the adoption of different rules as studied in the sorting tasks and development of category systems of different kinds.

The other unit of representation is about any situations in the environment. The situations can either refer to the spatial-temporal framed units in the environment which are studied in their own right. Or they are application situations defined by a sequence of states at different times and transformations of states over time which lead to the satisfactions of the particular concerns or needs of a person, such as the biological needs or social goals. In either of the cases, the representation and model of a suitably defined situation (which is the context of at least one identity) in the environment are to be constructed. Such applications which can be defined in terms of states and transformations over time are situations, which can be differentiated into the simple one with single individual or complex one with multiple individuals. The constructions also involve the representation of identities and transformations of different kinds.

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9See Chapters 5 and 6 for detailed studies on domain specialisations and the development of representation and knowledge of core-domains and identities in core-domains.

10See Section 5.4 for detailed study.
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On conceptual systems with core-domains and identities as parts and wholes

From the perspective of the situation-based theory in this thesis, the development of conceptual systems in general and the development of conceptual organisations in specific situations are both centred on the representation of identities\textsuperscript{11}. Starting with a natural-unit in the world as a whole, there are at least six major steps which have been gone through in the earlier development:

1. By 10-months, the world as a whole (represented by a single point) is differentiated into three ontological kinds, which are for the self, the identity of the meaningful size (i.e. it is in the common-sense-space and the object or the portion of substance can be grasped by hands), and the environment which is defined by the largest spatial extension which can be reached by the perception of an infant.

2. By 15-months or younger, another node of spatial relations is added to the cognitive structure. Spatial relations are important for defining locations and the latter kind is for the characterisations of the environment. The location of an identity is either in terms of a container for an object or the substances (e.g. milk bottle or a box), or the spatial context indicated by other identities or defined by the configuration of the other identities (Bremner, 1985).

3. By 24-months or younger, there is the development where three functional types can be differentiable for the objects in the common-sense-space. The objects can be the targets, they can also function as the locational cues, or used as tools for reaching targets, as demonstrated in Piaget’s study of means-ends coordination in infants of this age group (Piaget, 1972). The capability to embed means-ends coordination in a plan for a goal at this stage can imply directly that there are at least implicit representation of causations (for interactions) and temporal relations of a sequence of actions.

4. By the end of pre-operational period or earlier, there is another node which is added to the picture of the cognitive structure. This node is for internal parts of objects. Toys can be dismantled to see what are inside. The internal parts define a distinctive ontological kind in comparison with the standalone figure-kind objects because they are located within

\textsuperscript{11}For the conceptual structures of core-domains, see discussion in Section 6.3.
objects. They are also different from the *boundary parts* (which have direct functional relations to the concern of a person in terms of how the objects can be interacted with). Thus, the *single* point for an identity of the meaningful size is extended and substituted by three points for the figure, part, and context.

5. In the third and fourth level cognitive systems, both the *natural-units* for *parts* and *locations* can be studied in their own right. In such cases, the natural-units in the small or large spaces can be learned in their own right with further distinctions of “natural-units” for *parts*, *figures*, and *contexts*. By the third level cognitive systems, there are explicit specialisations of core-domains for identities in the common-sense-space and identities are studied within their core-domains (Keil, 1989a; Wellman and Gelman, 1992). By the fourth level cognitive systems, identities in the large and small spaces are also studied in their differentiated core-domains.

6. For a spatial-feature as a natural-unit in one of the Zubin spaces, it can also be in variously defined *situations* within the specific Zubin space. However, for the study of this spatial-feature, it can include contents studied in the smaller space and contexts defined in the even larger scale environment.

To summarise such data, the development of conceptual system starts with the identities in the common-sense-world. The development goes further when identities can further play the roles of parts or wholes in different circumstances. An object is learned as a figure first. It has played the two kinds of roles for being *parts* or *wholes* alternatively. For being a whole, it is a figure located in space-time. Then, it changes to be a part which contributes to the understanding of a location. While there are further development of understanding and representation of *locations* as a distinctive kind, to the object itself, it is a whole again. In this case, it can have its own internal parts and there is the further understanding and representation of the parts as a kind. These parts for *internal contents* and locations for *external contexts* are studied as figures in their own right. The contents can go smaller and smaller infinitely, and the contexts can go larger infinitely.

That is, there are two points to be made. Firstly, the cognitive system as the *structure-of-the-whole* is developed and defined with these identities which take the functional roles for being the *parts* or *wholes* and in *part-whole* relations. When the core-domain for an identity is explicitly
developed, the general view of the conceptual systems as a whole (i.e. including representation for all core-domains) can be re-defined. However, the part-whole relations of identities are established in two kinds of situations for identities. One refers to the core-domain situations where the representation of identities can be developed. The other refers to the applications where identities are involved. There is the same identity which takes different functional roles at different circumstances. The state of representation and knowledge of an identity is defined by the joint of the states of the representation and knowledge developed in these two kinds of situations.

Secondly, to study the state of the cognitive and conceptual structure (i.e. structure-of-the-whole), there are two levels of the part-whole relations. The first level is defined with a system of core-domains. The first level structural constraint on the representation of identities is about the system of core-domains for identities. The second level focuses on identities which are studied in core-domains. With the explicit core-domain for an identity, the explicit representation of an identity can be studied within this context. For the representation and knowledge of identities within a core-domain, three kinds of part-whole relations are relevant for the development of representation of identities. The part-whole relations of identities from different core-domains can be established in applications.

4.3.2 The structure-d-ensemble with identities in part-whole relations

The state of structure-of-the-whole is to support the representation of a system of core-domains. The structure-of-the-whole can be defined in terms of part-whole relations of identities and re-defined which takes into consideration that identities which bear part-whole relations can be from different core-domains. For identities as figures in their core-domains, they are treated as wholes in learning for developing representation and knowledge, but they can be the parts in applications.

In below discussion, firstly, the general issues in studying part-whole relations are clarified. The classic study of different subtypes of part-whole relations from Winston et al. (1987), which are derived from linguistic analysis, is also briefly reviewed. Secondly, the part-whole relations for identities in core-domains in spaces and the part-whole relations of core-domains are discussed. Thirdly, there is the discussion on the part-whole relations for the developing of representation and knowledge of identities within a core-domain.Fourthly, the discussion
is about part-whole relations involved in applications, which can include the instantiations of part-whole relations for the representation of identities.

**On part, whole, and part-whole relations**

The part-whole relation has always been an important subject in the classical merology and formal ontology (Simons, 1991; Smith, 1998; Varzi, 1996, 2003). The kind of semantic relations is perhaps also the most important semantic relations for the study of the environmental representation (Smith, 1993, 1995, 1998). However, in this thesis, the study of *parts, wholes, and part-whole relations* in themselves is not the goal of this thesis. The goal is to use these concepts to re-define the state of the *cognitive and conceptual structure* as a whole.

While *part-whole relations* have been commonly treated as one general kind of relations in formal logic, however, from linguistic study, subtypes of *meronymic relations* can be differentiated (Winston et al., 1987). In the classic study of Winston et al. (1987), six types of meronymic relations (See Table 4.2) were identified, which were based on the three dimensional considerations, called *relation elements*. Winston et al. (1987) called them *component-integral object, members-collections, portion-mass, stuff-object, feature-activity, and place-area*. The relation elements are called functional (whether the relations can be transitive or not), homogeneous (whether the part and whole are of the same substantial natures, e.g., a portion of a pizza is same as the pizza), and separable (whether the parts and the wholes can be separate existences or not, e.g., a tree and a forest both exist) which differentiate the nature of these relations.

The different meronymic types identified by Winston et al. (1987) bear certain relations to the part-whole relations and container-contained relations that are used specifically to define the part-whole relations for identities of core-domains in representation and in applications. However, the most significant differences of the system in this thesis from the system of Winston et al. (1987) lie in two points. Firstly, in this thesis, the explicit focus is on identities as *natural-units* in the environment which are *parts* and *wholes*. Thus, Winston’s feature/activity relations is excluded, however it is relevant for the development of events and event structures which are important for the knowledge of core-domain, in particular, the social domain. Secondly, in this thesis, the core-domains for identities in different spaces are explicitly taken into consideration in the study. In the proposal of Winston et al. (1987), the relation of *area-place* as a kind is about the relation of identities from different core-domains. This relation can be initiated when
Table 4.2: The six types of meronymic relations. From Winston et al. (1987)

<table>
<thead>
<tr>
<th>Relation</th>
<th>Examples</th>
<th>Relation Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component/Integral Object</td>
<td>Handle-cup, punchline-joke</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Members/collection</td>
<td>tree-forest, card-deck</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Portion-Mass</td>
<td>slice-pie, grain-salt</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>Stuff-Object</td>
<td>gin-martini, steel-bike</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Feature/Activity</td>
<td>paying-shopping, dating-adolescence</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Place/Area</td>
<td>Everglades-Florida, oasis-desert</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

one of the identities (i.e. either a study of the area or a study of the place) is studied in focus. When an area is studied, a place is a part of it. When a place is studied, the area is its whole. The rest four types of meronymic relations are mostly relevant for the study of identities (i.e. substances or objects) in the common-sense-space. These four subtypes will be discussed when they are relevant in below.

Developing a system of part-whole relations is important in its own right. Such a study is far beyond the scope of this section. A detailed discussion needs to take into consideration the different natures of the parts, the wholes, and the relations defined by them. That is, the understanding of the exact set of different part-whole relations is correlated with the understanding of the system of ontological-kinds for natural-units in the environment. Regarding this system of part-whole relations, two general positions are held:

Firstly, there are two primitive types of relations, part-whole relations (e.g. a handle of a mug) and container-contained relations (e.g. the water in the mug or the organs inside an organism) should be differentiated. The two are treated as subtypes of meronymic relations in the classic study (Winston et al., 1987).

The whole-part relation is applied to understand the relations of the world as the whole with the three spaces as its parts. For example, the earth which is conceptualised as a whole can be divided into the common-sense-space, the large-space, and the small-space. The relation
is also applied to understand the relations of a space and the core-domains within the space. The core-domains in the large and small space should be discussed separately from the core-domains in the common-sense-space. There are further distinctions of core-domains in different Zubin spaces.

The container-contained relation is applied to understand the relations of the environment as the whole and the variously defined situations (which are 4D units of substances) as its parts. These situations themselves can either form a hierarchy with the larger situation contains the smaller ones. For example, a region can have its sub-regions which can be derived following certain criteria. Or they can stay parallel to each other. For example, two geographical regions in different locations bear element-to-element relations. The core-domain situations are special situations because of their concrete contents. This relation is also applied to understand the relations of a situation as an abstract whole and concrete content within it as the parts. Such a situation can be modelled either in terms of a single point or a 4D spatio-temporal frame (such as in geo-coordinate system for their locations in space and Calendar for the time) in a coordinate system. The abstract frame defines a container (and the environment of substance outside the spatio-temporal frame).

Secondly, three general mechanisms, which allow the derivation of a part from a whole, are adopted in the below discussions. 1) One is called the arbitrary divisions which can be applied when the whole and the part share the same quality. For example, the substances to their samples, a fruit or a pizza to pieces from cutting it. The other is called structural divisions which can be applied when the part can be distinguished from the whole as of different qualities. For example, the “natural systems” (e.g. ore deposits) in the environment which can be separable from the background. 3) The third is called structural-functional divisions which can create a multiple-level structure. That is, there are both structural division where distinctive identities can be found in a situation and functional division where the natural-units for the internal contents and external contexts of the identities are also created.

**On structure-of-the-whole with a system of core domains for identities**

The cognitive or conceptual structure as a whole is defined by a system of core-domains (or a system of ontological-kinds of identities) which can be treated relatively separately\(^\text{12}\). Re-
Regarding the structure-of-the-whole, vertically, while the identities as natural units are in core-domains in space-time, there is correspondingly the dividing of the environment into spaces and from a space into core-domain situations. The first group of the part-whole relations refers to this kind which divides a whole into different parts, i.e. to divide the environment as a whole until an identity can be reached. This sets up the most relevant contexts for developing the representation of an identity.

![Figure 4.4: The part-whole for conceptual structures and systems](image)

Horizontally, the state of cognitive and conceptual structure is correlated with a system of core-domains. While the core-domains may be treated as relatively independent from each other, they are still related to each other because the identities of different core-domains bear certain part-whole or container-contained relations to each other in defining the world. Specifically, there are part-whole relations of identities from different core-domains of different spaces. For example, there is the part-whole relation between an identity (A) in the common-sense-space (as a part) and an identity (B) in a large-space (as a whole) when the identity (B) in large-space can be defined or characterised by the configuration of the identities (including (A) in the common-sense-space (e.g., the configuration of buildings for the built-up area of a city).
There are also the container-contained relations of identities from different core domains of different spaces. For example, an identity in the large-space can be the container for the identity in the small-space (e.g., an object in a box, in a cabinet, in a house, and in a town). The same identity can be conceived either as a part or a whole from different perspectives. For example, a building is a figure in B-space (which is a kind of container where people and other objects can be found). However, it is also an element (i.e. a part) for a city in C-space.

**On part-whole relations of identities within core-domains**

The part-whole relations are applied to study the representation of identities in a core-domain. A core-domain is a situation and a whole. It has at least an identity as its part. An identity which is studied as a whole in the core-domain is a figure. For studying an identity within such a situation, three groups of part-whole relations should be studied separately. The strict sense of part-whole relations and partonomies (e.g., those studied in linguistics (Winston et al., 1987)) is about the part-whole relations for the study of identities within a core-domain.

Firstly, the part-whole relations are applied to the study of the figure. With the figure being of an ontological-kind, there are different subtypes of the part-whole relations. 1) When the figure is conceived as substance, there is the part-whole relation of portions-substance. This relation is applied when the substance is studied with samples, i.e. a portion as a sample for the substance. This is essentially the same as portion-mass in (Winston et al., 1987). 2) When the figure is an object with clear-cut boundaries, there is the relation of the distinctive boundary parts of the object to the object. The boundary parts are for the characterisation of the overall boundary and the distinctive features of the boundary may be related to distinctive functions. For example, the distinctive function of a handle of a mug. There is the kind of (boundary) parts-whole relations and the distinctive boundary parts can be studied with increasing details with features defined over different scales. This part-whole relation is essentially the same relations as component-integral object in (Winston et al., 1987). 3) This part-whole relation can also be applied to study the natural systems in the environment. For studying the distinctive natural systems in different environmental settings, there is the inherent whole-part relation between a situation as a whole with the natural system inside it as an integral component. This inherent component is a figure to be studied in its own right. It is also a part and a contained component of a larger situation and the characterisation of it can define the larger situation.
Secondly, the part-whole relations can be applied to the relations of an identity (as the figure of a core-domain) to its internal contents. Depending on how the “natural units” for the internal contents of identities are defined, there are also several cases of the part-whole relation. For example, there are part-whole relations of some portions or samples of substances to the identity (e.g., organic materials for organisms), or the part-whole relations of the components (which are also parts with distinctive functions) to the identity (e.g., organs for organisms), or the even smaller units to study the samples or components (e.g., cells for organisms). The process of finding the smaller and smaller “natural units” in order to understand the differences of substances or identities in general is a general trend (Gelman, 2004; Medin and Ortony, 1989). There can be a few levels of the study of the substances in a situation with increasingly smaller and smaller “natural units”.

1. The relations between the internal parts $P_i$ and the objects (the complex objects, such as organism and complex machines)(This part-whole relations bear certain relations to the component-integral object relations in Winston et al. (1987), but the two are not exactly the same).

2. The relations between an identity $I$ and the portions of materials (samples $S$ of materials) inside the identity. The identity is the container for its portions of substances or samples of materials. For example, the relations between an object and the physical materials which make up the parts of it. The relations between cells and an organism are another case (This part-whole relations is essentially the same as the stuff-object relations in Winston et al. (1987)).

3. The relations between the particles $p$ for studying the samples $S$ and the fundamental particles $f_p$ (e.g., the atoms which make up the materials). The particles, or samples of substances, or parts are the containers for the even smaller units as the fundamental particles, such as atoms and molecules in physics and chemistry.

Thirdly, the part-whole relations are also applied to study the relations of an identity within the domain specific situations as its contexts. Generally speaking, the cases are about an identity which bears specific relation to its location. However, there is certain complexity which is related to the space of the identity and the different ways the location of an identity can be
defined (see Figure 4.2 and Table 4.1). There are at least two cases for container-contained relations:

- The *location* is defined abstractly with a spatio-temporal frame in coordinate systems. In this case, there may be a hierarchy involved when the situation in the spatio-temporal frame is not directly relevant for the identity (e.g., it is too large). There is further division of the spatio-temporal frame into smaller regions until the size of the region can only contain identities of spatial features defined over the same spatio-temporal scale as the identity of the figure.

- The *container-contained* relations between the background part of a situation as the location and the identity as the figure. In this case, the relation of an identity as the figure and its location is not a part-whole relation, but a container-contained relation. For example, the different kinds of natural systems studied in physical geosciences bear such relations to their surrounding situations.

When the location is characterised by one or more other objects, there are also a few cases where certain part-whole relations can be applied. However, in such cases, the whole is often considered non-integral. The other objects can also from different core-domains in the same space. In Winston et al. (1987)'s system, the equivalent relation is called member-collection relation:

- The location is marked by the distinctive *landmarks* for the ground. The identity does not usually have particular functional relations to the landmarks; rather the landmarks only mark the locations of the identity. However, the part-whole relation can be applied to the identity as the figure and the location. The relations of the figure to other objects as landmarks are spatial relations (i.e. on the surface) that can be modelled in Euclidean Geometry in terms of *distances* and *bearings*.

- There is the configuration-element relation when the location is characterised in terms of the configuration of other objects within the same situation. The location can be defined with the configuration of other identities (e.g., configurations of objects or landmarks) in the same spatial context (i.e. defined with spatial relations of objects in the same spatial context). The identity, which is the figure, is one of the elements among other identities.
The distinctiveness of this case lies in the distinctive nature of the whole, which is not a whole in the usual sense but a collection in nature.

- There is the collection-member relation between an identity as a member of a group and the group which is a collection of items.

There is a last note: For studying the relations of natural-units of different kinds in a core-domain, apart from the different kinds of part-whole relations, there are also the portions-portions relations, part-part relations, and the elements-element relations. The examination of samples with smaller particles and their configurations differentiate substances. The relations of measurements from samples define the natural systems in the large scale environment. The relations of part-part are within an integral object. The objects in an environment are elements of the environment. They can form simple collections, the peer-peer relations of people in a social organisation, or bear specific spatial relations in configurations.

**On part-whole relations of natural units in applications**

The part-whole relations involved in the study of identities within a core-domain are applied to represent an application where identities are involved for being parts. There can be one or several identities involved in an application. There are the instantiation of certain part-whole relations of identities which are considered as relevant for an application.

From the biological perspective, an application involves a situation which is the container and can have multiple sub-situations as locations for a sequence of the targeted objects. The situation for an application is a whole and a container which can contain several core-domain situations. For example, an event may happen in one environmental setting (e.g. inside the kitchen) or multiple environmental settings (e.g. at home and in school). If a situation is a container, and the objects are the contained objects of the situation, these objects are not the necessary parts of the container and can be move in and out of it. With core-domain situations as locations, the objects are either contained in their core-domain situations, or they are parts of them. In the second case, a core-domain situation constrains the movements of the contained objects and the possible interactions with them by a person.

The model of an application is defined with states at different times and transformations over time, which can be a complex situation which can involve multiple sub-situations. For modelling an application, it requires the temporal relations of identities and temporal period
which allow certain transformations happen over time. Regarding the temporal dimension, there are two other kinds of relations defined along the time dimension. One is the order of states (defined by the configuration of objects) along the time dimension (the objects may be in causal interactions over time). This is related to the development of a hierarchy of events. The other is the order of objects in an event in a sequence of actions in one place or a sequence of movements from one place to another. This is related to the development of sequences of events. The two formal structures, i.e. hierarchy and contingency, are important to define events and their relations, are important for the transformation kind of knowledge of core domains\textsuperscript{13}.

For constructing a model of an application which involves different identities, it also requires the models of identities, spatial relations of the identities and the specifying a spatial frame as the context. The sufficiently accurate understanding of these identities is often a prerequisite. For an application, two general kinds of knowledge of an identity are required. Firstly, it requires the knowledge for locating the identity in the environment. An identity is located in the context of its core-domain situation. Depending on the ontological nature, the core-domain situation can be within the common-sense-space or the large-space. A situation is the container which can contain single or multiple identities. This identity within a situation is an element or a portion of substance for the situation as a whole. To localise an object in the common-sense-space, more detailed knowledge of its locations is required, which can be about other objects which often co-appear in the same location.

1. The container-contained relation can be applied to the relation between an identity in a situation in the large space and the identity in a smaller situation in the common sense world. Both can be the context of identities studied in a core-domain\textsuperscript{14}.

2. When a location is defined in terms of the configurations of other objects in the same spatial context, an identity and its locations in the world can form another subtype of the container-contained relations\textsuperscript{15}.

\textsuperscript{13}For a complex situation with multiple identities, these identities can be of different kinds. They are also in complex spatial, temporal, functional, and causal relations to each other. For more discussion on modelling applications which involve such complex situations, see Section 5.4.

\textsuperscript{14}Such as the relations of identities in different Zubin space.

\textsuperscript{15}There are behaviour demonstrations that a child can search for an object in an old hidden place even if the object is shifted away from the location at stage IV. However, it can search an object in any location if it is shifted in front of her eyes, i.e. in a perceptual field, in stage V. At stage VI, children can find an object even if the object
3. For a situation with an identity inside of it as the figure, there is the rest part of the situation as the background. The background can be characterised by a distinctive landmark. Here, the relations of figures and the background is also a container-contained relation.

4. The relation between an object which is a container kind\(^{16}\) and an object which is contained in the container object\(^{17}\) defines a distinctive case of part-whole. The contained identities can be substance (e.g., the milk in a milk bottle) or objects (e.g., a ping pong ball in a glass). This kind of spatial relation is known by infants in stage III of sensorimotor period.

Secondly, it is about the knowledge of the identity itself, such as for identifications or re-identification and consequently the inference of its properties for action responses or potential uses. In this case, the patterns of movement, the boundary characterisations, and the internal contents of an identity are often involved. The knowledge of an identity can be used for its identification. The knowledge of the properties of the identity can also determine whether the identity can be involved in other uses. In this case, spatial and physical properties are important. If an application is about timely responses, planning appropriate actions, or decision making of projects, the knowledge of the transformations in the environment in its own right is necessary.

There are natural processes or events which can be associated with the identities in the large scale environment. For objects in the common-sense-space, interactions with other objects can also change the states of an object, the course and pattern of its movement. For objects of different ontological nature, there are different patterns as causations where they interact with each other. The predication of the location and state of an object at time also depends on the locations and states of other objects in the same location\(^{18}\).

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\(^{16}\)Such as a box or a building.

\(^{17}\)Such as a small ball which can be put in a box or a person who can be located inside a building.

\(^{18}\)The causal relation for interaction is one of the important components for the different kinds of causal knowledge and further development of causal knowledge of core-domains. For more discussion, see Section 6.2.
4.4 On structural constraints for identities-in-situations

While Millikan’s position of a common structure for the representation of the category of substance is adopted, to understand the development of conceptions of identities, a situation-based figurative understanding of the complex idea of the identity rules in Piaget’s theory will be given. Further, both the cognitive theories which address the issue of representation directly (e.g., (Smith and Medin, 1981)) and the cognitive theories which have emphasised the important constraints on representation of identities (e.g., (Carey, 1985; Keil, 1989a; Gelman and Markman, 1986)) are to be taken into the consideration for the elaborated account of Piaget’s identity rules.

For the issue of representation of identities, two major positions will be made in this section. Firstly, it is about the structural change for the development of conceptions of identities in the general functional constraints of learning and applications on the development of causal knowledge of different kinds. Secondly, it is about the structural constraint from the development of the system of categories within a core-domain, i.e. the conceptual re-organisation with the development of basic-level-categories.

4.4.1 The vertical and horizontal dimensions for conceptual systems

To study the development of representation of identities, there are the vertical and horizontal dimensions for the conceptual structure, which be explained in this subsection. They are crucial for understanding the structural changes for the representation of identities in conceptual systems in development. Firstly, the meanings of the vertical dimension as used in this thesis is associated with the development of conceptions of an identity on four different inclusive levels, namely, the conceptions for states, individuals, categories, and ontological kinds. Secondly, the horizontal dimension is about the development of the system of causal knowledge of different kinds. This dimension is not only important for understanding the specialisations of core-domains, but also the development of representations and knowledge of core-domains in general. It is also related to the development of basic level categories and category systems of core-domains.

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19 See Sections 6.3 and 8.3 for further discussions.
20 See detailed discussion in Chapters 5 and 6.
21 See the introduction in the next subsection. Also see detailed discussion in Section 6.3 for development of representation and knowledge of identities within core-domains in specific.
On vertical dimensions for conceptions of identities

The conceptions of an identity are on four different inclusive levels. The four levels of conceptions refer to different “mental structures” for assimilating the states of identities in the sensorimotor input from the environment. The four level conceptions of an identity can correspond to an ontological-kind (Keil, 1989a) (e.g. an animal), a specific category (Brainerd, 1978) (e.g. a cat versus a dog), an individual in four dimensional space-time (4D) (Elkind, 1969) (e.g. Mum), and the state of an individual at a time (e.g. a person in his childhood and in adulthood correspond to different states of the same person).

![Figure 4.5: The conceptions on different inclusive levels for identities.](image)

The four conception levels forms a hierarchy. Any one group on each of the conception levels can be treated as a category. However, the category is about a collection of identities or collections of states of identities (in the world at different times). The different inclusive levels mean that there are more or less numbers of identities or states of identities which can be included in the corresponding groups. From ontological-kinds, to specific categories, to individuals, to states of individuals, the inclusiveness is decreasing. That is, there are less and less identities which can be included into the corresponding groups.
Ontological-kinds as a level of conceptions have been studied in current cognitive theories which emphasise the constraints on the representation of identities. The ontological-kinds of identities may be understood as categories. However, they should be clearly differentiated from the specific categories for identities. While, an identity does not change its ontological nature, it can belong to different specific categories. It can change its categories in different applications since the same identity may play different functional roles in these changed circumstances and thus be grouped differently. A group of special categories, the basic-level-categories, will be emphasised for their cognitive values.

Categories as one level of conceptions for an identity is widely assumed in cognitive literature (Smith, 1989a; Markman, 1989; Hampton, 1993). The existence of this level conception is also implied in Piaget’s studies of sorting task and class inclusion task (Brainerd, 1978).

The conception of an individual is implied in the conservation task where an identity can be associated with multiple states at different times (Elkind, 1969). That is, it is a 4D existence. Another important issue for studying the representation of an identity in mind is that an identity is both an independent existence in the world and a member of a category. As a member of a category, the general knowledge about the category can be reliably inferred for a particular identity even though such knowledge was not acquired directly in sensorimotor examinations with this identity before. As an independent existence, it can have multiple states and the state at a time can be perceptually examined.

The state of an identity at a time is to be differentiated from the individual. An individual is a 4D existence and can have different states at different times as well as transformations of states over time. The conception of an identity in terms of its state at a time is widely assumed in perception literature and in image processing. The state of an identity at a time can include a set of physical measurements as well as spatial characterisations in terms of its shape or distinctive features of its boundary.

A state of an identity at a time can be used to assimilate other states in perceptual inputs. However, these other states in the environmental input can either belong to the same identity at different times, or the states belong to other identities. The two cases should be differentiated. However, this distinction was not handled in current theories of category representation and categorisations where the descriptions of states have been widely used in the judgement of similarities or differences (Smith and Medin, 1981; Medin, 1989; Ashby, 2005). For example,

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22Detailed discussion on basic-level-categories can be found in the next subsection, in Sections 6.3 and 8.3.
in current examples or prototypes based theory, the categorisation of an item is based on its similarity to the examples or the prototypes of categories. Depending on understanding, the examples or prototypes themselves can refer to the patterns in the perceptual inputs Brooks (1978), and in this case, the pattern of an item in perception is a state of it. The representation of examples or prototypes can refer to the descriptions with attributes (Smith and Medin, 1981) and the shapes of objects in 3D are the most emphasised attributes for similarity judgement.

**On horizontal dimension for causal knowledge of different kinds**

The horizontal dimension is about the development of causal knowledge. However, there are different understandings of causal knowledge for core-domains (Carey, 1985; Gelman and Markman, 1986; Keil, 1989a; Gopnik, 1996). In this thesis, the term *causal knowledge* is used in the most general sense to refer to the representation and knowledge in general which can be involved in the mental operations\(^{23}\) for building models of applications. They can be knowledge about *states* and *transformation* of the environment. For understanding the *states*, there are the knowledge of identities and knowledge of states at different times. For understanding the *transformations*, there are also the transformations of different kinds which involve either single identities or multiple identities.

From the perspective of the situation-based theory, the representation and knowledge which are involved in mental operations can be differentiated into four kinds, called the system of causal knowledge\(^{24}\). Specifically, there are the *causes* of existences, the *causal rules* or *causal conditions* associated with the single identities, the *causations* or *causal mechanisms* associated with situations involving two or more identities in interactions, and the general *casual constraints* in developing the understanding of the transformations in the world.

The **cause** of existence: The knowledge of the *causes* for the existences in the environment is the most fundamental kind of causal knowledge. The existence itself is also the **cause** for the possible psychological understanding of such an existence in the world. For any identity in the environment, it must have a cause. However, the exact causes for their existences may be

\(^{23}\)The detailed discussion on mental operations from the figurative perspective will be explained in Section 5.4.

\(^{24}\)The term *a system of causal knowledge* is used differently from the term *causal systems*. The latter refers to a special case of complex situations with consistence internal structure and coherent behaviour patterns. The former term is much general which can include different kinds of causal knowledge, including the concrete causal systems.
unknown. This kind of causal knowledge, which often depends on the perception of movements or the distinctive states of identities in contrast with the surrounding background, is important for the ontological distinction of identities in different spaces. It is also an important factor for differentiating natural objects from artefacts.

The causal rules and causal conditions: The general sense of the identity rule, i.e. the psychological understanding of an existence, can be differentiated into two subtypes, which refer to two families of causal knowledge associated with single identities. One is called causal rules, which refer to cognitive processes linking attributes to identities as individuals. That is, the causal rules are cognitive processes which use attributes for the cognitive functions of discrimination, recognition, identification, categorisation, and re-identification. The other is called causal conditions, which refers to a set of cognitive processes starting with identities or categories, then their attributes or properties. The cognitive processes can include the immediate action based responses or inferences of attributes. In the latter cases, the recalled or inferred attributes of identities can be involved in reasoning, planning and decision making. Not only are there different processes underlying these two families of cognitive functions (i.e. they can refer to different kinds cognitive processes), but also each of the processes can be distinctive for identities of different ontological natures. In the below subsection, a few crucial subtypes of causal rules will be further explained in terms of different cognitive processes.

The causations and causal mechanism: The knowledge of causations and causal mechanisms are applied to understand the transformation of situations which involve the interactions of identities. The distinctive causations and causal mechanisms as patterns for interactions are important for the differentiations of physics, biology, and social environment as core-domain. However, specialisations of core-domains also involve the knowledge for the causes of existence, and include the biology inheritance (Carey, 1985; Carey and Spelke, 1994) for the distinction of biology.

There are two kinds of further development of this kind of causal knowledge. Firstly, it is about the development of causal systems which refer to those concrete core-domain situations which have consistent internal structures and coherent processes and behaviour patterns. They can be treated as single identities with complex internal structures. Such causal systems can be treated as single components when they are involved in defining an even larger complex situation because of the coherent processes and behaviour patterns. Causal systems are natural or man-made systems which are complex situations in nature. Secondly, there are also further de-
developments of *causal knowledge* of core-domains in terms of developing abstract formalisation (Smith et al., 1985; Gopnik, 1996). For example, Siegler (1976) argued for the development of *rules* for understanding the states of physical systems. Gopnik (1996) argued for the *theory* *theory* of cognitive development, which emphasised the distinctive *causal theories* and *laws* of different *core-domains*²⁵.

The **causal constraint**: The *causal constraint* refers to the general principle to be followed for modelling simple or complex situations. It is about the *condition* for accepting the representation of a situation. For modelling any given complex situations, there are identities as the building blocks. The state of the situation can be defined with the states of the identities and their spatial configurations. The transformation of states of the environment can be observed in terms of the differences in two states over time. However, the changes of states may be caused and thus explained by *processes, events, or causal interactions*. The *rule* of this *causal constraint* means that a *global transformation* of states should be explained by the *localised changes* which are associated with either single identities or their interactions. This general *causal constraint* is not only important for the development of domain specific causal knowledge, but also important for the development of core-domains, application-oriented domains, and adapting the representation for any application situation in general²⁶.

**On knowledge of identities in terms of causal rules and conditions**

Cognitive literature is abundant with studies of cognitive processes. From the perspective of the situation-based theory, these processes are associated with different steps in processing environmental input. For example, a distinctive pattern is recognised in the perceptual input, then classified as a state of an existence belonging to an ontological-kind (e.g. an object with boundary), then it can be categorised as a state of an individual which belongs to a category, such as a dog or a table. Four kinds of such *cognitive processes* are taken as important for the *identification* of an existence as *a particular* and will be briefly explained below²⁷.

*Discrimination* and *recognition* of patterns: These processes are associated with the perceptual processes where differences in perceptual inputs can be captured and outlines of objects

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²⁵Further discussions can be found in Section 6.2.
²⁶Further discussions can be found in Section 5.4.
²⁷However, detailed study of such *causal rules* for each kind of these *cognitive processes* are beyond the scope of this thesis which focuses on the structural constraints of different kinds on representation only.
can be drawn. If there are 3D objects, the shapes in 3D can be constructed from the outlines in 2D images which are derived from different perceptual perspectives (Marr, 1982). However, the state recognised as a distinctive pattern in perception will be further processed. They are either identified as belonging to a new identity or the new state of an old identity.

**Identification:** The term identification can be used in the specific sense to refer to the process of classification of a recognised existence into an ontological-kind. The ontological-kind of an identity is often an implicit knowledge for an identity in earlier cognitive development (Millikan, 1998b). The attributes which are crucial for making ontological distinctions are the locations and the exact physical natures, which determine the functional roles of these identities to a person or to other identities.

Pragmatically, there are certain cognitive cues for classifying identities into ontological-kinds. The attributes which support (not define) the classification of identities into ontological-kinds can include such information as the clear-cut boundaries, the complexity of internal structures, absolute sizes, locations in space, the patterns of relations or interactions with other identities. In cognitive system, the different ontological-kinds can be understood based on the direct sensorimotor interactions with these identities by a person (Mandler and McDonough, 1998). These different attribute dimensions which contribute to the ontological distinctions are often associated with distinctive brain substrates (Humphreys and Forde, 2001).

**Categorisation:** The process is associated with sorting identities into specific categories (in particular the basic-level-categories which will be discussed in the next subsection). The cognitive literature is abundant with studies of such a cognitive process. From the perspective of a Millikanian view (the view is also emphasised in current cognitive theories), the formation of categories of identities should be constrained by two kinds of functional demands. One is the functional demand to support the inference of attributes and properties. The inference of properties of an identity is to support further cognitive functions, such as causal explanations (Keil, 1989a) or the judgement on the uses of an identity for certain circumstances because of certain properties (Ross, 1997; Markman and Ross, 2003). For such purposes, the identities which are included in a category should, firstly, share the functional values in terms of their uses. It is also a functional advantage if they share similar spatial locations so that they can be easily relocated. The similar patterns of functional relations to others or causal interactions.

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28 See Section 7.2 for the detailed study on the ontological natures and the cognitive criteria for the ontological distinctions of identities.
with others are often required too, so that the knowledge of how to interact with them can be used efficiently.

The other is the functional demand of efficient categorisation. Categorisation in general can consider either a single attribute dimension or multiple ones. From the functional perspective, the attributes of identities which are distinctive should be included in the rules for categorisation (Bruner, 1957). The attributes which are used for categorisation are often the perceptual ones. The perceptual attributes are pragmatically important for categorisation because they can be linked to pattern recognition in perceptual modalities. These cues for categorisation are often called the structural properties, including distinctive boundary features (Gibson, 1969), parts (Tversky and Hemenway, 1984), or certain configurations of features (such as for face recognition) (Johnson and Morton, 1991; Johnson, 2005). They are often reliable to categorise objects. However, the attributes for categorisations can also involve other non-structural dimension, such as distinctive movements and functional uses (Humphreys and Forde, 2001).

The re-identification: It is about the process that a constructed state in perception will be assigned to either a new identity or an old individual which has been experienced in the past. For any individuals, they hold certain positions in space-time and bear specific spatial, temporal, functional, and causal relations to other identities. From the recognition of a state to the re-identification of it as belonging to an old object, both the possible changes in shapes or changes of locations should be explained by the kind of transformations which are applicable to the identities, such as natural processes, events, or causal interactions.

Pragmatically, the process of re-identification takes into consideration the ontological nature of an identity. Depending on such nature, different rules can be developed for re-identification. For identities in the large-space, they usually have fixed locations. The re-identification can be based on their locations directly. For identities in the common-sense-space which can change their locations, different criteria can be used. For example, for a moving object, the rule requires either a trajectory can be established, or the changes of states or locations can be explained by the knowledge of possible transformations. The re-identification of an object can also use the knowledge that the spatial configuration as the context for an object has stayed unchanged. In biology, DNA information is reliable for differentiating not just species but individuals.
4.4.2 Basic-level-categories and category systems of core domains

The development of the conceptual system is driven by one fact that the representation in mind is inherently for a set of identities. In this particular subsection, the general position for the development of conceptual systems with categories and category systems is introduced. The idea of the basic level categories (Berlin and Kay, 1969; Rosch, 1978) will be explained. These categories are empirically identified in these classic studies, however, they will be used as the important conceptual construct for understanding the conceptual re-organisations in the context of a core-domain or sub-situations of a core-domain. From the theoretical point of view, two properties of basic-level-categories have made them important. One is that, within a core-domain or sub-situations of a core domain, they form a mutually exclusive set. The other is that they are associated with highest cue validities and category validities.

On vertical and horizontal dimensions in Rosch’s prototype theory

In terms of studying conceptual system, the prototype theory of Rosch (1978, 1983) is perhaps one of the most influential cognitive theories (Lakoff, 1987). There are two important claims with the prototype theory. One is that the representation of a category is in terms of prototypes or reference points (Rosch, 1983). The other is about the category system. For the category system, there are also the vertical and horizontal dimensions. According to Komatsu (1998),

“...the horizontal dimension distinguishes kinds (e.g., “dogs” rather than “cats” or “tables”), as well as varieties of kinds (e.g., artifact kinds rather than natural kinds). The vertical dimension distinguishes levels of inclusiveness (e.g., “dogs” rather than “animals” or “dachshunds”). As used by psychologists, the “basic level” refers to that point along the vertical dimension that strikes the best compromise between having too few categories (i.e., sacrificing inductive richness) and having too many (i.e., sacrificing cognitive economy)” (Komatsu, 1998, p.76).

The horizontal dimension is about different categories on the same inclusive level. The vertical dimension is about categories on different inclusive levels, such as the basic-level-categories, super-ordinates, and subordinates which defines a taxonomy. However, there is a new idea of basic-level-categories (Berlin and Kay, 1969; Rosch, 1978). According to Rosch

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29 The term is denoted with basic-level-categories in this thesis.
(1978), *basic-level-categories* are those empirically identifiable and cognitively significant categories. According to the idea of family resemblances of Rosch et al. (1976), a basic-level-category is represented with a prototype and can have a collection of individuals as its members. A category is derived based on the maximum similarity of individuals as members of the category and the maximum differences to individuals of other categories. *Basic-level-categories* are often considered as culturally independent (Berlin and Kay, 1969) in that the same set of categories, such as colour terms, can be found across different cultures. However, in the core domains of physics, biology, and social studies, the *basic-level-categories* may be culturally dependent in that different sets of *basic-level-categories* of a core-domain may exist in different cultures.

### On basic level categories in Rosch’s prototype theory

In this thesis, the idea of *basic-level-categories* of identities is adopted, however, under the condition that they are categories studied in the contexts of core-domains or sub-situations of core-domains. There are two properties which make basic-level-categories theoretically appealing. Firstly, *basic-level-categories* are considered mutually exclusive (Mervis and Rosch, 1981). Indeed, to develop a set of mutually exclusive categories is predetermined by the functional expectation in order to sort identities into different groups. With the mutually exclusive *basic-level-categories*, all identities within a core-domain can be sorted into their corresponding basic-level-categories in the corresponding core-domain. Secondly, the *basic-level-categories* are claimed to be the categories with the highest cue validity or category validity (Rosch, 1978; Johnson and Mervis, 1997, 1998; Johnson and Eilers, 1998). The highest cue-validity of the basic-level-categories often means the perceptual properties are highly reliable for the categorisation. To the objects in the common-sense-space, *basic-level-categories* are said to have distinctive parts (Tversky and Hemenway, 1984). The highest category validity means the inferences of properties can be reliably made once identities are categorised. However, the properties which can be inferred of a category or of an identity should also be useful. Indeed, according to psychologists (Gelman and Coley, 1991; Keil, 1989a), there are two families of functions to be supported by the representation of categories and inferences of properties. The functions are related to the accurate *categorisation* or *identifications* on the one hand, *inferences* of properties for further uses, such as *explanations* or *predictions* on the other hand. The importance
of the basic-level-categories lies in the good supports they can provide for these two kinds of functions.

In the theory of this thesis, the idea of basic-level-categories is crucially important for understanding the development of categories in the context of a core-domain. 1) There is always a set of basic-level-categories within the specialised domains for sorting identities into their corresponding groups. The development of a set of basic-level-categories for core-domains is a universal, culturally independent tendency. 2) The different sets of basic-level-categories of a core-domain are related to the different experiences of individuals. The development of such a set of basic-level-categories is a tendency and there can be a changed set of basic-level-categories (Johnson and Mervis, 1998; Johnson and Eilers, 1998) when there are more experiences with the identities in core domains. 3) This development of basic-level-categories for identities within a core-domain should be treated separately from the development of language names for categories, although the two are closely related.

The idea of basic-level-categories is taken as central for the further development of the conceptual system. The set of basic-level-categories defines a special kind of structural constraints for the domain knowledge of identities. 1) It is related to the further development of concepts in the Piagetian sense and the possible intensional definitions of basic-level-categories of core-domains. 2) Basic-level-categories are important for the development of the category systems for a core-domain. It is important to understand the two different kinds of taxonomic hierarchies (Rosch, 1978; Wierzbicka, 1984). One is the hierarchy defined with states of individuals, individuals as 4D existences, basic-level-categories, and an ontological-kind. The other is about the structure defined with subordinate (e.g. dinner table), basic-level-categories (e.g. table), and super-ordinates (e.g. furniture) studied in (Rosch, 1978). Although both kinds of hierarchies are called taxonomies, these two hierarchies are of different causes. The former is related to the innate change of conceptual structure. The latter is related to the conceptual re-organisation for the efficiency of information retrievals (Rosch, 1978). These points related to the basic-level-categories will be further studied in Sections 6.3 and 8.3.

**On categories of other ontological-kinds in languages**

Representation of categories has been a major focus in cognitive psychology. A category is a collection of identities following certain criteria (Markman, 1983). However, the categories
which have lexical names are not random collections, nor are these categories of the same natures. The systematic study regarding the nature of the categories is lacking\textsuperscript{30}. For the relevancy of this thesis, two other groups of studies of categories will be covered here.

Firstly, it is about the \textit{global categories} of Mandler. Rosch claimed that the basic-level-categories are the ones which develop earlier. This was challenged by Mandler (1988, 1992, 1996, 2004). They argued that infants learn the \textit{global categories} first, which are defined by the recall of representation in \textit{action schemes}. From the biological perspective, categories are usually formed based on the understanding of the biological functions of identities, which can be in terms of direct \textit{actions} upon the objects. This is a typical Piagetian view. However, there are two points to be noted. One is that objects of different shapes can share the same functional value, such as being food. The other is that while objects with same or similar shape (e.g., toys in Mandler’s studies) can be assimilated by the same kind of \textit{action schemes}. However, two real objects of different ontological-natures, even if they share similarity in terms of shapes (such as a toy horse versus a real horse), cannot be assimilated by the same kind of \textit{action schemes}.

The development of ontological-kinds for identities can be related to the differences in action-based recall. However, ontological kinds as categories for identities are given by nature, not determined by cognitive understanding. An ontological nature means identities of certain \textit{natures} exist in certain concrete \textit{situations} in the world. The natures of these situations can influence the learning of identities for a kind and the application of the representation for such a kind.

Once the same \textit{action scheme} starts to assimilate the same or similar shapes (which can be of different individuals), it can imply a category for the collection of identities which have similar shapes. However, such a capability does not imply the explicit distinction of the state of an identity from the identity as a 4D existence. The same \textit{action scheme} can be applied to objects or geometrical patterns. However, a basic-level-category of identities in this thesis is a collection of natural objects exist in 4D space-time, not a collection of items with similar shapes only.

Secondly, it is about \textit{collections} and ontological nature of other nouns in a language. According to Markman (1989), the nouns for concrete objects are among the first language terms a child can learn. However, the categories for concrete nouns studied in cognitive literature are of different natures. For example, Wierzbicka (1984) questioned whether some of the super-

\textsuperscript{30}But see (Medin et al., 2000) for an exception.
ordinates (e.g. furniture) studied by Rosch et al. (1976); Rosch (1978) share the same name as those taxonomic categories (such as those super-ordinates in biology). The *taxa* for organisms in biology are real kinds which are specialisations of the ontological kind for *living things*. According to (Wierzbicka, 1984), some *super-ordinates* (such as fruit, tools, and furniture) in the study of Rosch (1978) are *non-taxonomic*, but collections in events (Nelson, 1986), and any kinds of *collections* (such as things in a bag). These super-ordinates or subordinates are different kinds of collections. For example, they are collections of objects which bear spatial proximity (Markman, 1983; Mandler et al., 1987), are collectively involved in certain events (Nelson, 1986, 1993), or simply the *ad hoc* collections of objects for certain circumstances and functional purposes (Barsalou, 1985).

Indeed, the concrete nouns in a language can be names for different kinds of references. The references of language terms can correspond to these three ontological groups which are commonly called objects, parts, and collections. The language terms are understood as referring to the category of substances (Millikan, 1998a) as *natural units* in the world. The language terms are traditionally understood as the names for individuals and categories of identities. However, four kinds of references for concrete nouns are to be differentiated. That is, the names can be for *states* of individuals at a time, for *individuals* which are also members of real kinds, for an individual which is a member of functionally defined collections, and individuals in particular application situations (where they are members of a kind and studied in a domain perspective). There are also names for *parts* in language. Depending on the study area, these parts can be the distinctive ones which are studied specifically. For example, parts for complex machines in mechanical engineering. There are also names for various sorts of *collections* of identities or categories (e.g. a line of trees or a forest). There are not only the collections of objects in events, but also collections of objects in certain functionally meaningful environmental setting.

According to Markman (1983), the ontological kind of *collection* is also a primitive one. However, the collection kind can be differentiated into two groups. Some are just random collections and do not have consistent internal structure. There are collections of objects following a single variable, such as sharing a property or a function use. Others do have certain internal structure. These are collections of objects which appear in certain spatial locations or often embedded in events (Barsalou, 1985; Markman, 1983; Nelson, 1986; Wierzbicka, 1984). From the perspective of planning for goal-directed actions (often associated with a sequence of events), there are also distinctive events of core-domains. The development of taxonomies is
with super-ordinates and subordinates which are collections of objects or categories in certain *spatial contexts* and *events*. The compositions or collections of identities in certain locations and events as categories are for the convenience of frequent applications. However, the basic-level-categories, super-ordinates, and subordinates can all be involved in new applications which may also involve identities of different core-domains.

According to Nelson (1986), events (e.g., in plays) are important for the formation of categories, in particular the super-ordinates and subordinates which are collections of objects with certain shared functional roles or they are embedded in the same event. To Rosch (1978), these categories were considered as generalised or specialised from the basic level categories. When a person is involved in a situation and interacts with other identities within the situation, the focus can be either on the *actions* and *events*, or the *collections of objects* involved in the actions or events. When a study focuses on the objects in the situations, depending on the core domains, there can be functional categories\(^{31}\) associated with certain actions, the formation of super-ordinate *categories* (e.g., *kitchen utensil* or *furniture*) (Nelson, 1986), or the so called *ad hoc* categories (Barsalou, 1983) in an episode of experience defined with a sequence of events. When the situations to be studied are parts of the social environment, there are also the *functional organisations* (e.g., social organisations) of different kinds (such as schools, hospitals, factories, banks, and government agencies).

### 4.5 Summary

This chapter gave an overview of three levels of structural constraints on the representation of identities. Firstly, the “locations” of identities was discussed. *Zubin spaces* and *situations* as locations are distinguished. *Situations* are important because they are not only the locational constraints of identities, but also the distinctive units of representation themselves for characterising the environment. A few *formal subtypes* for describing situations as contexts of a figure were discussed. A few distinction of situations as contexts from the semantic perspective were also given, this includes *immediate situations* (relevant for understanding ontological-kinds), *core-domains*, learning, and applications. They are special cases of *situations*.

The structure-of-the-whole in Piaget’s theory was discussed in figurative terms, which is the *first level structural constraint* on the representation of identities. For the development of a rep-
CHAPTER 4. THE STRUCTURE-OF-THE-WHOLE

representation, there are three levels of organisation and three kinds of conceptual organisations, *individuals*, *core-domains* for individuals, and *complex situations* of applications. With the specialisation of core-domains for identities, the conceptual structure can be re-defined with part-whole relations. There are two levels. Firstly, the conceptual structure is defined with a system of core-domains. The identities of different core-domains in different spaces bear *part-whole relations* to each other. Secondly, there are part-whole relations which are involved in the representation of identities in core-domains and in application. These are relevant for the further study of conceptual structure of a core-domain, including formal schemata of identity representation.

The second and third level structural constraints from the conceptual structure and from category systems on the representation and knowledge of *identities* in core-domains were also introduced. Vertically, there are *conceptions* of identities on four inclusive levels for assimilating the states of identities in the environment. They are the conceptions on the levels of *ontological kinds*, *categories*, *individuals*, and *states* at a time. Horizontally, i.e. from the perspective of mental operations, there are four kinds of *causal knowledge* for assimilating the transformations. For concrete situations, the different kinds of causal knowledge include the *causes* of existences of identities, causal rules for identification and re-identification as well as causal *conditions* of inferences, *causal mechanisms* for interactions, and the general *causal constraints*. For identities within a core-domain, the development of *basic-level-categories* for identities was emphasised. Categories of other nature which are studied in cognitive literature were also covered.
Chapter 5

The specialisations of *core-domains* for the study of the environment

5.1 Introduction

The current dominant cognitive theories of representation and development often emphasise the constraints and context effects on category representation. However, there are concerns with the current states of these theories. This and next chapters are devoted to address such concerns in order to apply such theories to the purpose of modelling spatial-features which belong to different domains of environmental studies.

To the concern of this chapter, while the idea of *domain specificity* is widely accepted in these studies and theories of constraints, the concept of *domains* is unclear and there is the lack of an agreement on the system of the so-called *core-domains* for the environmental representation. The lack of agreement in understanding the nature of *core-domains* and the relations of different domains relevant for the environmental studies had made it hard to explain why *core-domains* are so special. Consequently, it is hard to specify the different *constraints* from a core-domain upon category representation.

In this chapter, the issue of domain specialisations will be the focuses. The key understandings will also be given to address the relevant concerns as seen from the perspective of the situation-based theory. Section 5.2 will examine the concept of domains and core-domains in the cognitive literature and explains the meaning of domains as it is adopted in this thesis. It points to the need to study a system of core-domain for the environment and understanding the criteria for the specialisation of core-domains. It also re-emphasise the functional principle as the general constraint upon the specialisation of core-domain and the development of representation and knowledge in a cognitive system. Section 5.3 will focus on the development of domains for the environmental studies, in particular, the system of *core-domains*
and *application-oriented* domains supported by the **Level-4** cognitive system. Section 5.4 will briefly explain the mechanisms of development for domain specialisations, from *core-domains* in the *common-sense-space* to those in other spaces and the representation of *complex situations* in general.

### 5.2 What are domains?

Domains are often emphasised for the important constraints they play on category representation. However, different researchers have quite different understandings on what a domain is. A diverse range of concepts are all taken as implying different domains which constrain the representation. In Karmiloff-Smith (1992), the domain differences are taken in terms of physics, biology, language, and narration. In Gelman (1990), the domain is about numbers. In Keil (1989a), different domains are essentially implied when concepts of different ontological natures are discussed. On the broader sense, the domain distinctions are in terms of the differences of *natural kinds*, *artefacts*, *nominal concepts*. In a specific sense, the domains correspond to the studies of *moral concepts*, *hand tools*, *kinship relations*, *meals*, and *cooking*. In (Chi et al., 1981), a domain can also refer to the game *chess*.

In order to model the constraints of domains on the representation of identities of spatial features, the exact meaning of a domain is to be clarified in order to understand their constraints. Hirschfeld and Gelman (1994) provided one definition, which they considered as “fairly uncontroversial”:

A domain is a body of knowledge that identifies and interprets a class of phenomena assumed to share certain properties and to be of a distinct and general type.

A domain functions as a stable response to a set of recurring and complex problems faced by the organism. This response involves difficult-to-access perceptual, encoding, retrieval, and inferential processes dedicated to that solution (Hirschfeld and Gelman, 1994, p.21).

Following this definition, there are two aspects about a domain. Firstly, a domain is about the study of a particular subject matter, i.e. “a class of phenomena”. Domains are differentiated because they study different phenomena. Thus, there are the distinguished domains for the studies of the environment, languages, and logics. Secondly, a domain is associated with
CHAPTER 5. THE DEVELOPMENT OF DOMAIN SPECIALISATIONS

the representation and knowledge of such situations which define the subject area of study. Karmiloff-Smith (1992) also defined: “a domain is the set of representations sustaining a specific area of knowledge”.

However, to study domain specificity on representation, the distinction between the phenomena versus their representation in mind is needed. A domain always involves both components. Objectively, a domain refers to certain situations in the world. The understanding of domains and domain distinctions should emphasise the corresponding specific situations in the world as their subject matters. This is about the Ontological perspective of domains. Subjectively, a domain can also be taken as a unit of knowledge which has a certain degree of consistency and coherency. Carey and Spelke (1994) called it the core principles. The understanding of a domain distinction should also emphasise the distinctiveness of representation and knowledge of a domain. This may be called the Epistemological perspective on domains. Most cognitive studies on domain specificity for category representation have weighted higher the Epistemological perspective on domains. However, the understanding of a domain is ultimately determined by the phenomena in the world which is studied.

5.2.1 On core-domains for the environment

The subject matter to be studied in this thesis is the concrete environment, which is defined in the general sense to refer to the world excluding the organism who perceives and conceives it. This general understanding of the environment as a single domain has made it no easier a task to integrate the domain specificity theories into a representation theory.

The point is, a complex subject such as the environment can also be studied with different focuses, from different aspects, and with the use of different methods. For example, the environment as a whole can be segmented into different regions, locations, and spatial features. These segments of the environment can all become the subject matters in their own right. Traditionally, the knowledge accumulated about the environment can focus on spatial features, or relations, or processes (Burrough and McDonnell, 1998). The representation and knowledge acquired by the selected focuses may or may not overlap. In some cases, the same “core principle” may unify these different aspects (e.g. natural systems studied in different domains of geology, hydrology, or climatology). In other cases, different “core principles” may define these different aspects or sub-areas of the environment as distinctive domains (e.g. the studies
of landscape, the urban development, and geographical regions). The environment is not only studied via the direct examination of it, but also learned via the language records of the representation and knowledge acquired by others. There are also the involvement of mathematical formalisations and computer simulations. Because of these differences, it may appear there are different sub-areas and different “core principles” for the environment in general.

Indeed, to apply the domain specificity, the concern is about the specialisation of the environment as a whole into certain meaningful “domains”. A particular domain of SISciences can refer to a collection of specific situations in the world, rather than the environment as a whole. While the situations are in the world, the knowledge of such situations is represented in mind. The representation of certain situations has to be distinctive in order for the specialisation of a domain for these situations. That is, the definition of a distinctive domain involves the distinctive patterns of representation and knowledge. Both the existences of certain situations in the world and their representations are important aspects to the specialisations of domains.

The following question is thus where to draw the boundaries of these situations in the environment under two conditions. On the one hand, the system of such situations can be sufficient to differentiate all the meaningful situations in the world. On the other hand, they have to be associated with distinctive patterns of representation in mind. Although a non-trivial task, evolution has equipped the brain to support the important domain distinctions (Fodor, 1983; Karmiloff-Smith, 1992; Millikan, 1998b). However, Keil (1994) criticised the studies of domain constraints on representation in general for the proliferation of domains and expertises:

“…there may be only a small number of these basic modes of construal that emerge in earlier life, say, half a dozen or so. Such a modest array of stance would mean that concept structure was neither reducible to one set of laws arising out of a single model of learning, nor splintered into a thousand different areas of expertise and skill. There may be enough diversity of these basic biases to help us understand the major different kinds of patternings in the natural and social worlds, but not so much as to turn the study of concepts into an endless catalogue of different structure in different tiny domains” (Keil, 1994, p.252).

“(W)e collapse together these different senses of domains at great peril. The fundamental modes of construal give us immediate intuitive feelings not only for how and why things are the way they are, but equally important, of what sorts of
things there are; they yield out ontologies. ... the sense of immediate explanation starts to fade, and is gone altogether, along with any ontological sense, as we move into the cognitively “blind” expertise of the chicken sexer” (Keil, 1994, p.252-253).

Indeed, the issue raised by Keil (1994) is quite relevant for two crucial concerns in order to assimilate these domain specificity theories into a representation theory for modelling in SISystems. One is about the core-domains for the environmental representation, more specifically, the set of core-domains as the “initial distinctions” for the study of the environment. Cognitively, certain kinds of domain distinctions are meaningful and crucial, while others are less so. Some domains are too general, while others are too specific. There is this pitfall when domain differentiations are mainly based on different concepts involved in the representation of a set of situations for a subject. In cognitive literature, it was generally argued “innate modules” (Leslie, 1994), “core knowledge” (Spelke and van de Walle, 1993; Spelke, 1994) or “core domains” (Wellman and Gelman, 1998) are extremely crucial for studying representation. However, there is a disagreement on what is the initial set of “core domains” for cognitive development. Further, the set of core domains in mind is not exactly the same set of core domains for the study of environmental representation. Regarding the representation of the environment, the set of the core-domains is neither clear nor systematic.

The other is about the criteria which define domain specialisations. In other words, the questions are why these core-domains become distinctive and crucial in their own right and what are the core principles which allow these certain situations of the environment to be treated as distinctive domains. These questions are about the distinctive nature of these core-domains, their crucial roles for further cognitive development, and their constraints for category representation.

On the core domains relevant for the study of the environment

Although the SIScience is about the concrete environment in general, there are differentiated domains which study the corresponding interesting entities or phenomena in different kinds of situations in space-time. For the theories of domain constraints on representation to be relevant, the set of “core domains” which are cognitively distinctive to the environmental representation should be decided.¹

¹The core domains of SISciences will be studied in Section 5.3.
In cognitive literature, there are different proposals of the initial domain distinctions which are relevant for the study of the environment. These are the domain distinctions a child seems to possess at a much earlier age. The first is the proposal of the innate modulars for objects and for agency (for living things in general) from Leslie (1994). The modular for handling objects is called ToBY (the Theory of Body Mechanism). The modular of agency is called ToMM (the Theory of Mind Mechanism), which is further differentiated into two components. The first component \((System_1)\), also called “Agents and Action”, is about “the agents and goal-directed actions they produce”. It is closely related to the mechanism of mental operations. The other component \((System_2)\), also called “Agents and Attitudes”, is about “mental states of agents” and their roles in producing behaviours. This second system of ToMM is closely related to the understanding of “representation in general” and development of “representation systems”.

The second proposal is about the so called core knowledge domains from Carey and Spelke (1996). The “core knowledge domains” include knowledge of objects (Spelke and van de Walle, 1993), knowledge of object categories (Mandler and McDonough, 1993), knowledge of people or agency in general (Leslie, 1994; Gergely et al., 1995), and knowledge of number (Wynn, 1992, 1995). Others also add the knowledge of space (Acredolo, 1978; Bremner, 1985, 1998) into the list of core knowledge domains. These domains are called “core knowledge” domains because the knowledge of these domains is considered largely innate and they define the foundation of cognitive systems (Carey and Spelke, 1994, 1996).

For the study of the environment, the third proposal of core domains is about the domains of physics, biology, and common sense psychology or the domain of folk psychology (Gopnik, 1996; Wellman and Gelman, 1998). These proposals are based on the differences in representations of artefacts versus living things (Gelman and Markman, 1986; Keil, 1989a), distinctive biological theories (Carey, 1985; Keil, 1989a), and the changes of mental states of a person on actions (Gopnik, 1996; Wellman and Gelman, 1992, 1998).

The three proposals of “innate modulars”, “core knowledge domains”, and “core-domains” all define the distinctive “cognitive domains” which are crucially important to cognitive systems. While most research agrees there are domain constraints on representation from a very early age, they have different opinions on when and why these core-domains become established. Some take these core-domains as perhaps innate, such as the study of Spelke and van de Walle (1993) on the domain of objects. The position that these core-domains are innate and given by nature often implies there is not much to be explored about the cause and mechanisms
of such a core-domain (Fodor, 1983), i.e. modularisation in the terminology of Karmiloff-Smith (1992).

In this thesis, to study the core-domains of the environment, rather than innate knowledge, Piaget’s constructive position of knowledge (Chapman, 1988) is followed. To understand domain distinctions, apart from the observations of empirical data, the process of domain specialisations is to be understood and the criteria is to be stated. Thus, a system of specialised domains can be listed following a certain principle criteria. Without a theory on the development of these domains, the proposed domains only form a collection rather than a system. For the system of core-domains which are relevant to the representation of the environment, they are not only about any domains, but also the ones on a suitable level of distinctions of the environment.

Regarding the domain of objects, Piagetian constructive theory can share the position that the representation in the brain of an organism and the mind of a person can start with the representation of substances in the world (see Section 2.2). However, it also takes that there is the qualitative change regarding the ways the identities in the world can be represented in the mind of a person. In Piaget’s theory, during the earlier stages of development, i.e. before stage IV of the sensorimotor period, the representation of identities is implicit in sensorimotor schemes. Only from stage IV after object permanency, there are explicit representations and the explicit distinction of two ontological-kinds, i.e. objects with clear boundaries versus stuffs for substances\(^2\).

Regarding the domain of numbers, this thesis takes the position that the development of numbers is genetically predisposed to develop in human. However, the domain of numbers is a distinctive area which is more relevant to the capability of abstract descriptions of the concrete physical world. There are developmental issues regarding what situations in the environment can be re-described and how. It is not only about counting objects, but modelling accurately the states of identities and the environment on the one hand, the transformations on the other hand. There are also developmental issues regarding the ways numbers can be represented and their meanings. Indeed, there are distinctive features associated with the learning of numerical systems. In those studies which were cited for the claim that the domain of numbers is innate, what has been studied is the capability of detecting changes in number of objects in certain spatial contexts (Wynn, 1992, 1995). Infants (as younger as 6 months old) have been shown to have such a capability and even the capability of expecting results of some simple arithmetical

\(^2\)For discussion on the earlier change of object representation, see Section 3.3.
CHAPTER 5. THE DEVELOPMENT OF DOMAIN SPECIALISATIONS

operation, such as adding or subtracting one object from a small collection in a display. The infants were said to be born with specialized neural substrates to support the need to categorise the world into small sets of objects, the same way as they were born with the ability to make colour differentiation.

Number’s names are often learned explicitly in counting game when numerical names are associated with two understandings, i.e. large and small numbers can reflect more and less of objects and large and small sizes of certain measurement of objects such as length. The meaning of numbers originates in operations (e.g., counting) rather than concrete objects themselves, although it might be the objects in the world which are to be counted. However, the explicit knowledge of numbers is associated with understanding of two kinds of relations, numbers of objects or relations of physical measurement. According to Piaget, the ability to think about the world in numerical terms starts to emerge no earlier than 5 years of age when children can pass the conservation task. It requires the prior development of transitive reasoning and putting two sets of objects into one-to-one correspondence (Butterworth, 1999).

Regarding the domain of spaces, this thesis takes the position that the representation of spaces is also genetically predisposed for higher animals. The domain of space is directly relevant for the environmental representation and there are developmental issues regarding the ways the space can be represented. The representation of space is not exactly the same as the representation of spatial locations for objects. While there are earlier representations of spatial locations for hidden objects in Stage V of sensorimotor period, the representation of spatial locations in terms of configurations of objects is developed until about 5 years of age when children can pass the three-mountain task. In Piaget’s theory, it requires the allocative representation of spatial relations of the objects within a larger frame (Brainerd, 1978). However, the spatial configuration for the large scale environment (e.g., configurations of buildings) becomes an explicit domain in its own right only at later stages of cognitive development (i.e. in the concrete operational period in Piaget’s theory) (Piaget and Inhelder, 1956).

The “core-domains” of physics, biology, and social studies of people are taken crucially important in this thesis for ontological-distinctions of objects as figures and their environment. However, instead of the domain of folk psychology, the third core-domain takes the domain of social studies. In both domains, the actions of people are the key subjects. However, there are

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3 See Section 4.2 on space and situations for the locations of identities.
4 More discussion on the development of representation of space can be found in Section 5.3.
two senses of *psychological causes* conflated in the studies of *theory of mind* (Harris, 1992; Wellman and Gelman, 1998; Wellman et al., 2001). The general sense refers to the effect of the *mental representation* and the *mechanism of operations* upon the decision of actions and behaviours in the environment. The specific sense refers to the direct involvement of the actions of the self as the causes for the changes of the environmental states. In the earlier ages, the actions of the self have been taken by children as the main causes for the changes of the environment. In the later stage, the causes of changes can be understood as lying in the environment. To understand these changes, the self becomes a *physical object*, a *biological entity*, and a *social member* among others whose actions can be the causes for the changes in the environment. These different roles played by the self in interactions with objects, organisms, and people can bring the earlier differentiated understandings of the *causal mechanism* and *causations* of the three *core-domains* (Harris, 1992). In Piaget’s theory, the pre-operational period is associated with the main phenomena as *realism*, *animism*, and *arteficialism* (Piaget, 1954; Chapman, 1988), which can be interpreted as about these changes.

### 5.2.2 On the criteria for explicit distinctions of core-domains

Apart from what is the set of “core-domains” for the study of the environment, there is another concern associated with these theories of constraints on category representation. That is, what are the criteria which can account for the specialisation of these “core-domains”? The understandings of what define a *core-domain* is directly related to the different sorts of constraints proposed in cognitive literature on category representation.

One of the important factors for differentiating core-domains is the ontological kind of identities (Mandler, 2000a). Indeed, some of the domain distinctions for identities are considered *innate* to an organism because the objects in these domains can be differentiated at a much younger age. For example, Mandler (2000a, 2004) argued that even infants can make rudimentary differentiation of ontological kinds and domains for identities, which can be based on the *shapes*, *movement* and *behaviour* patterns, and the *ways these identities can be interacted with*. For example, living things can be differentiated from physical objects because they can self-initiate actions while physical objects cannot. The movement trajectories are also different for these two groups (Mandler, 2000a). While all objects can be touched, the feeling from the touching of an animal (e.g. a cat) is different from touching a physical object (e.g. a toy). Phys-
ical objects do not make noise unless they are moving fast, they do not move by themselves, and some can be held in the hand and kicked by the foot. People can be differentiated from physical objects or animals because people can respond to the cries of an infant without direct physical contacts. There is also the capability of recognition of faces in general and human faces in particular in the infants (Johnson and Morton, 1991; Gauthier and Nelson, 2001). All of these are based on the direct interaction by a person, and the differences are explainable with rather coarse differentiations along attribute dimensions.

In the theory of Keil (1989b), the issue of domain specificity is closely linked to the different representations for ontological natures of categories because they support different kinds of inferences. The objects in different core-domains, i.e. the physical objects (Spelke and van de Walle, 1993), living things, such as animals (Carey, 1985; Keil, 1989a; Atran, 1994), and people (Wellman and Gelman, 1998) in social domain are taken as belonging to different ontological kinds. However, there are not only different representations for identities of different ontological kinds. For the representation of identities of the same kind, there is also an issue of development of representation within their core-domains$^5$.

Other theories proposed that core-domains are distinctive because of the development of distinctive theories for each of the core-domains (Carey, 1985; Smith et al., 1985; Gopnik, 1996; Wellman and Gelman, 1992). For example, folk psychology is proposed as the one of core-domains (Wellman and Gelman, 1992, 1998). The core-domain of folk psychology has focused on the development of theory of the mind, which can be linked to the earlier mentioned study of Leslie (1994) on the modular of agency (ToMM). The theory of the mind explains the actions of behaviours in terms of mentalist states, such as beliefs, desires, and intentions. Development means at different ages, different mental states, such as beliefs and desires, are involved in behaviour explanations. Four years old is a crucial age for the development of folk psychology. Here, children older than this age can pass a set of cognitive testing, including appearance-reality task, understanding false pretense, and theory of mind task. Younger children have difficulty to succeed at these tasks. Unlike the innate theory, the proposals for the core-domain of folk psychology often emphasise the construction rather than innateness of knowledge (Wellman and Gelman, 1998).

For biology, the explicit specialisation of the core-domain is also based the distinctive causal knowledge (Carey, 1985). According to Carey (1985); Carey and Spelke (1994), the biology

$^5$See the earlier discussion in Section 4.4. Also see more details in Sections 6.2 & 6.3.
becomes distinctive only when children can understand the biological inheritance. Based on biological inheritance as the criteria, the domain of biology is considered a later development which has become an independent area only when a child is about 6 or 7 years old (Carey and Spelke, 1994):

“First, children resemble their parents. Black parents tend to have black children. . . . Second, the mechanism underlying this resemblance crucially involves birth. . . . To be credited with a biological concept of inheritance, children need not understand anything like a genetic mechanism, but they must distinguish the process underlying family resemblance from mechanical or psychological processes. At a minimum, children should realize that the process through which an animal originates - birth - is crucially involved in the process through which animals come to have their specific characteristics (Carey and Spelke, 1994, p.186).

However, there are also certain concerns with this set of proposals. Firstly, the idea of causal theories is rather complex itself and was not very clearly defined Fodor (1994). In the theory theory, the development of causal theories is argued for the development of cognitive systems in general (Carey, 1985; Gopnik, 1996). Gopnik (1996) gave her definition of what can be called as changes of theories which is parallel to the paradigm change in the classic work of (Kuhn, 1996)). It often involves the “axiom” and uses the axiom to re-construct the knowledge of the whole domain, such as the adoption of atoms to study physics (Smith et al., 1985). The description of knowledge often involves mathematical formulations. Secondly, causal theories are also emphasised as the constraints on the development of representation of categories in the core-domains (Keil, 1989a; Medin, 1989; Gelman and Markman, 1986; Gelman et al., 1994; Gelman, 2004). However, the causal theories in these studies are somehow different from what were studied in (Gopnik, 1996) for cognitive development. The kind of causal theories of (Keil, 1989a) is related to the inferences of properties for causal attributions and explanations. The kind of causal theories of (Medin, 1989; Gelman et al., 1994; Gelman, 2004) is related to searching the “essences” of representation. Thirdly, there is also a particular issue regarding those distinctive causal theories for the different core-domains. Specifically, it appears that the proposed distinctive causal theories to explain the development of physics Smith et al. (1985), biology (Carey, 1985) and folk psychology (Wellman and Gelman, 1992) follow their distinctive

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6See the earlier discussion on different kinds of causal theories in Section 4.4.
and non-related principles. These may imply that either these different core-domains are not derived from the same general mechanism of development, or their developmental mechanisms have diverged only after these core-domains are specialised.

Explicit causal relations in interactions for core-domains

The issue of criteria for understanding a domain is important. Whether a domain is considered as innate or constructed can depend on different criteria. That is, the studies of different aspects of a core-domain can indeed be taken as the arguments for either the innate or constructed nature of the core-domain (Flavell and Miller, 1998; Wellman and Gelman, 1998). For example, another often cited evidence for biology as an innate core-domain comes from the anthropological study of languages of different cultural groups (Atran, 1994, 1998; Atran et al., 2004). Atran and associates have found the universality of biological taxonomies of different native cultures as well as the similarity of such folk taxonomies with the scientific taxonomies. However, whether such evidence can be taken as innate biology is uncertain. The similarity in taxonomies can be explained by other proposals.

If the criteria for the specialisation of a core-domain can be based on the different ontological nature of identities alone, then the constraints of domains and ontological-kinds may stay non-differentiated from each other. This is perhaps the case in the earlier developmental period until the third level cognitive systems. The initial ontological distinction of identities is about the objects versus stuff. This can be based on sensorimotor experience. For example, objects have clear boundaries. Sometimes, the objects also have distinctive boundary parts (Tversky and Hemenway, 1984), which allow distinctive ways to interact with such objects and thus support different functions. After the development of the third level cognitive systems, the ontological-kinds and core-domains for objects should be differentiated. The physical objects, animates, and people studied by psychologists are different ontological-kinds, however, they are components for the core-domains of physics, biology, and social environment respectively, not the same as these core-domains themselves.

In this situation-based theory, a domain refers to certain situations in the environment and an organisation unit of representation and knowledge for such situations in mind. A general

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7 See the discussion on structure versus contents in Section 6.3.
8 Roughly the beginning of the concrete operational period in Piaget’s theory. For more empirical studies, see (Carey, 1985; Gelman and Markman, 1986; Keil, 1989b).
situations for a *core-domain* can have two or more identities of the same ontological nature. A situation with a single identity is a simplified case. As a complex situation, it can include not only the representation of *identities*, but also the *relations* of identities which constrain the transformations in the world. For example, the *core-domain* of biology includes not only the representation for the *living things*, but also the relations of *individuals* in ecological systems and in taxonomy and the relations of *internal organs* to the normal functions of the organisms.

Both *identities* and *causal relations* are important components for *situations* of the environment and should be considered for the specialisations of core-domains. The direct observations and sensorimotor experiences with *identities* of different ontological existences can lead to the differentiated patterns of representation in mind (Humphreys and Forde, 2001). The differentiated representations of *physical objects*, *living things*, and *people* are well supported for higher animals (Millikan, 1998b). However, for *core-domains* of *physics*, *biology*, and *social domain* to become distinctive, there are not only distinctive representations of *objects*, but also distinctive *causal relations* when they interact with each other. There are distinctive patterns when identities of different ontological natures interact with each other, such as the patterns of interactions of two objects, two people, or two animals.

For the specialisation of *core-domains* and the development of *domain representation and knowledge*, the important role played by the explicit representation and understanding of *causal relations* will be emphasised. The term *causal relations* of identities is about the cases when two or more identities from a core-domain are interacted with each other which can bring changes to the states of the involved identities. The term *causation* is used to refer to relation of *cause-effect* when two physical objects are involved in interactions as studied in (Leslie, 1994). However, it refers to the explicit knowledge of such interactions rather than the implicit representation in perceptual habituations in infants. The term *causal mechanism* is used to refer to the exact procedure in the interaction. When two objects interact with each other, there are changing rules for understanding such interactions in order to make predictions of the changing *states* of the involved identities (Siegler, 1976).

**On domain specialisations and development of domain knowledge**

To study the constraints on representation in cognitive literature, there are indeed two kinds of processes. One is about domain specialisations. The other is about the development of domain
representation and knowledge. The two processes can be understood and studied separately; however, they should also be unified with a single theoretical account of development. This account of the cognitive development should not only make it clear the underlying rules for domain specialisations, but also the development of domain representation and knowledge. The latter can is directly relevant to a systematic study on the constraints of core-domains on the representation of identities.

In Piaget’s theory, this general process of development is explained in terms of the biological functions of assimilations and accommodations (Piaget, 1972, 1977; Phillips, 1981). In this thesis, the situation-based Ontology is introduced to provide a figurative understanding of the cognitive and conceptual development studied in Piaget’s theory. This situation-based account emphasises the functional principle for the structural changes of cognitive and conceptual systems, including the development of core-domains for natural-units in the common-sense-space and in other spaces and the development of the representation and knowledge of core-domains.

Both kinds of development are in close associations with a figurative understanding of the mental operations, i.e. to support the representation and knowledge for applications in the world. The development of a cognitive system is about developing the structure to support the representation of the increasingly complex situations in the world. This is about the constraints of applications in the general sense on the development of cognitive systems. It is the demands of applications which constrain the state of the structure in general and representation and knowledge of core-domains in specific, including the representation of identities.

5.3 On core-domains and domains for SISciences

The specialised core-domains are empirically observed in cognitive studies and the scientific domains for the environment are studied in SISciences. These specialised domains for the environment can be understood and unified into a single situation-based framework of cognitive development.

The explicit understanding of certain situations as a distinctive domain is correlated with the four levels of cognitive systems. For a study of core-domains, the system of core domains is an

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9Further studies in this chapter will cover the development of the system of core-domains for the environment.

The development of representation and knowledge of core-domains will be studied in Chapter 6.

10see Section 3.3.
important issue. To SIScience, the system of domains supported by the **fourth-level** cognitive system is defined by the *core-domains* and *application-oriented domains*. These domains correspond to *situations* in *common-sense-space* and in the large space. These specialised domains can be understood as developed along the *horizontal* and *vertical* dimensions.

- Horizontally, there are *core-domains* which are developed in association with the three functional distinctions of situations for studying identities in the environment (which are directly biologically relevant). There are *core-domains* which study the *figures*, the *contents* of the figures, or the *contexts* of the figures in their own right. The *figures* which are targets by the direct actions of an organism are in the *common-sense-space*. The *core-domains* for the *contents* can involve the “natural-units” in the *common-sense-space* and *small space*. The *core-domains* for the *contexts* can be about “natural-units” defined in the *common-sense-space* and the *large space*. However, for any *natural-unit* in the world in their own right, the three *functional components* can also be applied for its study.

- Vertically, there are also distinctions of core-domains which exist in the same space. The *core-domains* in cognitive studies are mostly about the further distinctions of the *figure* kind of spatial-features in the *common-sense-space*. These identities as figures in the environment can be directly interacted with by a person. The distinctions of the figures are closely related to the increasingly detailed information of the contents and contexts about the objects, from the simple distinction of stuffs versus objects, to the simple versus complex objects (which has both components of boundary and internal parts), to the natural physical objects versus the complex living-things (which have distinctive causes of existences). Domains are for the situations which contain these differentiated objects.

### 5.3.1 On development of domains in the second level cognitive systems

Following Piaget’s study, the development of a cognitive system starts when *the self* and *the environment* are explicitly separated in the mind of an infant of 1-month old. By then, the actions of the self can be differentiated from the impending changes of the environment upon the perceptual systems of the self. Since the distinction of the self and the environment, identities in the world will be further differentiated based on the actions and the internalised action schemes applied to them by a person. By stage IV, the identities in the environment can be
represented in their own right as existences in the environment, i.e. Piaget’s object permanency. This understanding of objects is the starting point for conceptual development.

The second level cognitive systems can support an explicit core-domain of physical substances and objects. There are not only explicit representations of “natural-units” as identities, the “natural units” can be differentiated into stuffs versus objects with clear boundaries. The development of the core-domain of physics is supported by the well developed perceptual system. There are also the preliminary functionally differentiated domains which study the natural units as figures and the contexts of the figures. This subsection is about such fundamental domains, namely, the domain of physics, of perception for studying properties, and the domain of the environment for locations.

The development of representation of physical identities

The earlier development is associated with the study of identities as physical entities. To study the objects in the surrounding environment, there are the developments of two sets of brain structures to provide such supports. One is the action-based study of the figures as targeted objects, such as in Piaget’s theory and other interactionists’ theories (Bickhard, 1998, 2001; Glenberg, 1997). Objects bear direct functional roles to the concern of a person and can be acted upon by the person. The objects and their functions are understood in terms of the internalised action schemes which can be applied to them (Piaget, 1962; Phillips, 1981). The other is about the domain of perception for studying the properties. However, the perceptual modalities are not restricted to study physical substances.

In Piaget’s theory, the representation of objects involves the coordination of hands-and-eyes. The actions upon objects are important for assimilating the visual input into the action-based understanding of the objects. The representation of shapes is a different issue from the representation of an object (Piaget and Inhelder, 1956). The explicit representation of an object is only achieved in stage IV with object permanency in mind when the object is understood as an existence in its own right and can be located at a position. The locations can be indicated or defined by other objects (Bremner, 1985). The evidence comes from the observation that infants in stage IV can search for hidden objects. The differentiation of the environment is no longer purely contingent upon the actions of an infant. Identities are not only differentiable based on their affordances to the actions of an infant, they are also studied in terms of their
relations to other objects, in particular, their similarities and differences along different attribute
dimensions, such as functions, spatial properties, and physical properties.

Mandler and McDonough (2000); Mandler (2000b) argued that younger children at stage
III of Piaget’s sensorimotor period can form categories of objects based the studies of recalls
of suitable action schemes to accommodate different objects. However, objects at this stage
may be grouped together because of distinctive perceptual features, which can incur distinctive
action schemes by direct associations. The state of an object in perception and the identity as an
individual in a location are different understandings. Around Stage IV, patterns of interactions
of two objects can be observed directly in a perceptual field (Baillargeon et al., 1995; Bail-
largeon, 2004). However, cognitive understanding of objects and objects in interaction requires
understanding explicitly that the different states belong to the same object or different objects.
The cognitive understanding of an object as a distinctive individual starts to develop in stage V
children (Xu and Carey, 1996).

The understanding of the domain of physics continues to develop in the later periods of the
cognitive systems. While in the earlier time of the pre-operational period, objects are examined
for their functional purposes, there is also the explicit distinction of parts from the figures which
possess the parts. Both figures and parts can be treated as existences in their own right and can
be studied for their material components. Further development of the physical domain is closely
related to the study of properties for understanding the physical materials (Smith et al., 1985).
The study of parts can influence the explicit distinctions of objects into core-domains of physics,
biology, and social studies. However, the configuration of distinctive body parts for different
biological functions is an important criterion for the differentiation of biological kind. In the
formal operational period, the different sensorimotor based examinations of physical entities or
phenomena are not restricted to those with the sizes of A-space or smaller. The physical entities
or phenomena which can be studied are in different spaces.

The development of structures in perceptual space

The development of perceptual modalities in human matures earlier and is the foundation for
the studies of physical substances and objects (Gibson, 1988; Johnson, 2005; Gopnik, 1998).
The earlier developed sensorimotor modalities are relevant for picking up the relevant cues by
an organism from the environment to differentiate the environmental situations. However, the
biological rather than strict physical principle should be followed to understand these measurements in perceptual modalities (Lockhead, 1992). The development and measurements in perceptual systems may be better understood in terms of following the psychophysical principle which maximise the relevant distinctions along certain dimensions (Lockhead, 1992; Goldstone, 1998).

In sensorimotor period, different identities are often directly indicated by their distinctive perceptual properties. The initial active bonding of perceptions is to study and describe the *figures* (i.e. the objects as wholes) or *contents* of figures (e.g. the parts) with spatial and physical properties. They are the perceptually measurable. A property for one object is derived from the comparison with same kind of properties of other objects. The perceptual development depends on what sorts of sensors can be developed in a species which help to discriminate the identities in the environment with the use of perceptual cues. Distinctive colours can be used for indicating a category. In some animals, the differentiating an identity in distance is mainly in terms of distinctive perceptual properties belonging to an identity (Allen, 1998). However, the *properties* which can be perceptually differentiated are not restricted to *physical properties* for differentiating substances. The patterns of *movements* and *motor behaviours* are crucially important (Freyd, 1987; Lu and Sperling, 1995).

Spatial properties are crucially important for differentiating objects. There are *distinctive features*, *spatial properties* such as *shapes* in 2D images and 3D forms. In perception literature, representation of shapes (Marr, 1982; Kellman, 1984) and colours (Boynton, 1988; Byrne and Hilbert, 2003) are also well studied. In human, in the earlier stages of the sensorimotor period (stage I-III), the representation of an identity can include different attributes for differentiating the identities. At about stage II (i.e. about 4 months of age), an object can be represented perceptually in 3D shape (Kellman, 1984; Kellman et al., 1987, 2005). The 3D shapes for an individual are different from the 2D images in a series over time. There are also the subsystems which handle the construction of 3D shapes for objects from 2D images. The representation of faces in earlier development (Johnson and Morton, 1991; Johnson, 2005), which is taken as one of the important factors for social cognition, is also related to the development of the perceptual modalities for handling configurations.
CHAPTER 5. THE DEVELOPMENT OF DOMAIN SPECIALISATIONS

The development of cognitive representation of environmental states

The domain of the environment or the space is about the study of the spatial contexts for people or other objects which are interested by people. The kinds of spatial relations which can be understood earlier are about the container-contained relations (e.g., milk in bottles and toys in drawers) and the relations of objects which are “on” or “under” other objects (e.g., on the ground).

In the second level cognitive system, with the development of object permanency, there are the implicit representation of spatial locations to facilitate the searching of hidden objects (Bremner, 1985). In this case, the spatial context of an object is defined in terms of the configuration of objects. The configuration of objects helps to indicate the objective position of an identity in the environment. However, the focus is on the figure and the location is treated as one of the attributes, the contextual attribute, for the figure.

However, the spatial contexts are not only locations for figures, but also exist in their own right. Although closely related, the study of locations of different kinds is to be differentiated from the “spatial contexts” of a figure. The spatial contexts as locations can be studied and characterised in their own right. There are differently defined locations which are spatial features studied in the large scale environment. The representation of large scale situations in the environment (in 4D) can be further differentiated into those studied in different Zubin spaces, from A-Space, to B-space, to C-space, to D-space. The domains of SIScience are developed based on the understanding and further differentiations of the environment as the ground and spatial contexts for objects and a person.

A spatial context should be clearly differentiated from a perceptual field\(^{11}\). Both a perceptual field and a spatial context can be a container for the state of an object. They are also contained within a larger spatial context in the world. However, a perceptual field is defined in 2D space. The state of an object which is embedded in a perceptual field is captured from a particular perspective. A spatial context is inherently in 3D. A spatial context can be constructed from multiple perceptual fields and each perceptual field may in turn include more than one identity. A particular object at a time is located in a spatial context. However, a spatial context can become a distinctive unit in its own right, which is a state of a situation at time. The representation

\(^{11}\)The perceptual system can handle spatial patterns with a few objects which bear spatial relations to each other and they are in the same perceptual field. The number of objects which can be handled in a perceptual field is limited (Cowan, 2000).
of a spatial context is a conceptual reconstruction with multiple identities in relations. It is an environmental state relevant for an application.

In Piaget’s theory (Bremner, 1978b; Brainerd, 1978), for representing a spatial context, there is the developmental change from egocentric to allocative representation. The egocentric representation of the environment is defined in terms of spatial relations to the self. The allocative representation of the environment is defined in terms of spatial relations of the objects themselves. In the sensorimotor period, the representation of space is largely egocentric where the space is defined in terms of the spatial relations of a person to the objects in the environment. The allocative representation of space is a later development until the later stage of pre-operational period (Piaget and Inhelder, 1956) where the environment or the context of a particular object can be defined with the other objects in themselves.

For allocative representation of the environment, the ability required is not only to hold a single object or a collection of a few objects, but also to keep the spatial configurations of multiple objects. In Piaget’s own study, the earlier spatial representations in children (who are near the end of the pre-operational period) were investigated with the so called three-mountain-task (Brainerd, 1978). The standard setting in the Piagetian task involves a model with three little hills in configuration and each hill is distinctive. A child is led around the model. Then a child is stopped at one position and asked what he may see if he was standing on the opposite position across the model. A child is only asked to point to one of the prepared pictures. Children in the pre-operational period often fail the task, suggesting they could not take a different perspective. The claim that children who fail the task lack the capability of taking different perspectives was questioned by other psychologists (Brainerd, 1978). However, one of the key elements in Piaget’s three-mountain-task lies in the fact that the children have to handle spatial relations objectively and maintain the cognitive representation of the spatial configuration in their mind. The test is about the different perspectives for the representation of the environment with multiple objects in a configuration, it is not about the different perspectives of a single object. The standard Piagetian three-mountain-task requires the children to preserve and hold the relative configurations of the objects in the environment and recall or construct the projections with the relevant perspectives.

For the capability of taking different perspectives, two kinds of projections and manipulations in mind should be differentiated. One is about the construction of a 3D shape of an object from a sequence of 2D images taken from different perspectives. The perceptual modality is
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equipped with this capability. The capability of explicit understanding and modelling the state of an identity at a time is achieved perhaps when a child can start drawing a 3D object on a paper. Here, there is the projection of the object into a 2D shape. The representation of a 2D form or image for the representation of an individual is currently adopted for the representation of spatial-features in SISystems. The 2D projection can be sufficient for the representation of certain 3D spatial-features in the larger scale environment.

The other is the representation of an object as a 4D existence in association of a sequence of 3D states of the object at different times. This is a later achievement. It requires that the identity as a whole is to be explicitly differentiated from the state of it a time. The state of an object is defined in 3D space. The sequence of states of an identity at different times can be integrated into the representation of an identity as a whole. The different states of the same identity are often the 3D images at different times. Indeed, the change of states of an identity is calculated for the particular motor pattern, which can be characteristic of the identity. This general understanding that an identity can have changing states over time is not only used to exclusively identify an object. The general understanding on the change of states of an identity over time is associated with study of the processes of natural systems as well as the representation of transformation of spatial context overtime in general.

To summarise, the domain of space is about the context of figures and the functional distinction of environmental situations. The explicit representations of spatial relations of different kinds have prepared the possibility to represent any spatial contexts. The explicit representation of a large scale environmental setting with the configuration of landmarks is possible only in concrete operational period in Piaget’s theory (Piaget and Inhelder, 1956), i.e. the cognitive system has reached the third level.

5.3.2 On core-domains for figures in the common-sense-space and beyond

For objects as figures in the common-sense-space, there are three core-domains in terms of physical domain, biology, and social domain. These three core-domains are correlated with the development of second, third, and fourth state of the cognitive systems. That is, the domain of physics starts to develop in the pre-operational period. The domain of biology becomes explicit and begins to develop further since the concrete operational period (Carey and Spelke, 1994). The domain of social environment becomes distinctive and develops further after the formal
operational period (Phillips, 1981). The representation and knowledge of these core-domains can continue to develop in the rest of the life time.

Two issues will be covered in this subsection. One is the distinction of *folk psychology* studied in the psychology literature versus the *domain of social environment*. The other is about the formations and specialisations of *core-domains* for identities in the large-space in the fourth-level cognitive systems.

**On *folk psychology* versus the *domain of social environment***

According to the psychologists, *core-domains* in terms of *physics*, *biology*, and *folk psychology* are differentiated based on the ontological kinds of identities and the theories of these domains (Gopnik and Wellman, 1994; Wellman and Gelman, 1998; Gelman, 2004). However, in this thesis, three core domains in the *common-sense-space* are *physical domain*, *biology*, and *social domain*.

The different views of the *core-domains* are related to the adoption of different criteria for domain specialisations. In this thesis, the explicit understanding of specialisation of *core-domains* involve two criteria. One is the *ontological nature* of identities within a core-domain. The other criterion is the explicit differentiations of *causations* of different kinds which involve two identities in interactions, such as the interactions of two people, two objects, or two animals. The distinctive patterns of *identities in interactions* play a crucial role for the formations of core-domains as distinctive units of representation. With this criterion of explicit *causal relations*, instead of *folk psychology* (Wellman and Gelman, 1992, 1998), the *social domain*, i.e. the environment defined by other people should be the third core-domain.

In Flavell and Miller (1998), the social domain is understood in a broader sense, which is about the understanding of others’ minds, their behaviours and interpersonal relations. *Folk psychology* is about the earlier understanding of this broader domain. It focuses on *the mind* and *actions*, rather than the environment. It is the foundation for the two branches of studies. One is development of understanding of *representation* in mind (Flavell and Miller, 1998). There are significant observed changes in the understanding of representation in a child about 4-year-old. For example, *appearance* may be differentiated from the *reality*, the representation can change over time, different people may have different representation about the same circumstance (i.e.

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12 See Section 5.2.
understanding of other people’s minds), and own’s belief may be wrong which can be restricted by direct perceptual experiences (Flavell, 1999). The other is the theory of actions. In folk psychology, the actions of people can often be explained in terms of their beliefs, desires, and intentions (Wellman and Gelman, 1992, 1998).

Indeed, if the distinction of core-domains is based on the ontological-kinds of identities only, it is hard to make distinction of folk psychology and the domain of the social environment, given both are about people. However, the core-domain of folk psychology is different from the core-domain of social studies. The folk psychology (Wellman and Gelman, 1998) studies an ontologically distinctive subject compared with those of the core-domains of physics and biology. The theory of folk psychology is linked to the innate modular for agency proposed by Leslie (1994). The described changes studied by the theory of mind (Wellman and Gelman, 1992, 1998; Wellman et al., 2001) is related to the changes in the module of mental operations. However, the domain of physics and biology are about simple or complex situations in the environment. The social domain is also about situations of the environment defined by other people.

The domain of social environment is about people and their interactions. The theory of folk psychology is also the root for the development of knowledge of social behaviours, individuals, and social organisations studied in the social sciences. For the development of representation and knowledge of the social environment, it requires certain levels of development in mind in terms of representation and the understanding actions of other people. The development of knowledge of the social domain is mainly in the formal operational period (Phillips, 1981). The distinctive pattern of cause-effects which define the social domain starts to be understood when a person interact with other people. The person can predict the representation in the mind of other people and project the understanding of the possible actions of the self (if the self is in the similar environment) to the understanding of other people (Harris, 1992). In the social domain, the individuals and social organisations are treated as separate entities. A person can play different social roles, which bear direct relations of their behaviours. Performing well in a social role can increase the psychological well-being of a person.
The development of **core-domains** in the larger space for the environment

Spatial-features in the environment can be differentiated into those contained in situations in the four Zubin spaces, i.e. the table-top (A-space), cityscape (B-space), landscape (C-space), and larger spatial regions (D-space). The situations in the four spaces are classified into distinctive core domains. The **core-domains** in the larger scale environment refer to the environmental situations of different kinds in the B-, C-, and D-space. Generally speaking, these **spatial features** are either for characterising the ground (e.g., a landmark) or parts of the environment (e.g., natural physical systems). They are also containers (e.g., a house or a city) and locations in terms of configurations (e.g., configurations of buildings) for the environmental settings of a person and other objects.

**Spatial features** of container-kind (e.g. house or buildings in B-space) or locations defined with configurations of objects (in A-space) can be explicitly represented in the second level cognitive systems. However, the representation of **locations** as **environmental settings** with configurations of landmarks can be constructed only in the concrete operational period (Piaget and Inhelder, 1956). In the fourth level cognitive system, i.e. the formal operational period, there is the possibility to represent any situations in the environment in Euclidean Geometry.

The **spatial-features** which are located in situations in the large-space pose constraints on the positions of spatial features in the **common-sense-space**. **Spatial-features** of larger sizes can contain the **spatial-features** in the smaller space. The latter are **parts** or **elements** (such as a city can be defined in terms of configurations of **buildings** and other **landmarks**). For example, objects in B-space can function as the location of a person or other objects in A-space. Spatial features, such as **environmental settings** (e.g., hospitals or cities), can be the locations for spatial-features in B-space. Spatial features in D-spaces, such as **geographical regions**, can be the locations for those in other spaces.

The **spatial-features** in the large scale environment are directly relevant to the studies of SISciences. There are different representations and knowledge about **spatial-features** in different **core-domains** in different spaces. The differences depend on the development of cognitive and conceptual structure in general as well as the experience with the situations of the corresponding core-domain in the environment and language or other symbolic representation of the

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\[13\] See Section 4.2 on the discussion of the four Zubin spaces and the spaces and situations as contexts of identities.
explicit knowledge of the core domain. Not only identities in different spaces are of different ontological natures, the representation of an identity is also constrained by the representation of other identities in the same core-domain. Detailed study on the ontological distinctions of spatial features in large-space can be found in Section 7.3. The discussions on the constraints of ontological-kinds and states of core-domains on the representation of identities can be found in Section 8.3. For understanding the different representations of identities in their corresponding spaces, there is also the constraint from the accessibility (e.g., identities in large-space cannot be accessed easily be the sensorimotor modalities). Spatial-features in C-space and D-space require a mature cognitive and conceptual structure. The understanding of the existence of such spatial-features as wholes (e.g., the study of natural physical systems) depends on the projection of formal schemata for identities in the common-sense space. Some spatial-features are to be formally defined first, then their boundaries in space-time can be drawn (e.g., different soil types or spatial patterns studied in social geography).

5.3.3 On development of application-oriented domains for situations

In the fourth-level cognitive systems, there are not only core-domains in different spaces, but also application-oriented domains which are developed for those situations which have been repeatedly studied. The figures or patterns in the application-oriented domains are included in the system of ontological-kinds for spatial-features which are relevant to SISystems\textsuperscript{14}.

In this subsection, three families of the application-oriented domains will be studied. Firstly, it is about the development of the scientific domains for studying the physical objects and organisms. Secondly, there are the application-oriented domains as super-domains for complex situations which can involve identities from different core-domains. Thirdly, there are also the developments of application-oriented domains as sub-domains for simple or complex situations, including those for the social environment. These further developed super-domains and sub-domains are also related to the various scientific studies.

The development of scientific domains of physics and biology

In the fourth level cognitive system, there are further development of scientific domains for studying physical objects and organisms. There are two dimensions to understand such further
domain specialisations.

Firstly, there are the further development of the scientific domains for the study of physical objects and organisms. These scientific domains are derived from and within the two core-domains in the common-sense-space. An identity belongs to a core-domain and is a member of an ontological-kind. Its representation is restricted by its inherent ontological-kind. Although this identity may be located in a particular space, there are parts and contexts of it which can extend into the smaller space and larger spaces respectively. The scientific domains are devoted to study these parts and contexts. However, the knowledge of these application-oriented domains in different spaces should be assimilated into the study of physical objects, organisms, and people in their core-domains. With these scientific domains which study the “natural-units” of smaller or larger sizes, the original core-domain will become the super-domains.

In the domain of physics, there are particles in the smaller space, physical entities in common-sense-space, and natural systems in the large environment. These identities are all included in the physical domain because the same causal theory is applied to explain their characterisations (i.e. in terms of physical properties and patterns in interaction with other identities in the environment). The causal theories of physics have been the crucial factor for studying physical environment. They can be applied to study the core-domains in different spaces.

In biology, the super-domain corresponds to the scientific domain of biology, which is different from the folk biology. The scientific domain of biology includes all organisms. Here, the domain of zoology and botany are treated as two sub-domains. For studying the contexts of an individual organism, there is the systematics as a sub-domain, which studies the taxonomies for organisms and species. There is also the study of ecological systems which can refer to situations defined with other organisms of different species which may interact with each other. These organisms bear certain inherent relations, including inheritance and the relations of predator-prey. For studying the content of an organism, there are the sub-domains which include the scientific domains of anatomy, physiology, pathology, cells, and even biochemistry.

Secondly, there is the further specialisation of the core-domain of physical objects into the natural sciences which study the natural existences of the identities versus engineering which focus on manufacturing new products. The physical objects can be further differentiated into those belong to the sub-domains for natural substances versus man-made artefacts. Here, causes for the existences of the identities are the defining criteria. The domain of engineering
is related to the productions of physical artefacts of different degrees of complexity and for different functions. As an academic domain, it is often for the productions of complex machines. This distinction of physical sciences versus engineering is not only applied to the objects in A-space, but to other large spaces. For example, there are the designs and constructions of buildings in B-space, the designs of cities in C-space, and some administration boundaries (e.g., states or countries) on the D-space.

The specialised sub-domains and sub-situations of the social environment

One group of application-oriented domains is called the sub-domain, which are derived from the specialisation and differentiation of core-domain specific situations. For the development of sub-domains, there are at least two cases. One is about the development of domains based on the further distinctions of identities of a core-domain. The other kind is related to the further distinction of sub-situations of a super-domain.

Firstly, sub-domains are about the further specialisations of core-domains for identities in a space. For example, the core-domain for natural systems can be differentiated into different domains of geosciences. The domains of geology, hydrology, climatology, and geography can be taken as sub-domains of the core-domain for natural systems. They are natural systems of different kinds. On the one hand, these geoscientific domains have the similar form and are ontologically similar in nature, but different in terms of their physical characterisations. On the other hand, in such specialisation of core-domains, the kind of causal knowledge of a core-domain shall be kept, but different models for different kinds of natural systems can be developed\(^\text{15}\). However, in some cases, the further distinctions of a core-domain can lead to different categories, rather than sub-domains. For example, while the size of a situation in a space (i.e. resolution and extension) is an important factor for specialisations of the core-domain for studying the landscape in C-space, it is sometimes also important for the formation of categories for identities. The landscape with substances of the same kind can be differentiated depending on the sizes. For example, there is pond, lake, sea, and ocean.

Secondly, sub-domains are about the further specialised representation and knowledge for special situations, called sub-situations, within a core-domain. This kind of development is ap-

\(^{15}\)The specialisations of the ontological kind as natural systems can lead to the different sub-domains of geosciences. The specialisations of the living things lead to the taxa on different inclusive levels in the biological taxonomy. However, the mechanism of specialisation for these two can be taken as the same.
plied to social studies, where the area as a whole is ultimately defined with two basic elements of individual people and the interactions of people. However, there are also other social identities developed on different scales. In this development, the domain of social studies is not only a core-domain, but also a super-domain for the social environment as a whole and a sub-domain for the social environment of an individual. In the former case, the social environment has the power relations of people that have been gradually established in the past (perhaps generations of) interactions and these relations are further institutionalised and reflected in the social architecture and state for a population at a time. In the second case, people and their interactions with others are still the primitives to define social organisations and their behaviours. Thus, there are social units for the individuals, the communities, social organisations, cultural groups, and populations within political boundaries. The studies of these social entities as identities of different kinds (e.g., kinships or other social-cultural-economic institutions or organisations) in their own right define the scientific areas as the sub-domains of the social environment as a whole. There are also the demographic studies of patterns and geographical regions of various kinds, which are often formed based on social-ethnic-economic measurement over aggregate data (i.e. census tracts).

These social entities as identities can be described with the same set of social-economic variables which allow the differentiations of the social contexts for these social identities. However, while the causal mechanism of interactions of individual people can be kept, there are differentiable functional relations of these social entities to the concern of a person or other organisations. That is, social organisations are distinctive in that they are functional units in the environment of a person. There are also distinctive mechanisms for understanding the interactions within and between social organisations. The mechanism for a person to interact with the social organisations (i.e. external factor) is a different one from the mechanism which run the social organisation itself (i.e. the internal structure). The mechanisms of internal interactions within the social systems or organisations and these as effective causes for the overall behaviours and functions of such organisations can be significantly distinctive from the basic patterns of interactions of two people. However, the detailed studies of the social sciences is beyond what are covered in SISciences and should be covered in this thesis.
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The generalisation of complex situations and super-domains

One kind of application-oriented domains may be called the super-domains. They are complex situations which include identities from different core-domains. Super-domains are derived from the generalisation and composition with the core-domain situations. Specifically, a complex situation can have multiple identities, which are either from the same or different core-domains but in the same space. There are also the complex spatial, temporal, and causal relations of these identities. These identities belong to core-domains and core-domains are also important since there are distinctive patterns of causal knowledge of core-domains for describing the interactions of identities. A complex situation can be treated as a whole when it has a coherent internal structure and consistent behaviour patterns. For super-domains, there are two cases:

The first kind of super-domain is about the environmental situations of a person defined with objects in the common-sense-space. That is, the super-domain refers to the situations which involve identities of different core-domains in the common-sense-space which bear complex relations. In this sort of application-oriented domains, the basic causations and causal mechanisms for the interactions of individuals are kept. However, there are complex patterns for such interactions. The environment is often about the complex situations which can have identities from different core-domains in the common-sense-space and thus causal mechanisms working inside, such as an ecological system. There are also the special cases of systems which involve organisms of different species.

The second is about the situations which are defined with the combinations of identities in different core-domains and in different spaces. They can form super-domains which are defined with the large scale identities from physical, biological, or social environment. For example, there are real estates and urban development in B-space and C-space respectively. To the concern of SISystems, the geographical regions are important, which are complex spatial features in D-space. They may be treated either as complex situations or identities of complex kinds. For being complex situations, there are interactions of identities with each other from the same or different core-domains. However, such interactions can happen on different scales and may be restricted by the different boundaries in the physical and social environment. For geographical regions as spatial features studied in D-space, the process of regionalisation has always been an interest for the geographers (Golledge, 1993). However, this is a very complex
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topic, since such geographical entities are hardly controllable by any individuals. It is a kind of historical kind (Millikan, 2005) and the formation of it can take generations to develop.

The geographical boundaries of these regions, in some cases, can be matched to administration units of different levels. These kinds of geographical concepts are strongly influenced by cultural effects (Smith and Mark, 1998) and formalised and generalised based on certain relations of the social-economic variables. That is, to understand such regions, there are those seemingly man-made boundaries on the one hand, attributes which are relevant for the differentiations of regions on the other hand. However, the boundaries and the descriptions with social-economic variables are for the descriptions. They are not necessarily about the forces for the regionalisation. There are also variously defined spatial patterns which are studied in D-space. Although social patterns studied in geography and the natural physical systems (studied in geology, hydrology, and climatology) can both be defined with a set of variables, that is, they share the same formal schema, they should be treated as different ontological-kinds. Their definitions have emphasised different causes.

5.4 Development of core-domains to support applications

Although the operational aspect of cognitive systems is not the focus of this, some general positions about the module of mental operations are needed since the functional principle is adopted to understand the specialisations of core-domains and the development representation and knowledge of core-domains. These positions will be covered in this section.

Firstly, the situation-based figurative perspective of mental operation is given. Secondly, two sets of mechanisms for the further development core-domains in different spaces and development of application-oriented domains are clarified. Based on the understanding of these mechanisms, the formal structures developed for core-domains in the common-sense-space can be projected to study the situations in the small or large spaces, i.e. the structural mapping of Gentner (1983); Gentner and Markman (1995). Thirdly, issues related to the construction of a representation for an application in terms of states at different times and transformations over time will be examined. Such issues are also directly related to modelling the application demands from the domains of SISciences.\(^{16}\)

\(^{16}\)Core-domains which were studied by the psychologists (Carey, 1985; Keil, 1989a; Wellman and Gelman, 1992) are cognitively crucial for two reasons. One is that there is a robust pattern of representation and knowledge
5.4.1 On mental operations for applications

Although the thesis focuses on the state of cognitive and conceptual system, some general issues regarding the development of cognitive systems will be discussed in this subsection.

In Piaget’s grand theory of cognitive systems, he argued there are four qualitatively different styles for problem solving Piaget (1977). He proposed four periods for cognitive development based on the different styles. In the earlier sensorimotor period, a child can only sense from and act upon the environment directly. In the pre-operational period, objects can be identified based on their physical properties and locations. There are explicit representation of parts for objects and locations for objects in the nearby surroundings. In the concrete operational period, a child is capable of representing larger scale environment and one kind of reverse thinking in thought. In the final formal operational period, the mind is largely developed to the stage capable of targeting all sorts of problems. A person can formulate hypothesis and design experimentation for testing\(^{17}\).

Below discussion will clarify a figurative understanding of mental operations based on Piaget’s theory and the idea of situations. The developmental changes in the operative style of the cognitive system are related to the underlying structural changes in representation. However, for any applications of the cognitive systems, they are defined with states and transformations are the two aspects for the representation and models of situations in the mental operations.

A figurative understanding of mental operations

For an organism in the environment (or a person), it can be in different circumstances and face different sorts of needs and demands. These are either internally generated needs by the person (e.g., finding foods) or externally imposed demands upon the person by the environment (e.g., avoiding the imposing danger). To satisfy these needs and demands, it may require the person to

\(^{17}\)See the review of Piaget’s theory in the books of Brainerd (1978); Chapman (1988).
act or interact with the environment. The representation and knowledge about the environment are often needed in order to support these interactions.

The module of mental operations is about the mental structure for handling the demands upon a person. From the figurative perspective, the process of the mental operation is about constructing a representation or a model for a properly defined situation (Johnson-Laird, 1983) in order to address a demand. Thus, each of such processes can be called an application of the cognitive system and it involves the applications of representation and knowledge of the environment in mind (however, it can also include the case of goal-direct learning of the environment). In some kinds of applications, the demands to be satisfied often involve the actions in or reactions to the things in the environment. For example, when a person has to find food in order to satisfying the basic biological need. Usually, in order to fulfil a certain task like this for satisfying the biological demand, the representation or a model of a relevant situation can include three components. 1) It involves the setting of a proper temporal frame for the task of finding food to be realised. 2) It requires the inferring the right kind of identities (e.g., finding the bread or biscuit) and locating them once they become targets (e.g., buying in shops or finding at home). This often based on the knowledge of different categories of their physical properties and spatial locations. 3) Once targets are set, the next is about reaching the targets in the environment. It sometimes requires the changing of current locations of a person to the locations where the targets can be found on the one hand, using certain tools for grabbing and holding the objects. Certain, it also requires the identification of those found in the environment before certain actions are carried out.

This figurative understanding of the module of mental operation is closely related to the literature on problem solving. In the study of memory, the issue of problem solving by the use of the representation and knowledge in mind is associated with working memory (Baddeley, 1986). In cognitive literature, the different styles in problem solving are called strategies (Bruner et al., 1956). The procedural differences for problem solving were studied in a considerable number of publications on the cognitive processes called problem solving. There are studies on differentiating the logic-based reasoning and the analogical reasoning (Cheng and Holyoak, 1985; Rips, 1990). A problem solving design may be called a production. Here, the term productions can be used in the general sense to refer to the processes in mental operations, where the applications of representation and knowledge are for understanding the world and decision supports of certain actions in the world. The design and manufacturing artefacts is a special sense for the
term production.

**On situations defined in the module of mental operations**

Following Piaget’s theory, 1) the interactions with the environment are preceded by the mental operations which retrieve or construct the representations of certain environmental situations relevant for the particular concerns of a person at that time. 2) From the perspective of a situation-based theory, the process of mental operations is about constructing a representation for a situation. The four periods of mental operations in Piaget’s theory are understood as corresponding to capabilities to handle different kinds of situations by the cognitive and conceptual systems. 3) The capability to deal with different situations depends on the capability to assimilate and represent the *states* and the *transformations* of the environment with sufficient accuracy. The sensorimotor and pre-operational periods are experiences-based and the situations which can be handled by the cognitive systems at these periods are rather limited to the near surrounding. Only in the concrete and formal operational period, the situations which can be represented are well extended in space-time (i.e. beyond *here-and-now*).

A position has to be clarified regarding how a situation is represented in the module of mental operation. In the figurative theory, the situations in mental operations are represented in terms of *states* and *transformations*. The *states* are about the environmental states which are understood by a person as relevant for a particular cognitive task at hand. There are at least two states of the environment. One of the states is the current environmental state. The other is the state where the targeted objects should be located. The two environmental states are either at different locations or the same location but different times. The state of the environment at a time can be defined with the representation of identities as the building blocks. The representation of states is constrained by the general representation and knowledge of identities in mind and the exact states of the environment at different times. The representation of identities in mind can be used to assimilate the states of the environment. The representation and knowledge of the cognitive and conceptual system in mind can also determine the possible targets which can satisfy the demands, to locate the targets, and to reach them. The perceptual inputs are processed for the timely adjustment of a plan.

The *transformations* are about changes of the states over certain periods of time. The transformation is about the means or routes which lead the changes from one state to another. There
are two points regarding the change of states. One is distinction of two kinds of applications. One refers to the application with an active agent in that the transformation from one environmental state to another can be brought in by the actions of a person (e.g. a person who broke a glass, made dough from flour, and moved from one city to another). The person is also an agent of actions directly who has access to the necessary means for reaching ends. He has action repertoire and action skills, builds up the memories of events and procedures, and sometimes access to other tools and means (such as a vehicle for travelling long distance). The other refers to the applications where the person only performs a passive role and the transformations of states are brought in by the changes of the environment itself. In such cases, the representation and knowledge of the transformations of different kinds in the environment are important for making timely predictions. Secondly, there is the general constraint to study the changes of states in the environment. That is, the global change of states over a time period defined by the differences of two environmental states is the constraint to the integrations of the localised changes. These localised changes are of two kinds, which are either the changes involving single identities, or changes associated with two identities in interactions.

5.4.2 On specialisations of core-domains in applications

In cognitive and developmental literature, the development of cognitive systems may be driven by two mechanisms. One is the so called structural mapping (Gentner, 1983; Gentner and Markman, 1995). That is, the structure in one core-domain is applied to another (Carey and Spelke, 1994) based on the judgement of similarity and analogy. The other is about the application of the formalisation of the same kind of structure to different domains, such as in the proposal of Duhem (cited in (Carey and Spelke, 1994)) where the physical domain is mapped to mathematics first, and then applied to other physical domains. This mechanism is relevant to the studies of transformation kinds of knowledge.

In this subsection, firstly, the mechanisms for further domain specialisations in terms of specialisation and generalisation and representation of arbitrary situations with decomposition and combination will be stated. Secondly, the important roles of core-domains are emphasised because of their two conceptual primitives, the representation of identities of an ontological-kind and distinctive causal knowledge. The core-domains developed for situations in common-sense-space are not only distinctive (as found in cognitive studies), but also sufficiently general
for representing and modelling any other situations. Thirdly, the development of core-domains in other spaces will also be discussed. The situation-based theory can explain the structural mapping in terms of projections of formal schemata of the primitives of core-domains (i.e. the ontological-kind of identities and causal knowledge) and the core-domain situations as wholes to study any situations.

**On the mechanisms of cognitive development with core domains**

From the perspective of the situation-based theory, for the representation of identities, there are different formal schemata for identities of different ontological-kinds. The formal schemata are applied for the representation of identities in core-domains which are either in the common-sense-space or in other spaces. The formal structure for the representation of any situations (either simple or complex ones) can be defined with identities in relations. That is, the projections of formal schemata for identities and causal knowledge of core-domains can be involved. For the formations of core-domains in different spaces and the development of application-oriented domains, there are two notes regarding the mechanisms:

Firstly, the representation and knowledge of a generic situation, including core-domains in other spaces and application-oriented domains for complex situations, can be derived from different mechanisms with core-domains as primitives. On the one hand, there are the mechanisms of decomposition and combination. The decomposition of a situation means a complex situation can be divided and studied with a set of primitive core-domain situations. The primitive situations can have simplified formal structure (e.g., a simple situation with a single identity). The mechanism of combination is to develop a structure for a complex situation with the combination of the primitive situations. On the other hand, there are the mechanisms of specialisation and generalisation of situations. Specialisation is about the mechanism that situations which share the same formal structure can be further differentiated. For example, simple situations with single identities can be differentiated with the consideration of the ontological natures of the properties for identities within the situations. The formal structure of a complex situation with two objects in interactions is applied to study situations of different core-domains. For example, the core-domains in the common-sense-space can be differentiated not only because they have identities of different ontological natures, but also there are different causations for cases where two or more identities interact with each other. Generalisation is about the mecha-
anism which is related the development of the abstracted representation of the situations of a core-domain, such as causal theories or causal laws which are developed under the general causal constraint. The generalised theories and laws of physics can be applied to the situations defined with physical substances or objects in the common-sense-space as well as those physical sciences in the small or large spaces.

Secondly, it is about the roles played by the formal logical-mathematical systems upon cognitive development in general and development of domain representation and knowledge specifically. In Piaget’s theory, the development of abstract re-descriptions in logical-mathematical systems is possible in the formal operational period. The development of the formal logical-mathematical systems brings new ways to study the situations and changes in the environment. Following Piaget’s position, although the development of formal logical-mathematical systems contributes to the development of conceptual systems and transformation kind of knowledge of a core domain, cognitive development does not rely on the logical-mathematical systems. The development of logical-mathematical systems is an important subject in its own right, however, it is not the focus of this thesis.

For representation of identities, however, formal logical-mathematical systems may be relevant on two accounts. On the one hand, the development of mathematical systems contributes to the geometrical descriptions of the states of identities (i.e. 3D shapes) in three dimensional space as well as the numerical measurements of physical properties of different kinds. On the other hand, the formal logical system is closely related to the reasoning and planning. There are also the formal rules of induction, deduction, and abductive for reasoning and inference. However, in cognitive literature, the concept of similarity is emphasised for learning and categorisations (Sloman and Rips, 1998). The analogy-based reasoning is often emphasised over logical-based reasoning (Rips, 1990; Sloman, 1996).

For the knowledge of transformations, the development of mathematical system is important for the study of transformations of different kinds which cannot be handled by the sensorimotor modalities directly. The formal mathematical models can be developed for such transformations. There are the mathematical models for the processes associated with identities, correlation rules in empirical studies of natural systems, those generalised causal mechanisms for the concrete domain specific causal systems or functional organisations, and the formalised causal theories and causal laws. However, there is the distinction between the representations for the transformations of situations of different kinds over time and the formalisations of such
transformations in mathematical forms. The domain specific causal systems which have the solid existences should be distinguished from the formalised causal theories and causal laws for core-domains which are formal mathematical re-descriptions of causal knowledge. The cognitive system can handle the transformations in the environment without the explicit knowledge of the mathematical formalisation.

**On projecting formal schemata for natural-units in different spaces**

For a situation in the environment, there are two kinds of sub-situations. One is about situations with single identities (These identities are the focused figures in core-domains). The representation of identities develops during the learning, which is for identification, categorisation, and re-identification of identities on the one hand, the accumulation of information which can be relevant for the involvement of the identities in applications on the other hand. The other refers to those situations with two identities which may interact with each other over time (e.g., interactions of two objects in common-sense-space), or with their surrounding (e.g., a natural system in its background).

While the system of core-domains is important to define any situations, it is because of two distinctive components of core-domains are the conceptual primitives to define any applications. One is about the identities which are figures and studied in a core-domain. The identities as figures of a core-domain belong to one ontological-kind and restricted by the same kind of formal schemata of representation. The other important aspect of a core-domain is its distinctive pattern of causal knowledge. The causal knowledge of a core-domain can refer to either the causal knowledge associated with single identities, or the causations and causal mechanisms for situations with identities in interaction or causal systems. There are also the abstract generalisations of domain specific causal rules, theories, and laws.

In order to understand the natural-units as figures and the situations for the figures in other spaces, the formal schemata for identities and core-domains in the common-sense-space are often applied. For example, the formal schema for the physical objects in the common-sense-space is applied to study the natural systems in the large scale environment. The formal structure for the configurations of objects in A-space are applied to represent the configurations of landmarks for the environmental settings of different kinds (e.g., hospitals, schools, and the neighbourhood) and built-up of urban areas in C-space. Indeed, the formal schema for the
representation of people is the most complex one, which can be specialised and applied to the
representation of identities of other ontological kinds.

Firstly, this projection of formal schemata of objects in the common-sense-space to study
those in other space is needed, which is because the identities in other spaces cannot be percept-
ually examined directly or can only be examined partially. Their states are either too small to
be observable by the naked eye or extend too far in space to be captured as a whole by the eyes.
The transformations of spatial features in the smallest space takes too short a time to be noticed.
The transformations of spatial features in the larger space can take too long for a person to
perceive and represent directly. The formal structures for identities in the common-sense-space
can be applied to the models of identities of other spaces because the identities in other spaces
are also subjected to the sensorimotor examination with the same set of sensorimotor modalities
of a person and they can be considered as sharing the same formal characterisations as identities
which are located in immediate situations. However, for different ontological kinds, some
attribute dimensions are unavailable for differentiating identities of certain ontological natures.

Secondly, the identities of core-domains in different spaces can also be studied with the
same set of causal knowledge associated with the identities in the common-sense-space. That is,
regarding the knowledge of the identities in different spaces, the same functional constraints on
the development of causal rules and causal conditions of inferences can be applied to the studies
of identities and their core domains in different scales, i.e. the sub-domains of the physics
in different spaces. Although there are different formal schemata for identities of different
ontological natures, the relations of properties-to-identities for causal rules and the relations
of identities-to-properties for causal conditions are applicable to identities of all kinds and in
every space.

Thirdly, the causal knowledge of other type can also be applied to the study of the core-
domains in other spaces. The causations for the interactions of two objects can be applied to
study situations in the common-sense-space. Indeed, the different patterns of interactions with
physical objects, animates, and people are often taken as the foundation for their ontological
distinctions (Mandler, 2000a, 2004). There are explicit distinctions of the different patterns
when two physical objects, two animates, and two people interact with each other. These are
taken as the criteria for the explicit specialisations of core-domains for physics, biology, and
social domain of the environment. For the study of natural-systems of different kinds, apart
from the processes for the changes of states associated with the natural systems, the knowledge

of transformations can be about the cause of existence, i.e. the conditions of emergence of certain phenomena (some of them cannot be observed directly). However, there are not only the causal relations of the natural systems with their contexts (i.e. the causes or conditions of existence for these natural systems), but also the possibility to study the causal mechanisms for the interactions of different natural systems (i.e. to define a large environmental system).

5.4.3 On representing an application with states and transformations

The development of cognitive system is towards the possibility to represent any situation in the environment. The possibility of representation for any situation is also related to the development of global coordinate systems in Euclidean Geometry (Piaget and Inhelder, 1956; Humphreys, 1983; Boroditsky, 2001). The development of different kinds of causal knowledge of core-domains in the common-sense-space and other spaces can be involved in the representation of a situation.

This subsection will discuss another perspective when domain representation and knowledge are applied to define an application, namely the representation of an application in terms of states and transformations in the module of mental operations. The states of representation and knowledge of core-domains are indeed important constraint for the accurate representations of newly encountered simple or complex situations in the environment. Two issues will be covered. Firstly, it presents the main points of the situation-based account on the development of representation of environmental states for any arbitrarily specified situation. Secondly, the main points on the representation of transformations of different kinds for any arbitrarily specified situation will be given. Thirdly, the two sources for the development of knowledge of transformation kinds are clarified for understanding the restrictions in their applications.

On representing states of arbitrarily defined situations

The representation of a specified environmental context at a time has been the central issue in the study of representation in SISystems. The representation of the environmental state at a time within a spatial context can be constructed directly with the identities as the building blocks. For assimilating the state of a situation at a time, identities, spatial relations, and topological relations of identities are important for defining the state.

The representation of a state of a situation at a time is about the environmental state at a
time within a particular spatial context. This environmental state can extend in space. Identities from different core-domains in different spaces can be involved for the representation of the environmental state. The identities in different spaces form part-whole or container-contained relations to each other. The identities in one-space can bear certain spatial relations to each other. Spatial relations are applied to two independent elements within a spatial context which can be modelled in terms of distance and bearing. There can be the configurations of objects in the same space (e.g., physical objects or people). The topological relations are applied to model the relations of identities from core-domains of different spaces. There are container-contained relation between the spatial context as the whole and the elements within it and whole-part relation between an identity and its internal contents. These two kinds of relations can define the state of an environment at a time.

The accurate representations of a state at a time relevant for an application shall depend on the set of identities and their states in a suitable spatial context. For the state of a situation at a time, there are multiple identities in the same space which bear certain spatial relations to each other. However, identities on different spaces may be recognised and included to define the state of the application at a time. For the representation of a complex spatial context relevant to an application, on the one hand, it is possible that the identities from the larger spaces are involved. The identities of large-spaces are of different ontological kinds and can pose important constraints. On the other hand, for the representation of states of an environmental setting at a time, the representation of the objects themselves is also an important topic. There are also the internal parts and material components to be taken into considerations. Thus, the environmental state can be represented in hierarchies, and each of the hierarchies represents a portion of the environment studied by a core domain in one of the spaces.

For the accurate prediction of a state in the environment at a particular time, the setting the sufficiently comprehensive and accurate spatial context is important. Thus, firstly, these identities in larger space can be taken into consideration because they bear functional relations to the figures in terms of being the contexts to the identities as figures and constraints for their transformations. Secondly, other objects in the same space and same context have to be taken into consideration since the spatial relations are an important kind of constraints for locating a target as well as for predicting the possible interaction over time. Thirdly, the detailed knowledge of the processes and behaviours of the identities can be crucial, which depends on the knowledge of the internal structure of the identities and the causal contributions of the internal
components or parts to the overall behaviours (e.g. in understanding the normal functions of a complex machine or an organism).

**On representing transformations of arbitrarily defined situations**

There are complex patterns of changes over time. The transformation of states of the situation as a whole can be defined with the transformations of different kinds associated with these identities (in the situations). Transformations of different kinds can all be involved for predicting the states of the complex situations over time.

For modelling the transformations of an individual, the processes or behaviour patterns of identities (as individuals or categories) and possible events. The processes are determined by the natures of the identities. The possible events (which are caused by others in the same contexts) can be constrained by the functional relations of an identity with others.

The models of transformations are also constrained by the knowledge of causal relations, i.e., the knowledge of causal mechanisms and causations for interactions of identities of core domains. There are two families of cases based on whether the identities keep their separate paths or they can interact with each other at some time over time. In one family of cases, although these identities on the same scale can bear causal relations to each other when they meet, such causal relations do not get instantiated. That is, they do not interact but keep their independent and parallel trajectories over time. In the second family of cases, there are the complex causal relations of identities when they are involved in interactions. These complex causal relations are to be differentiated and studied in their corresponding core domain contexts. That is, the causations for physical objects, for organisms, and for people are treated differently. They are the primitives and should be integrated in the explanation scheme for the overall changes of the states of the complex situation over time.

For modelling the transformation of a situation over a time period, the temporal relations of identities in situations are to be taken into consideration. The temporal relations pose certain “global constraints” on the general plan of transformations. The temporal relations of two objects can have different implications for identities of different core domains. For example, in biology, there is the kind of temporal relations of parents and children. In physical domain, to construct a complex machine, a set of objects (or parts) can be involved in a sequence of interactions and to be integrated together. In social domain, a sequence of events lead to a goal
CHAPTER 5. THE DEVELOPMENT OF DOMAIN SPECIALISATIONS

define a script (Schank, 1977), and in each of the events, there are several interactions with
objects or people. (e.g., in the well discussed eating in the restaurant script). The scripts of
events are well emphasised for the development of conceptual system (Nelson, 1986)). In these
cases, the temporal relation is about the order of objects which are to be interacted with.

For understanding the changes of the environmental situation, the representation and knowl-
edge of transformations associated with identities in the environment are particularly important
for the capability of inferences and prediction of states. The capability of inference of a past
state is important for the purpose of causal attribution, causal explanation as well as potential
adaptation of causal knowledge. The capability to predict a state at a future time is important
for the purpose of planning of actions and decision making of projects. To represent and model
the global transformation (which lead to the satisfaction of an internally determined goal), the
representation of different kinds of transformations and the causal knowledge of different core-
domains as primitives can be involved in explaining and defining the causal mechanism for the
global changes of states of an application.

The last issue to emphasise is about the two sources where the representation and models of
these primitive transformations can be acquired. Firstly, the causal knowledge can be derived
from experience, including the empirical generalisation of similar cases. The transformation of
a complex situation with multiple identities can be defined with the transformations of some
primitive situations, which include situations with single identities or two identities in causal
relations. Corresponding to simple situations with single identities, there are the representation
and knowledge of different transformation kinds, such as the movement of physical objects, the
actions or behaviours of a person or other animates, processes as changes of states of natural
systems, and events associated with natural phenomena. The knowledge of causations for
interactions can also be involved.

Secondly, causal knowledge can also be derived from the specialisation of the general causal
theories and laws. The physical theories and laws for the study of objects and material in the
common sense world can be applied to the study of natural-systems of different kinds. Indeed,
to study the identities in the small or large scale environment, the scientific methods are called
in. This means, either there are the use of instruments for detecting the identities (such as
those in the smaller and larger spaces which are beyond the capability of naked eyes), or formal
definitions are given to identities as spatial phenomena based on a selection of variables. The
entities and phenomena cannot be examined as wholes directly but via the samples (e.g., the
larger scale natural systems physical science and spatial patterns studied in social geography). When the physical laws are applied to the studies of patterns defined with both physical and social variables (e.g. the law of gravity applied in social studies (Couclelis, 1986)), the relevancy of such laws for the explanation of the phenomena of interest may be restricted because of the high level of abstraction which ignore the underlying mechanism for the changes.

5.5 Summary

The meaning of domains as used in this thesis was clarified. A domain refers to a set of specific situations in the world. However, the distinctions of domains are based on the different subject matters as well as the distinctive patterns of representations and knowledge in mind. While functional principle was emphasised in general for understanding domain specialisations and domain representation and knowledge, the criteria for the specialisation of core-domains of physical objects, animates, and people are the ontological-kinds of identities and the distinctive patterns of causations when two identities of the same ontological-kind interact with each other.

The specialised core domains and application-oriented domains for the environment were discussed, which are correlated with the development of cognitive systems. From the cognitive perspective, there are vertical and horizontal developments of core-domains. At the second level cognitive system, there are the explicit distinction of physical objects from the study of attributes and locations. At the third and fourth level, there are the distinguished core-domains of physics, biology, and social domain for objects in the common-sense-space. At the fourth level, there are also core domains in different spaces and the further development of application-oriented domains which are for the distinctive and frequently studied situations. For the study of the environment, the list of the relevant domains can include both the core-domains in the large space and the application-oriented domains which are either sub-domains (e.g., geology, hydrology, and climatology for different natural systems, science versus engineering for natural objects versus artefacts) or the super-domains (e.g., physical environment in general, the domain of ecology, or study of regions).

The mechanisms for the development of core-domains in other spaces and applications in general were also covered. The developmental mechanisms can include the decomposition of a complex situation into core-domain situations and then the combination of these core-domain situations for understanding the process and behaviour of the complex situation as a
whole. Domains can also be derived from the generalisation and specialisation of core-domains. For developing the core-domains in other spaces, the formal schemata for the primitives of a core-domain in the common-sense-space can be projected. For any situations, they can be modelled by the states at different times and transformations over time. The accurate models of states and transformations depend on the models of identities of different core-domains and knowledge of transformations. The representation of environmental situations can be supported by the two conceptual primitives, i.e. the identities of an ontological-kind and distinctive causal knowledge.
Chapter 6

The development and constraints of core-domains of the environment

6.1 Introduction

The current dominant cognitive theories often emphasise the constraints and context effects on category representation. However, depending on researchers, there are different proposals of constraints in terms of domains (Gelman and Markman, 1986; Gelman et al., 1994; Wellman and Gelman, 1992, 1998), ontological-kinds (Gelman and Markman, 1986; Keil, 1989a), development of causal relations and theories (Carey, 1985; Gopnik, 1996; Wellman and Gelman, 1992, 1998), contexts (Murphy and Medin, 1985), and category uses (Ross, 1997, 2000; Markman and Ross, 2003). To account these different kinds of constraints requires a principle to unify these different theories.

In previous chapter, issues related to the specialisation of core-domains and application-oriented domains were discussed. This chapter is devoted to a systematic study of the state of a conceptual system of a core-domain from the perspective of a situation-based theory. There are two sections to elaborate the general positions.

Section 6.2 will clarify the position that state of the conceptual system of a core-domain is about the state of representation and knowledge. To study a core-domain, there are three components, namely, core-domain situations, representation, and knowledge. With the distinction of representation versus knowledge, the constraints of a core-domain can be differentiated into two groups, namely, the constraint of the ontological-kind on the representation of identities and

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1To study the constraints on representation, a distinction has been made between a conceptual system of representation as a whole and the conceptual system for the representation of a particular core-domain was made in Section 4.3. The conceptual system as a whole is defined with identities in part-whole relations. However, from the data in cognitive studies, these identities are differentiated into core-domains and there are further developments of the core-domains.
the constraints from the development of four kinds of causal knowledge. This understanding of the state of a core-domain, which is defined with identities and knowledge of transformations, allows the systematic explanation of other domain constraints studied in cognitive literature.

Section 6.3 will extend the distinction of structure versus contents to study the representation and knowledge of a core-domain. The distinction of structure versus contents is applicable to the study of both identities and core-domain situations with multiple identities. For identities, apart from the formal schemata for the representation of identities and structures for two types of knowledge, the development of basic-level-categories will be emphasised. For complex situations, four kinds of category systems are discussed as the generalised formal structures for modelling such complex situations. The basic-level-categories and four kinds of category systems define the third level structural constraints on the representation of identities\(^2\).

6.2 On representation and knowledge of core-domains

Core-domains are considered cognitively important (Keil, 1989a; Wellman and Gelman, 1992). The situation-based theory developed in this thesis explains the distinctiveness of core-domains from three aspects. Namely, core-domains are special because of their existences in the environment, the development of representation of core-domain situations, and the development of knowledge of such situations.

In this section, there are two theoretical concerns. One is to understand the state of representation and knowledge of a core-domain from the functional perspective. This can explain the distinctive roles of a core-domain for cognitive functions. The characterisation of the state of representation and knowledge of a core-domain is in terms of the representation of identities of different ontological-kinds (Millikan, 1998b; Boyer, 1998) and the state of four kinds of causal knowledge. The other is to provide a systematic account of the different kinds of constraints of core-domains on category representation, which were well emphasised in cognitive literature (Carey, 1985; Keil, 1989a; Wellman and Gelman, 1992; Gopnik, 1996; Gelman and Markman, 1986). The characterisation of the representation and knowledge of a core-domain in terms of identities of a distinctive ontological-kind and the distinctive pattern defined by the four kinds

\(^2\)The exact states of these two groups of formal structures, namely, the set of basic-level-categories and the state of the four kinds of category systems, are important for the state of conceptual system of a core-domain and for assimilating the language codes of knowledge about a core-domain.
of causal knowledge can serve this need.

6.2.1 On representation and knowledge of core-domain situations

From the situation-based perspective, a core-domain refers to a distinguished set of situations in the world. The representation and knowledge of a core-domain is about such situations. The representation of a core-domain is developed in experiencing such core-domain situations in the concrete physical world. The explicit knowledge of a core-domain is developed when the representations of core-domain situations can be recalled or the understanding of such core-domain situations can be inferred for further applications.

Three issues will be discussed in this subsection. Firstly, three primitive types of core-domain situations will be distinguished, which are important for understanding the development of representation and knowledge of a core-domain. The distinction is based on the internal structures of these core-domain situations (i.e. the number of objects and their relations). Secondly, the functional perspective will be re-emphasised to understand the development of the representation and knowledge of core-domains. Namely, the development of representation and knowledge in general is to assimilate and represent the states and transformations of the environment. The specialisation of a core-domain is because of the distinctive identities and causations of the core-domain for such cognitive functions. Thirdly, it explains that the knowledge of a core-domain is developed for constructing the representations of core-domain situations in general, which can be differentiated into those for the identities, causal relations, and complex core-domain situations.

On core domains as situations with identities-in-contexts

A core-domain refers to situations in the environment which can be defined with identities in their immediate contexts. There are three primitive types of the core-domain situations which are important for studying the development of representation and knowledge:

The first primitive type of core-domain situations refers to those with single identities. The representation for such core-domain situations is about the representation of identities, which support the functional expectations to assimilate attributes and to predict states of the identities.

The second primitive type of core-domain situations refers to situations with two identities of the same ontological nature and the two identities bear simple causal relations to each other.
For example, they interact with each other when they meet at a time point. For a situation with two objects of the same ontological-kind in causal relations, there is a simple domain specific causation for it, which is equivalent to a case of means-ends coordination. That is, there are the simple causal mechanisms regarding the way the identities interact with each other and causations for the predictable changes of states of the involved identities. For such situations, the ontological natures of the identities matter, given there are different patterns of causations if identities of different ontological-kinds interact with each other (e.g., two people versus two physical objects).

The third refers to the complex situations with multiple identities. However, the identities in the situations belong to the same ontological-kind (e.g., three objects in a room or three buildings in an area). These identities can define systems or organisations within a core-domain. The causal systems (e.g., complex physical machines) and functional organisations (e.g., social organisations) can be treated as wholes because their consistent internal structures and coherent patterns of behaviours. However, the complex core-domain situations as the general cases can be derived from the combination of the two primitive types (i.e. situations with single identities and situations with simple causal interactions). They should be differentiated from these causal systems or functional organisations on the one hand, the complex situations which involve identities from different core-domains on the other hand (e.g., a person and two more objects in an open area). In the latter case, there are complex situations beyond a single core-domain. An example can be the complex ecological systems in the large scale environment.

On representation for the states and transformations in the environment

In this thesis, the functional principle is followed to understand the representation in mind in general. The representation in mind has to serve two groups of functional expectations. One is to assimilate the states of the environment. The other is to assimilate the transformations of different kinds in the world.

For assimilating the states of the environment at times, the representation and knowledge of identities or core-domains in general are important. While the representation of identities starts with a common mental structure (Millikan, 1998a), this common-mental-structure has diverged over evolution and development (Millikan, 1998b). There are specialised mental structures for

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3 See Section 2.3 on the functional principle for the development of cognitive systems and the functional expectations on representation in general and on representation of identities specifically.
the representation of identities of different ontological-kinds. The identities in the environment can be sorted into core-domains and the identities as figures of the core-domain share the same ontological nature. The representation of these identities is constrained by their ontological-kind and there is a distinctive pattern for the representation of an ontological-kind in brain (Humphreys and Forde, 2001).

For assimilating the transformation of states of the environment over time, the representation and knowledge of changes of different kinds are important. The representation and knowledge of natural processes, causations, events, and the contingency of events in general can all be involved. Generally speaking, while the representation of transformations can be defined with the changes of states over time, the transformations can be associated with single identities or the interactions involving two or more identities. That is, such changes of states can be differentiated into two groups and a few kinds. Associated with single identities, there are the representations of transformations as the causes for existence, the causes of appearances in locations (e.g., either by the self-initiated movement or by other force), and the transformations of states or shapes over time. Associated with two or more identities, there can be the causation kind of transformations for the cases where identities interact with each other. The explicit understanding of a core-domain for objects in the common-sense-space can be based on the ontological nature of the identities and the distinctive pattern of causal knowledge, in particular causations for the interactions of identities.

A core-domain can be specialised as a larger unit of representation and knowledge because the two kinds of primitive “mental structures” which are used to assimilate of and accommodate to the states and transformations of the environment are both distinctive. The two representational components are the conceptual primitives for the two basic types of core-domain situations. One is about the individual identities in the environment. The other is about the causations when two objects interact with each other and this interaction may cause the changes of their states. However, the distinctiveness of a core-domain in representation and knowledge is determined by the distinctive situations of a core-domain in the world. It is the distinctive existence which determines that the representational components of such situations are distinctive. The development of representation and knowledge of a core-domain is correlated with the understanding of such situations. These two primitives can be involved in defining other situations of the core-domain. In the meanwhile, there are further developments of the repre-

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4 The nature and the meaning of the constraint of ontological-kinds will be studied in Chapter 7
sentation of identities and causal knowledge of a core-domain. Indeed, the functional principle (i.e. the functional expectations from the representation system) can be applied to understand the specialisations of core-domains on the one hand, the development of representation and knowledge of core-domains on the other hand.

**On knowledge of core-domain situations of different kinds**

The issue of representation for the transformations of core-domain situations as wholes is also important. The causal knowledge of a core-domain is about the transformations of core-domain situations. The core-domain situations refer to those specific simple or complex situations in the environment with identities belong to the same ontological-kind. The case of complex situations involving multiple identities can be further differentiated into three formal subtypes, including collections of simple situations, causal systems such as complex machines or sub-situations as social organisations which function as wholes, and any other complex core-domain situations.

Firstly, for situations with multiple identities, if these identities within the situations only bear spatial and temporal relationship to each other, such situations can be defined in terms of the conjunction of several simple situations. For a situation with two or more identities of the same ontological nature and the identities in the situation bear spatial or temporal relations only, the situation can be decomposed into two or more simple situations of single identities. The complex situation as a whole, on the other hand, can be formally treated as a simple combination of the multiple simple situations.

It is rather common that a complex situation can involve multiple identities but these identities are related to each other in space only. For two identities bearing spatial relation only, these identities can keep their separate courses of development over time and they do not meet or they do not interact even they meet each other at some times. The situation as a whole is defined with a collection of identities, and the state of it at a time is defined by the configuration of the states of the identities. If identities do not interact with each other, sometimes, the differentiation of the ontological natures of these identities do not matter. However, the functional distinctions of these identities (to the concern of a person) are still needed and there is the possibility that these identities will be connected by the actions of a person. That is, a person will interact with these objects in sequences for functional purposes. These sequences of actions by a person who interact with a sequence of objects often define events.
For identities of same ontological nature, they may form either complex systems (e.g., physical machines) or functional organisations (e.g., social organisations). These correspond to the second type of complex situations of a core-domain. For a situation with more than two objects of the same ontological-kind in causal relations, there can be a causal system as a whole where the identities within it can form a complex chain of interactions. A functional organisation can include many people. However, what is important is that such core-domain specific situations as complex causal systems and functional organisations can be treated as wholes similar to individual objects. They are associated with coherent internal structures and bear certain relations to their contexts on the one hand, distinctive but also consistent processes and behaviours on the other hand. However, these systems or organisations as wholes may be considered as figures studied in the further developed scientific domains.

The third type of complex situation is a generic type which can be decomposed into multiple identities, their relations, and interactions. For a general case of complex situation with multiple identities, these identities can bear spatial relations, temporal relations, functional, and causal relations to each other. The representation of such a situation can be constructed with the three groups of primitives, i.e. the representation and knowledge of identities in the situation which can belong to different core-domains, relations of identities in space-time, and causations if two of the identities interact with each other. The representation of a generic situation can also be defined in terms states at times and transformations over time. The representation and knowledge of different core-domains can be applied to understand and represent any arbitrary situations. That is, they are involved in constructing the models of application situations in mental operations. The state of representation and knowledge of a core-domain can influence the representation of a situation in terms of different degrees of accuracy and in different forms of expressions.

6.2.2 On states of core-domains as the constraints on representations

The state of knowledge of a core-domain is defined by the developmental states of the different kinds of causal knowledge which constrain the representation of identities. This subsection will explore the “causal knowledge” of a core-domain and explain the different kinds of domain constraints on the representation. However, the different constraints of core-domains on rep-
sentation in cognitive literature can be explained in a single integrated framework because the situation-based theory has provided a unified understanding of four kinds of causal knowledge.

The state of a core-domain in mind is defined by the further experience, generalisation of the experience, and abstraction of representations. Firstly, the constraint on the representation identities from the ontological-kind and the constraint from the development of causal knowledge of a core-domain will be distinguished. Secondly, the development of causal theories such as those studied in (Gopnik, 1996) is correlated with the state of knowledge of a core-domain. There are domain specific causations and causal mechanisms, causal systems, as well as abstract generalisation of causal laws. Thirdly, the different understandings of the constraints on category representation in current domain specificity theories of representation can be related to the different functional uses of the knowledge of identities. These functional expectations demand certain attributes to be included in the representation of identities.

**On constraints in terms of ontological-kinds and causal knowledge**

In cognitive and developmental literature, the most emphasised constraints on representation are either in terms of ontological-kinds of concepts (Keil, 1989a) or core-domains (Gelman et al., 1994). Ontological-kinds and core-domains are both related to special situations in the world which contain the identities. They are the larger units of representation and knowledge in mind which are embedded in cognitive structure.

While ontological-kinds and core-domains are closely related, the two ideas may have different references in the world and different implications in terms of being the constraints on the representation of identities. Unfortunately, the distinction of these two kinds of constraints has remained unclear in cognitive literature. However, the explicit distinction of core-domains from ontological-kinds for being the constraints on representation is important for modelling identities in SISystems.

From the perspective of a situation-based theory, the constraints of an ontological-kind and a core-domain can be differentiated. The constraint of an ontological-kind on the representation of identities is from the sensorimotor experiences with the identities. For understanding the constraints of ontological-kinds on the representation of identities, two points are to be kept in mind. One is that an identity in its context. The direct context (i.e. the location) of the identity puts constraint on the possible sensorimotor experience with the identity. The other
aspect of this constraint is related to the fact that different attributes of identities (e.g., physical properties, locations, or processes) are collected to support different functional uses in the first place. These identities of a core-domain can be involved in different situations in the world and can be differentiated based on not only their perceptual properties, but also their functional roles.

To study the constraint of a core-domain on the representation of identities, it should be clear that while a core-domain (in the world) is about a situation defined by an identity in its context, however, the state of representation and knowledge of a core-domain is defined by the collection of such core-domain situations. The representation and knowledge for the collection of domain specific situations define the state of a core-domain in mind. Thus, regarding the representation of an identity, the commonly discussed constraints of a core-domain can be differentiated into two kinds. One is from the ontological nature of the identity itself and from all other identities of the same kind. The other is the understanding of causal knowledge in general and the causal knowledge of interactions in particular.

The development of causal knowledge and theories of core-domains

The knowledge of a core-domain has developed based on the explicit understanding of different kinds of representation about core-domain situations. The casual knowledge in the general sense is associated with the four general groups of transformations which can be involved in mental operations for applications.

However, in the specific sense, causal knowledge is associated with the aspect of transformations of the environment. The development of causal knowledge or causal theories (Smith et al., 1985; Carey, 1985; Gopnik, 1996) is about the changes in understanding the transformations of the environmental situations. The knowledge of such transformations is developed within the general causal constraint where the global transformations can be understood in terms of localised changes. The causal knowledge in such accounts can be associated with the representation and knowledge of the transformations of identities in terms of processes (e.g., changing states or positions over time), conditions of emergence (e.g., empirical studies of causal rules based on the correlations of variables), domain specific causations and causal systems (e.g., causal theories), and transformations of domain situations as wholes (e.g., Newton’s

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6 The different constraints on the representation of an identity will be further studied Chapter 8.
7 See the system of different kinds of causal knowledge discussed in Section 4.4.
laws of physics). The change of theories is also about the reconstruction of a core-domain with new axioms and the development of formal descriptions of the transformations for core-domain situations. The formalisation is about the models of transformations of different kinds in mathematical systems (Smith et al., 1985; Gopnik, 1996). It is often taken that to develop the formal models in mathematics is the ultimate goal for the study of science.

While some psychologists argued that the development of theories can explain cognitive development (Gopnik, 1996; Wellman and Gelman, 1998), the situation-based theory argues for the functional expectations to drive the cognitive development. However, for the representation and knowledge of a core-domain, there are both the formalised descriptions in mathematical systems (i.e. empirical rules, causal theories and causal laws) and the concrete domain specific causal systems (e.g., complex machines in physics and organisms). There are indeed two kinds of development related to causal knowledge. On the one hand, the theory change is associated with the increasing departure from the concrete understanding of specific cases (i.e. concrete systems) into the abstract mathematical expression (Gopnik, 1996). The causal knowledge in mathematical models is important since they can be applied to study concrete situations. The general the causal knowledge, the wider applications it has. The causal theories or laws are often applicable to a large number of domain specific situations. On the other hand, there is also the change from abstract mathematical formalisations to concrete productions in engineering. For the knowledge of a core-domain, there are further developed causal systems which are associated with complex machines in physics and the complex biological organisms where internal body parts are associated with biological functions (Carey, 1985; Carey and Spelke, 1994).

The causal knowledge of identities as the constraints on representation

There are different constraints of causal knowledge on the representation of identities. Firstly, the constraint is from the causal knowledge of different kinds. That is, specific to core-domains, whether certain kinds of causal knowledge are better developed or not. For example, the knowledge of an individual is important, which is correlated with the study of the behaviours and processes on the one hand, the prediction of possible abrupt changes of states at certain times on the other hand. However, studies of individuals in different spaces have different emphases. For core-domains in the common-sense-space, the causations and causal mechanisms for the
interactions of objects are important. Such kind of causal knowledge can become an attribute to an object. For identities of core-domains in the large space, such as the natural physical systems, the causal conditions of existence are emphasised.

Secondly, the representation of identities are learned and studied for different functions and constrained by these functional demands. Apart from the cause of existence, two kinds of causal knowledge are associated with single identities. One is the family of cognitive processes as the causal rules, which are related to re-identification ultimately. During the process towards re-identification, there are also steps of identification and categorisation. The other is the causal conditions, which are related to the functionally meaningful inferences. Such inferences can allow the judgement of the potential uses of identities and how the identities can be found, identified, and acted upon. In other words, the development of representation of identities with selections of attributes is inherently constrained by these functional expectations. The knowledge of identities is to serve these functions.

The functional expectations underlying the causal rules and causal conditions are crucial constraints on representations of identities. The functional purposes in learning the causal rules are for identification, categorisation, and re-identification. The representation of an individual or a category can be derived from comparing the representations of all identities in a core-domain. The causal rules can use different kinds of attributes, such as overall shapes, physical characterisations, internal parts, and distinctive processes. The neo-essentialists’ theory (Gelman and Medin, 1993; Gelman, 2004) argued that finding the “essence” of a kind is an innate tendency. However, the tendency may not be about seeking the “essences”. Rather it is finding the most relevant information in a context for the functional purposes of categorisation and re-identification.

The functional purposes of making reliable and useful inferences require certain causal conditions, i.e. the establishment of certain categories for sorting identities. Keil (1989a) argued that categories of different ontological-kinds are represented differently because empirical data has shown they can support different patterns of inferences. Indeed, ontological-kinds, categories, and individuals are all conditions to provide the useful recall or inference of properties of identities which can explain behaviours, make attributions of causes, and allow identities to be involved in different kinds of applications. The inference or prediction of the state of a complex situation depends on not only the representation and knowledge of causations for interactions, but the transformations as processes, behaviours, and events. These transformations are
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associated with *identities* and can be inferred or predicted based on proper *causal conditions*.

The inference of properties is not random, but to support specific functional needs. These functional expectations are to be satisfied and certain properties can support these functional demands. The roles of potential uses of the category knowledge often influence what can be included in the representation (Ross, 1997, 2000; Markman and Ross, 2003). For example, the learning for medical diagnosis and for cure can lead to different information included in the category representation. The functional purposes of learning individuals are for the potential uses of the identities. Thus, the various situations in the world where the identity can be found are examined so that they can be located later. The causal relations of identities with others in interactions are included so that predictions can be made when such interaction does happen.

6.3 On **structure and contents** of core-domains

The state of a conceptual system is an important constraint on category representation. The representations of categories are constrained by the conceptual structure and there are the context effects on the representation of categories (Murphy and Medin, 1985). In cognitive literature, certain understandings of the conceptual structure are often implied when the category representation and category systems are discussed. For example, taxonomies were discussed in Rosch (1978) for the category system. The “conceptual structure” in the discussion of Murphy and Medin (1985) is equivalent to a structure defined with *categories in relations*. However, their focuses were not on the semantic relations which are involved in defining conceptual systems.

Conventionally, the study of such conceptual structure is via the study of the language systems (Fodor, 1975; Evens, 1988; Lehrer and Kittay, 1992). Such studies often focus on *semantic-relations* (Evens, 1988; Lehrer and Kittay, 1992; Miller, 1995) and there is a diverse range of *semantic relations* studied in literature, such as *part-whole relations*, *class inclusive relations*, and the *relations in frames*. Indeed, the language systems (and other forms of symbolic representation) bear close relations to a conceptual structure and representation, and it is an important topic in cognitive science to study the relations of the two (Millikan, 1998a; Franks and Braisby, 1998; Gauker, 1998; Gendler, 1998). However, neither the lexical structure nor their relations to the conceptual structure in mind are the focus of this thesis.

From the perspective of the situation-based theory, the study of conceptual structure in gen-
eral\(^8\) and the conceptual structure of core-domains in specific are both important for understanding the knowledge of identities. The conceptual structure of a core-domain itself is also an important kind of structural constraint on the representation of identities. The development of the representation of a core-domain is closely related to the representation of core-domain situations as particulars and the generalisation of such representations. This section will focus on the structure of domain representation and knowledge.

There are two cases to be discussed separately: Firstly, the distinction of structure and contents is applicable to the study of representation and knowledge identities as individuals. The formal schemata for the representation of identities as individuals, and the knowledge of identities as particulars, and the knowledge of basic level categories for identities will be discussed. Secondly, the formal structures for the representation of complex situations with two or more identities will be studied. The generalised representation and knowledge of a complex core-domain can be expressed in four kinds of category systems.

6.3.1 On structure and contents for identities

The representation and knowledge of individuals is one of the central issues for the conceptual structure of a core domain. For the individuals in the environment, there are three kinds of representation units which are relevant. Firstly, it is about the formal schemata for the representation of individuals from sensorimotor experiences. Secondly, it is about the knowledge of identities, which supports the re-identification of the identities, inferences of properties, and reasoning with them. The third is about the development of basic-level-categories for the individuals in a core-domain. A category means a collection of identities. However, the set of basic level categories are not arbitrary collections. They are developed because of the function-based conceptual re-organisations. The set is also an important index for the state and the quality of representation and knowledge of a core-domain.

On representation of identities with states and transformations

The representation of an identity has developed when the identity was examined in sensorimotor experience. An individual is about a continued independent existence in space-time. For the representation of an identity as a figure, there are two aspects of states and transformations to

\(^8\)See Section 4.3.
be learned. However, the learning of an identity is not only about the overall description of the figure, but also its internal content, external context, and their contributions to the states and transformations of the identity.

Figure 6.1: The generic formal schema for the representation of identities.

Generally, information which is learned about an identity can include descriptions for three components\(^9\). Firstly, it is the description about the figure, which can include the different states of the identity at different times and processes or patterns of behaviours over time. The state at a time can include physical properties, overall shape, distinctive boundary parts as features, or the configurations of the parts, and the location. For the same identity, there can be different states at different times. The different states are either because the identity itself has changed over time (e.g., when a child grows up, the physical states at different ages can be significantly different), or because the identity has changed its locations (e.g., a person moving from one city to another), or both. Depending on the identity, there are transformations of different kinds which can account for the changes of states, such as their own processes (e.g., growing old, rolling down a hill), causal interactions with others (e.g., two objects interact with each others),

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\(^9\)What can be learned about an identity is determined by its ontological nature.
natural events (e.g., floods), and artificial events upon them by the actions of a person.

Secondly, it is the description about the content or the internal structure for a figure. The representation of the content can include internal parts, portions of material, the patterns defined by the configurations of parts, or functional relations of the parts which contribute to the study of the individuals as wholes. The internal parts or material components can be examined with increasing details by going to smaller and smaller units.

The third type of information of an identity is about its contexts, such as spatial locations and applications they can be involved in. The descriptions of the contexts can be learned in variously defined situations which contain the identity. These situations as the contexts of the identity can include other identities. The other identities which define the contexts are either from the same or different ontological group and thus in the same or different core-domains. The distinctive causal knowledge associated with the identity can be learned when it interacts with other identities. The causal relations of the identity to others can be taken as the causal attribute of the identity.

**On knowledge of individuals as 4D existences for application situations**

The knowledge of an identity is about an identity as a 4D existence which can be involved in different uses and it can have different states at different times. The knowledge of identities is also about the properties of an identity which can be acquired for re-identification, inferences, and reasoning about it (Millikan, 1998a). That is, the relevant information of an identity can be recalled or inferred for different functional purposes.11

The knowledge of an identity is about knowing it as a functional component for variously defined applications. If an identity is involved in a particular application, it means that the identity can be used in a certain way and can be found in a kind of situations in the environment. Once identified, identities can be evaluated, located, identified, and acted upon appropriately based on the previously learned knowledge about them. In organisms, the knowledge of the functional uses of identities can be learned either in direct actions upon the identities where the identities are involved, or in imitations and plays where identities are imagined to be involved (Piaget, 1962). These applications can also be recalled different in analogical reasoning (Vosniadou and Ortony, 1989) if similar application demands are faced. However, to support

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10See the first subsection in Section 4.3 on the two senses of identifications and knowledge of identities.
11See discussions in Section 6.2.
the involvement of the relevant identities in applications, i.e. similar identities can become the substitutes, identities are to be organised into categories. The conceptual re-organisation is to develop an organisation for the identities within a core-domain. The identities which share the similar functions are grouped together. Under this condition, the ones which appear in the similar locations form a category.

While the earlier categories are formed based on the shared action schemes (as implied in Piaget’s action based account and extensively studied by Mandler (2000a)), the matter of category formation in the conceptual re-organisation also takes consideration of other dimensions. The conceptual re-organisation means while identities which share similar functions are in one group, the group can be further differentiated while those identities which also share the similar patterns in representation schemata are kept in one group. Those which do not share the similar pattern of representation will be sorted into different groups. The purpose of such conceptual reorganisation is also for the development of efficient causal rules for categorisation. In the meanwhile, the shared functions of the identities are kept. This process can result in the explicit understanding of ontological-kinds of identities and the development of basic level categories.

For the knowledge structure of identities in a core-domain, basic-level-categories are important. But it is not accidental that basic-level-categories have the highest cue validities for identification and highest category validities to support reliable inferences. They are functionally meaningful categories to start with and they can support efficient classifications and the most meaningful inferences for potential applications.

The representations of identities as the particulars are for two groups of functional purposes, which define two formal structures for the knowledge of identities as causal rules and causal conditions respectively. The causal rules are for the identification, categorisation, and re-identification of the state (of an identity) in the perceptual input. The knowledge of identities of this type is about the knowledge of boundary conditions (of ontological-kinds basic-level-categories, and individuals in space-time). The information gained about an identity, such as its form at a time, distinctive features, or its internal content, can often be used pragmatically for such functional purposes.

The other group of functional purposes is closely related to support the potential appli-

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12The distinctions of ontological-kinds are supported by the modules in brain directly (Millikan, 1998b; Boyer, 1998). Also see (Fodor, 1983)’s argument of modular theory. However, the modules in his discussions are mainly the perceptual devices, not the cognitive units of representation for identities.
cations of an identity with reliable and meaningful inferences. The knowledge of identities is to establish the categories as the causal conditions to support inferences. The knowledge of identities involves attributes which are stored in the formal schemata for the representation of identities. The attributes of identities which can be learned are generally about states and transformations for the three components as figures, contents, and contexts. The attributes of different kinds are also useful for different purposes.\textsuperscript{13}

On representation of basic level categories of individuals

The development of basic-level-categories (Berlin and Kay, 1969; Rosch, 1978) for identities in a core-domain is emphasised in this thesis. The development of the basic-level-categories is structurally significant for two reasons. First, basic-level-categories form a set of classes which are mutually exclusive. Thus, identities within a core domain can be sorted into their relatively independent groups. Second, the basic-level-categories are associated with maximum cue validities and category validities\textsuperscript{14}.

Both the formation and the knowledge of a category are influenced by all identities in the core-domain and the alternative categories. Rosch (1978) argued that the identities within a category share the maximum similarities and the identities from different categories are significantly different. The knowledge of a category can also maximise the differences of the individuals of the category along certain dimensions in order to support the further differentiations of the individuals. The knowledge of a category is not a simple generalisation of all the members which share similarity in shapes or states in general. Rather, it is derived with the consideration of functional differentiations in the first place. The characterised representation of a basic-level-category will emphasise the shared functional roles of identities by making sure

\textsuperscript{13}For problem solving, identities can be involved because of certain physical and spatial properties they possess. The physical and spatial properties can allow the judgement on whether an identity can be involved in certain uses, e.g., whether it is the wanted food. Distinctive physical properties can allow specific uses of them for making certain products. The inferences of locations can determine whether or not they can actually get involved because of their locations, i.e. they may not be reachable. Distinctive spatial properties can allow certain ways of interaction with them. The knowledge of an identity should provide explanations of behaviours or understanding the potential changes (Keil, 1989a). The inferences of processes, behaviour patterns, or possible causal interactions of an identity are relevant for the attributions or predictions of its states at different times. In case where the prediction of the future fails, the causes can be examined.

\textsuperscript{14}See Sections 4.4 and 8.3 for more discussion on categories and basic-level-categories.
that the identities of the category all have the physical or spatial properties which support the functions. However, other different attributes of the identities are also collected since they are relevant for other functions. The common locations are for their locating. The overall states, processes and behaviours can be relevant for categorisations.

The development of basic-level-categories depends on two conditions. Firstly, it is the constructions of two cognitive units for an identity, one for the representations of an individual and the other for the knowledge of an individual. The representation of an identity as an independent existence is directly based on the sensorimotor examinations, which is constrained by the ontological nature of the identity. The knowledge of an identity depends on the representation. However, the knowledge is about the retrieval of the information from the representation of an identity for different cognitive tasks, such as re-identifications or supporting the applications of the identity.

Secondly, the development of basic-level-categories is associated with the general capability of conceptual re-organisation of a core domain. The development of basic level categories is related to the capability for category formation based on the consideration of multiple dimensions rather than single one (Smith, 1989b). In certain domains, the set of mutually exclusive categories can be derived based on the highest cue validity, that is, the use of perceptual properties for classification. However, in most domains, there are the considerations of both structural and at least one functional dimension for the distinctions of identities (Mandler, 2000a). The functional demands of re-identifications and useful inferences to support applications have effectively limited the attributes which are actually involved in the explicit knowledge of identities and categories (i.e. even though more attributes can always be found for the identities, the non-useful ones are seldom kept).

The development of basic-level-categories which are constraints on the representation of individuals is an innately determined tendency. The development of a set of basic-level-categories is applicable to the study of identities of all domains. The exact set of basic-level-categories of a core-domain at a time reflects the quality of the conceptual systems of a core-domain. They are associated with the increased capability for efficiently handling as much as possible individuals in the core-domain. However, as observed in empirical data (Johnson and Mervis, 1997), the set of basic level categories can change overtime. The changed set can be caused by the increased experiences or the development of conceptual re-organisations, such as the adoption of different rules for sorting all identities into categories or the specialisations of sub-domains.
of a core-domain.

However, the meaningfulness of a particular set of basic-level-categories may depend on either the quality of the set of basic-level-categories developed at a time or the nature of the core-domain with identities of a distinctive ontological nature. For example, in the studies in geosciences, the basic-level-categories may be considered less valuable. From the functional perspective, the value of a basic-level-category is essentially judged based on its supports for re-identifications and inferences of properties about the individuals as members of the category. However, the identities in the large-scale environment are the ones which are fixed to the locations in the environment. As stated in (Smith and Mark, 1998, p.309), “geographic objects are not merely located in space, but are tied intrinsically to space in a manner that implies that they inherit from space many of its structural (merological, topological, geometrical) properties”. The fixed locations of spatial-features in the large space make them easy for re-identification and consequently inferences of information about the individuals. However, the causes for their fixations to places may be different for different spatial-features in the large-space. When these identities in large-space are studied in their own right, the categories of them are still needed for the general knowledge.

6.3.2 On structure of core-domains in terms of category systems

The representation and knowledge of a core-domain is also about the complex core-domain situations as particulars\textsuperscript{15} as well as their generalisations. The generalised representation of such core-domain situations can be structured in four kinds of category systems, the partonomies, events and event structures, causal knowledge, and taxonomies. These four kinds of category systems will be discussed in this subsection. Events, event structures, and causal knowledge are important for the transformation aspect of the environment. Partonomies and taxonomies are important for the states of identities and complex core-domain situations with multiple identities.

On part-whole structure for states of identities

The representation of an identity as a 4D existence with attributes is correlated with the development of partonomies of its core domain. That is, the partonomies define the generic formal

\textsuperscript{15}See Section 5.4 for the general structure of an application involving a complex situation.
schema for the representation of individual identities within a core-domain\textsuperscript{16}.

When an identity is studied in its core-domain, the development of representation has three kinds of part-whole relations enriched. One kind of part-whole relations is between the identity as the \textit{figure} and its \textit{boundary parts}, i.e. the part-whole relations of the \textit{overall shape} of an object with its distinctive \textit{boundary features}. The other is about the identity and its \textit{internal parts}, material \textit{components}, or \textit{samples} or \textit{data supports} where properties can be measured over. The third is about the relations of an identity to its differently characterised locations.

The formal structures of the part-whole and part-part relations and subtypes of them are applicable to different core-domains. The different partonomies in different core-domains lie in that different \textit{levels} in the three groups of part-whole structures can be developed. There can be multiple levels of parts for physical machines and biological individuals. There may be only one level of particles for physical substances which explain the different textures and properties of the substances. During the development of representation for identities, the part-whole hierarchies are associated with more levels since \textit{parts} and \textit{internal components} can become increasingly smaller. The contexts in space-time are increasingly larger and more complex. Both kinds of development can be driven by functional demands.

When an identity is involved in modelling applications, there are two cases where part-whole relations can be applied. Firstly, it is about the representation of an environmental state. An identity as an element can contribute to the definition of an environmental setting at a time. For each of the involved identities, it is located in a place. Either it bears member-collections or part-configurations relations to other identities (i.e. \textit{spatial relations} of identities). Or it is an entity which is contained within a larger identity (i.e. in \textit{topological relations}). The knowledge of the contexts for an identity (i.e. a figure in its context) is involved for locating the identity. The other two kinds of part-whole relations can be involved for identification or re-identification. Secondly, in an application, an identity is either a final target, or an intermediate goal. In either case, the identity has to be located and reached. There is also the case where multiple identities are organised into element-element relations along time (i.e. \textit{temporal relations of identities}). Further, there is always the general constraint from the application situation as a whole which contains the identity as one element (in container-contained relations along time).

\textsuperscript{16}See detailed discussion in Section 4.3 on the development of part-whole relations for identities.
On part-whole structure of events and system of causal knowledge

The causal knowledge and event structures are relevant for the representation of the transformations of core-domains. However, the importance and enrichments of these two kinds of category systems depend on the nature of the core-domains and sub-situations within a core-domain. Causal knowledge is important for physical studies. Events and event structures are more common in the studies of the social environment. The system of causal knowledge has been discussed in detail in Section 6.2. This subsection will focus on events and two event structures\(^{17}\).

Depending on the core-domains, events may be understood differently. For example, in studying the natural systems, events can be associated with the sudden changes in the environment, such as flood, earthquake, and tornado. The studies of such sudden changes are either about the conditions (i.e. the causes) or the patterns of changes (i.e. the processes). In social domains, events are either associated with a sequence of actions and interactions, or they are associated with occurrences which mark the distinctive periods of a life. The actions upon a sequence of objects are organised towards certain specified states, which are usually the internally motivated goals by a person. Either the actions of other people or the actions of a person herself can be directly involved in the changes of the environment. Different events can imply different objects are to be interacted for reaching different goal states.

The events can be defined over different temporal scales, i.e. they can be accomplished within different time periods. Some events are once in a life time (e.g., birth and death), others may be repeated several times (e.g., graduations from schools, several marriages, changes of works). Some events constantly happen. Events can also be differentiated based on whether the actions involved happen in one location (e.g., eating dinner at home) (Nelson, 1986) or the actions involved can be differentiated into those which happen in different locations (e.g., going to a restaurant for a dinner) (Schank, 1977).

The event structures are in terms of the contingency of events and hierarchies of events (or hierarchy of goals). The part-whole relations are important for studying the relations of identities in applications and for the development of event representation and structures of events. That is, the events and the development of event structures are learned where the representa-

\(^{17}\)Also see Section 4.3. However, detailed study of events and event structures for core domains are beyond the scope of this thesis which focuses on representation of identities.
tion of changes of a core-domain can be modelled with the part-whole relations of identities in temporal dimension. For example, in a mental operation motivated towards a goal, a targeted object is to be reached and it is located in an environmental setting. To reach the target, a person may go through a sequence of locations. In this case, there are part-whole relations between the environmental state and the objects within it on the one hand, the sequences of events to go from one location to another.

**On taxonomies for core domains**

For the representation of a core domain with a collection of identities, there is the development of a system of categories, commonly called taxonomies, for organising these identities. However, the taxonomies studied in literature for categories of identities can be differentiated into two kinds. Basic level categories are crucial for the development of these two kinds of taxonomies.

The first kind of taxonomy refers to the hierarchy within a core-domain which is defined with *an ontological-kind, basic-level-categories, individuals, and states* of individuals at different times. The conceptions on these four inclusive levels can all be used to assimilate the *state* of the environment in perceptual inputs. This structural constraint is shared by all core-domains.

The second kind of taxonomy refers to the hierarchy which is formed starting with *basic level categories* (e.g., table) to *super-ordinates* (e.g., furniture) and *subordinates* (e.g., dinner table) (Rosch, 1978). However, the super-ordinates and subordinates are categories of different natures in comparison with basic-level-categories (Wierzbicka, 1984). The super-ordinates and subordinates are collections of objects within certain *spatial locations* and with certain functional meanings. Such collections can be meaningful because the identities in the spatial locations are often involved in the repeated *events* (Nelson, 1986). The generalised super-ordinates (e.g., furniture) are also collections of basic-level-categories of objects.

There are three more points to be made. Firstly, depending on the core-domains, these two taxonomies can be merged into a single one. For example, with the development of the scientific domain of biology, there is the single ontological-kind of living things. A single scientific biological taxonomy is possible because all organisms share the same biological cause of existences (Carey and Spelke, 1994; Millikan, 2005). From living things to different species, the biological taxonomy can have taxa on different inclusive levels. However, it is not about
instantiation of a kind. Indeed, Ghiselin (1974) and Hull (1976, 1978) argued that species are collections of individuals and the relations of taxa on different ranks in biological taxonomy also bear member-of relations. There is the causal dimension to study the relations of taxa on different ranks. The distinction of species can be based on morphological cues, such as, a) the simple versus complex kind with boundary and internal organs as two separate components; b) the complex objects with or without dedicated functional parts or organs. However, physical objects do not form one simple hierarchy of inheritance. They are not even studied within a single sub-domain. The ontological-kind of physical objects in the common-sense-space can be differentiated into artefacts versus natural substances or objects.

Secondly, this kind of organisations with basic-level-categories, super-ordinates and subordinates are essentially about representation of complex situations which have multiple objects. When such complex situations are studied in different core-domains, there are different conceptual units developed for these different core domains. In biology, the identities in a collection can be differentiated into two kinds of systems. One is the development of the biological taxonomy and the other is the development of ecology systems which also study the complex relations of the individuals of different species. In the physical environment, the collection kind is applied to organise artefacts of different functions. However, this environment can be further differentiated into sub-situations and objects are sorted into these sub-situations. In social domain, this hierarchy is associated with organising activities of the daily life. However, there are also sub-domains of the social domain, which correspond to the studies of different social groups and organisations. When there are further specialisations of core domains into sub-domains, the taxonomy is applied to identities in sub-domains.

The development of this second kind of taxonomies starts with identities and their contexts and the application contexts can be variously defined. The third point is about whether the complex situations should be represented as collections of identities as categories or the events where objects are embedded. The choice perhaps depends on the focus, i.e. whether focus on the states or the transformations. This second type taxonomy is important in the study of physical objects and bear bears a close relation to the development of the representation of events (Nelson, 1986). For example, the subordinates (e.g., whiteware) are collections of objects. They are often associated with certain spatial locations in the smaller scale (e.g., in A-space or B-space) and repeated actions and activities in the daily routines of a person. However, events and event structures can often refer to the large organisation units of actions or activities
in the life of a person.

6.4 Summary

In the situation-based theory, the distinctiveness of core-domains was understood from three aspects. Namely, core-domains are special because of their existence in the environment, the development of representation of such core-domain situations, and the knowledge of such situations.

The state of representation and knowledge of a core-domain is defined by the ontologically distinctive identities and the development of causal knowledge about identities, their interactions, and the transformations of complex core-domain situations as wholes. The causal knowledge associated with single identities and the causal knowledge associated with situations involving the interactions of identities are two conceptual primitives. The position on the state of representation and knowledge of a core-domain can systematically explain the various kinds of domain constraints proposed in cognitive literature on the representations of identities.

The distinction of structure versus contents is applied to understand the conceptual system of core-domains. The structural aspect of domain representation and knowledge should be differentiated from the exact states of core-domains in mind. For identities of core-domains, there is the generic formal schema for the representation of identities from the sensorimotor experiences. The knowledge of identities derived from the representation supports the two general functional expectations from the representation of identities. The development of a set of basic-level-categories for a core-domain indicates the state of domain knowledge. The core-domain situations, which can be represented as particulars, are generalised as knowledge structured by the four kinds of category systems, with partonomies, causal knowledge, events and event structures, and taxonomies. These formal structures can be logically specified.
Chapter 7

On the nature and system of ontological-kinds of spatial-features

7.1 Introduction

This and next chapters are devoted to understand the constraints on the models of identities in core-domains or application-oriented domains. Pragmatically, to the concern of designing a new SISystems, it has to specify the information architecture based on what kinds of contents are to be supported. For specifying the new information architecture for a SF-SISystem, this thesis has provided a situation-based theory of cognitive systems and discussed the various kinds of structural constraints on the representation of identities. The fourth level cognitive and conceptual structure is to be modelled. This structure-of-the-whole is correlated with a system of core-domains and application-oriented domains. For modelling core-domains, the identities in such domains are to be modelled. The constraints on modelling such identities are also to be further specified.

In this chapter, the nature of ontological-kinds and the constraints from the development of cognitive structure on representation of identities will be studied. The latter is correlated with the development to support a system of ontological distinctions of identities in the environment. There are two main sections. Section 7.2 is on the nature of ontological-kind. A realist’s view is adopted. Specifically, the ontological nature of identities refers to their existences in the world which constrain their representations. The cognitive criteria for the ontological distinctions of identities will also be discussed. Section 7.3 will discuss the system of ontological-kinds supported by the fourth level cognitive system. The development of cognitive system in general has posed the structural constraint on the representation of an identity in that whether a certain ontological-distinction can be made explicit. In the discussion of the system of different ontological-kinds of spatial features for SIScience, the ontological-kinds of identities in the
common-sense-space and those in the large space will be studied separately.

7.2 The nature of ontological-kinds of spatial features

This section will briefly review the studies of neurosciences on representation of concepts of different ontological-kinds. They have provided evidence that the representations of identities of different ontological-kinds in brain are different (Humphreys and Forde, 2001). In other words, such studies agree with the proposal that the ontological natures of identities constrain their representation (Carey, 1985; Keil, 1989a; Gelman and Markman, 1986).

However, two theoretical positions will also be clarified. One is the realist’s position adopted in this thesis in understanding the ontological natures of identities. Namely, the ontological-kinds of identities are determined by their own existences in the world. The physical natures of identities themselves and the situations and spaces the identities are located in have put inherent constraints on the representation of identities. The other is about the cognitive criteria in understanding the ontological distinctions of identities. For the knowledge of ontological distinctions of identities, both the functional and structural dimensions should be taken into considerations. The functional, structural, formal, and relational criteria will be explained.

7.2.1 On representation for categories of ontological-kinds in brain

In the past decades, the study of the representation of concepts of different ontological-kinds in a brain has been an active area in neuroscience. A considerable amount of data has been collected with patients who have selected deficits in recognition and memory tasks (Warrington and Shallice, 1984; Humphreys and Forde, 2001). These patients have difficulties to deal with categories of one kind (such as animals), but perform normally when they are tested with categories of another kind (such as tools). Data of this sort has prompted scientists to suggest these categories of different kinds are represented differently in mind.

There are two major families of theories, depending on whether the representation of a category shall be localised or not. One proposed that representations for different kinds of categories are in different localised brain areas. The other proposed there are the different weightings of different attributes, and the attributes may be in different areas. For example, Warrington and Shallice (1984) proposed there are two independent systems. One is evolved
for representation of functional information, the other for structural information. The functional information is more about the kind of actions which can be applied to the members of a category, such as the different functions of different tools. The structural information is more about the forms of objects which are derived from the visual sensory input. The functional information is important for non-living objects, while structural information is important for living things.

However, data collected in the past has presented a rather complicated picture (Humphreys and Forde, 2001). Recent studies on neuroimaging have collected more data which challenges these earlier theories. These studies have shown that the representations for concrete nouns, such as living things and artefacts, are in similar distributed patterns involving multiple brain areas (Humphreys and Forde, 2001; Martin and Chao, 2001). This is taken as one of the most significant findings because these two sets of nouns are taken as belonging to different ontological kinds and it was expected that different localised areas for their representations might be found. However, the behaviour data collected from patients has surely shown the certain levels of dissociations of memory for different kinds of things and the selective damages of memory for different kinds of information.

There are also studies on the reactions of single neurons to the stimulation patterns of different ontological-kinds, such as faces, hands, houses, and locations. The single neurons in mind react selectively to the stimulation patterns of a particular kind only (Gross, 2000, 2002). Nevertheless, such data does not necessarily mean that the representation of identities should be interpreted as being localised in these single cells. Rather, these cells may simply play the roles of connecting the two or more regions which process different sorts of information and such information can be applied to the representation of identities belonging to different kinds.

Indeed, there are reasons to believe that the representations for animals and for artefacts are different because of the observed dissociations of corresponding memories in functions. However, the neuroimaging data has also shown both structural and functional properties are involved in the representation of categories of different kinds. These studies may provide reasons to believe that these different properties are weighted differently for the representation of categories of different kinds. However, the distributed but similar patterns for objects of different kinds (i.e. all involving a few different brain areas) imply a different theoretical approach is needed.

To explain the distributed patterns in brain for the representation of categories of different kinds, Humphreys and Forde (2001) proposed the hierarchical interactive theory (HIT). The
HIT theory rejected the proposal that there are isolated unique areas for representation of categories of different kinds. Instead, it extends the position of Warrington and Shallice (1984) to interpret the observed dissociations of memory functions. The proposal is that the structural and functional properties are relevant in different degrees for categories of different kinds, such as artefacts versus living things. Different brain areas for handling these different kinds of information can all be activated for either category. However, they are activated with higher or lower degrees of intensity when there are different kinds of categories to be represented.

The HIT model has also added another dimension into consideration, i.e. the linkages of different areas which are for processing information of different kinds. The different patterns in linking these areas can be related to the representation of categories of different kinds. The HIT model of Humphreys and Forde (2001) has explicitly taken the processing procedures into consideration as well, which is called the hierarchy of processing. The differences in representation are not just in the sense of involving different areas, but also in the sense of the exact routes to follow, such as from where there is the first activation in one brain area, then to the next area. The same area can be visited at different times. The process stops when an answer can be given to the question asked by an experimenter.

**Understanding the different patterns for different ontological-kinds**

From the perspective of the situation-based theory, to explain the data from neuroscience for the representation of categories of animals and tools, two conditions should be taken into consideration first. One is that the representation in mind can be focusing on identities. The differentiations of identities can be based on both the perceptual properties and actions upon them. In these theoretical studies cited in (Humphreys and Forde, 2001), the perceptual properties include shapes which are called structural properties and the actions upon the identities are called functional properties\(^1\). Following Piaget, the perceptual properties are to be assimilated to action schemes, rather than simple associations of these different properties. The other is that the explicit distinction between explicit conceptions for an identity which are derived based on the comparisons with other identities and language based re-descriptions for the representation of an identity should be maintained. That is, data collected by using category nouns and pictures of objects may be studied separately because the two kinds of stimulations can be associated with

\(^1\)However, these understandings of structural or functional are specific and different from the same terms as they were used in this thesis, see Sections 2.3 and 2.4 for the relevant discussion.
different patterns of activations, and thus contribute to the complexity of results from empirical studies.

The theoretical explanations for the different distributed patterns of representation for the representation of different categories in the brain (Humphreys and Forde, 2001) involve various kinds of attributes for explaining the differences in the representation of categories. However, there are three cases for understanding why different attributes are relevant for different ontological-kinds. Firstly, for identities of different core-domains, the sorts of attributes which play the more important roles are different. That is, all different kinds of attributes may be involved for identities of different kinds, however, they are weighted differently for different ontological-kinds in categorisations and identifications. For example, shapes perhaps are important for differentiating all sorts of things. The processes, patterns of movements, and patterns of behaviours are used by people to make the distinctions of animates or other people in the environment. Functional properties (i.e. based on actions upon the objects) are more important for artefacts\(^2\). For categories which are groups of identities embedded in events and locations, the shared events and locations are important attributes for them.

Secondly, the involvement of different kinds of attributes is because these attributes are only available to the particular ontological-kinds, they are not available for other ontological-kinds. Indeed, the representation of identities in a core-domain is often associated with a set of core-domain specific attributes and the values along the attributes which are important for categorising identities. For example, for differentiating substances which have neither clear boundaries nor internal parts, the physical properties and textures of the substances are important. For simple objects with clear boundaries, there are not only the overall shapes, but also distinctive parts and distinctive functions (both the functions of the objects as wholes as well as the functions which are often associated with the distinctive boundary parts). The self-initiation of actions and natural processes of development are relevant for reliably distinguishing animals and people. However, these dimensions of changes are usually irrelevant for categorising physical objects. Regarding the identities in geoscale, the ontological nature of an identity is directly related to what kinds of attributes which can be involved in the representation of states of the identity. For the complex environmental settings, such as a city, the complex internal structure is important. For a natural physical system, the physical variables are important for its study.

Thirdly, the hierarchical processing in the model of Humphreys and Forde (2001) implies

\(^2\)Although the similarity in functions should be supported by the similarities in physical and spatial properties.
that the task of categorisation of an item shall involve the progressive processing. The idea of increasingly detailed categorisation of an item is compatible with the idea that the conceptions for an identity are on different inclusive levels, namely, the states, the individuals, specific categories, and ontological-kinds. During each step of processing, an item will be categorised into a group which corresponds to one of the different inclusive levels. For the stimulation in the environment, the state of it is examined with the sensorimotor modalities and will be classified into a core-domain and an ontological-kind. Then it is sorted into one of the basic-level-categories. At last, it can be identified as the state of an old or a new individual. Correspondingly, in each level of processing, the perceptual properties will be examined in the relevant level of details.

7.2.2 On the nature of ontological-kinds of identities

There are different patterns in brain for categories of different ontological-kinds. This point may suggest that the idea of ontological-kinds of identities may be defined or formalised based on these different representations. However, the constraint of an ontological-kind is also commonly interpreted as implying that different kinds of attributes are involved in the representation of identities or different attributes play different weights in the representation (Gelman and Markman, 1986; Keil, 1989a; Humphreys and Forde, 2001). Thus, there is a circular argument if the different ontological-natures of identities are defined in terms of their involving attributes of different kinds in the first place.

Different kinds of attributes may be relevant for representation of identities of different ontological kinds, however, one of the key issues to be addressed is why different ontological-kinds are associated with different attributes. To understand the ontological-kinds, this thesis takes the realist’s position and will be explained in this subsection. The central position is that the ontological-kinds of identities are determined by their own existences in the environment. However, for the ontological distinctions of identities, there are both ontological and epistemological factors to be taken into consideration, as discussed below:

The realist’s understanding of the ontological nature

The identities of spatial-features as natural-units exist in certain spaces and last certain time periods. Ontologically, the ontological distinction of an identity is ultimately determined by its own nature of existence in the world. The ontological distinctions of identities are determined
by the very existence of these identities themselves in terms of their physical natures, locations
in space-time, and their relations to others.

Epistemologically, for the identities as *natural-units* to be represented, they have to be func-
tionally relevant and the representation is constrained by the development of cognitive and
conceptual structure. There are inherent constraints from the existences of identities in the
world upon their representations in mind when the representation is learned via sensorimotor
experiences with them.

That is, ontological nature of the existences and cognitive development both determine the
ontological distinctions and their representations. Firstly, the situations in spaces where iden-
tities are located determine inherently the functional roles of these identities for being relevant
to the study of contents (e.g., the parts) or the contexts (e.g., the containers). The spaces and
situations as the locations also influence *when* and *how* these identities can be represented. The
identities in the *common-sense-space* can be represented in the first and second level cognitive
systems, the identities in the large and larger spaces can be explicitly represented in their own
right in the third and fourth level cognitive systems.

Secondly, the exact physical natures of the identities also pose the inherent constraint on
the representation of identities. For example, the identities in the *common-sense-space* bear
certain functional roles to the concern of a person and can play a functional role in applications.
The functions of these identities are inherently constrained by their physical natures and spatial
characterisations. There are always the *physical properties* and sometimes distinctive *spatial
characteristics*. These attributes are directly related to the perceptual differentiations of sub-
stances and the understanding of the functional roles of these identities to the biological needs
of a person (such as food, mates, tools, toys, or dangers).

**Ontological distinctions understood from the perspective of cognition**

While the ontological natures of identities are determined by their own existence in the envi-
ronment, the understanding of the ontological distinctions of the identities is an issue of Epis-
temology. This thesis has adopted the functional principle to understand the representation of
identities as *natural-units*. Following this principle, the identities to be represented need to have
certain functional values. They have to bear either the functional relations to the concern of a
person or functional relations to other identities.
The epistemological perspective is critical for understanding the ontological-kinds which are embedded in a cognitive system and constrain the representation and knowledge of identities. From the perspective of a situation based theory, the functional principle as the general constraint for the development of cognitive system of representation as a whole (of relations) should be differentiated from the functional characterisations of identities (understood in actions). On the one hand, the functional principle is the ultimate constraint on the development of cognitive system. On the other hand, an identity can be sorted into one of the ontological kinds based on the distinctive functional roles to a person and functional relations to other identities.

Thus, this adoption of the functional principle marks two fundamental differences of the study of ontological-kinds in this thesis from those studies in SISciences, e.g., Tomai and Kavouras (2004); Visser et al. (2002); Gahegan et al. (2003); Kokla and Kavouras (2001). Firstly, the functional connections of identities mean the identities which are to be represented do not form a simple collection. There are not only ontological distinctions of identities for sorting identities into groups, but also a system of ontological-kinds which is formed by these ontological-kinds, rather than a simple collection of them. The ontological-kinds in the system define a structure where the identities bear part-whole or container-contained relations to each other.

The functional drive has brought the structural changes to the representation system in mind. The cognitive systems at different levels are correlated with different systems of ontological-kinds of identities, i.e. the representation of an identity which belongs to one of the ontological kinds can be supported. The four levels of cognitive systems mean that there are four corresponding systems of ontological-kinds of identities. Cognitive development means that with each step of development of the cognitive structure, either there are new ontological kinds which can be studied and represented distinctively, or an earlier ontological kind can be further specialised (e.g., objects become physical objects, organisms, or people) which leads to the different forms of representation for the same identity. Cognitive development is associated with the support of a correspondingly increasingly complicated system of ontological-kinds for identities of spatial-features. For the purpose of modelling in SISystems, the fourth-level cognitive system and the system of ontological-kinds of spatial-features supported by this cognitive system should be emphasised.

\[3\text{See Section 7.3 for detailed discussion on the ontological kinds of spatial features supported by the fourth}\]
Secondly, the different ontological-kinds are meaningful because they can capture not only the functional differences of the identities which belong to the ontological-kinds, but also the differences regarding the forms of representation of these identities. Both the functional roles of identities and the formal characterisations can be used as important aspects to understand their ontological groups.

While ultimately, what can be included in the descriptions of identities are determined by their ontological existence, the possibility of explicit and detailed study of identities (which are members of a certain ontological-kind) is determined by the development of a cognitive system. This development of cognitive and conceptual system of representation itself is constrained ultimately by the functional expectations from a representation system. These are the key Piagetian epistemological positions which have been adopted in this thesis and explained from a figurative perspective. For example, for identities in the common-sense-space, the animate is treated as a distinctive ontological-kind from physical object until the third level cognitive system when they can be associated with a distinctive set of characterisations. These attributes are learned for better prediction of their behaviours and possible interactions with others. For identities which are in certain situations in large spaces studied in SIScience, the representation of their ontological-kinds can be developed at certain levels of cognitive systems because they are important locational constraints. The formal schemata of representation are different in comparison with those for identities in the common sense world because of the restricted accessibility and their natures of being locations. The development of the conceptual representation of a natural-unit, however, also requires the comparisons of it with other identities of the same ontological-kind which can bring structural changes to the conceptual system of a core-domain and knowledge of different kinds about the identity.\footnote{See Chapter 8 for more discussions on the different sorts of knowledge for identities and different sorts of constraints on the models of identities as individuals.}

7.2.3 On cognitive criteria for ontological distinctions

The ontological distinctions of identities, i.e. sorting identities into ontological-kinds, can be understood from a few cognitive criteria, called functional, relational, structural, and formal factors. The meanings of these different criteria will be further explained in this subsection.
The functional roles of identities for ontological distinctions

The functional dimension is important for understanding the ontological distinctions of identities. However, the functions of identities are understood on two levels. One is to the concern of a person, which allow the identities in the common-sense-space (which bear direct functional relevancy to the biological needs of a person) to be differentiated from the identities in the small and large spaces (which bear only indirect functional relevancy to the biological needs of a person). The other is to the concern of other identities, namely, whether the identities are relevant for the studying of the contents or the contexts of the objects in the common-sense-space. This second level of functional understanding means that the identities in their corresponding situations can be further differentiated based on what kinds of functional relations they have to the identities in other situations. For example, locations studied as identities in different Zubin spaces can bear certain functional relations to each other.

The ontological distinction of identities takes into consideration of the functional roles of identities. For identities as figures in the common-sense-space which can be acted upon by a person, they can either satisfy the biological needs (e.g., water, food, and mates) or they bear certain functional relations to the identities which can satisfy the biological needs of a person. In the first case, these functional roles are learned in direct actions and understood in terms of the suitable action schemes applied to them. In the second case, the identities are only relevant to a person indirectly, such as being used as means or locational cues.

Identities in the common-sense-space can be differentiated into three ontological groups, i.e. physical substances or objects, organisms, and people. While the functional uses of these identities may not be the only criteria which differentiate them into ontological-kinds, the direct and indirect functional roles of these identities do contribute to these ontological-distinctions. For example, food comes from other organisms, either the organisms as wholes or their parts. Physical objects can be the tools or container which can be used to reach and hold the substances. Other people in the social environment of a person can be used to satisfy all sorts of needs even though some kinds of uses are forbidden.

The ontological distinction of identities in the large space also takes into consideration the functional relations of the identities themselves. However, these identities are locations of different kinds. Indeed, the functional types for such identities can be understood from two perspectives. Firstly, they are the characterisations of the natural environment of people. For
example, the natural systems in C-space characterise the large scale natural environment. Such characterisations bear either direct or indirect relevancy to people. Landscapes and events associated with certain natural systems can bear direct functional relevancy to the concern of a person. For example, events such as volcano eruptions, earthquakes, floods, and forest fires can pose danger to lives. Other natural systems may not be directly relevant, such as ore deposits. They are functionally relevant for extracting minerals which can then be used for making other objects or constructions in large scale.

Secondly, their functions are mainly restricted to being the contexts for the targeted figures of the common-sense-space directly or indirectly. The locations for a small object in A-space can be a container or the configuration of other objects (Bremner, 1985). The container can also be an A-space object (e.g., a box). The locations for people or other objects are often the large entities in B-space, which can either be the natural ones (e.g., caves) or artefacts (e.g., buildings). The B-space objects can simply be the landmarks for places. There are also configurations of landmarks or buildings. The objects in B-spaces are also the container for objects (either the contained or the container) in A-space. The spatial features in C-space, such as cities, are locations for people, B-space entities, and environmental settings (defined by the configuration of B-space entities and certain types of activities of people).

The functional characterisations of the identities play crucial roles to make ontological distinctions of identities. However, the functional characterisations include the understanding of the objective relations between and among identities themselves and subjective choices of the roles these identities play. That is, such relations of identities can be understood from two perspectives. One is about the relations of identities in the representation system. For example, in a core-domain, identities can play the roles as the figures, the contents of figures, or the contexts of figures. The other is about the relations of identities in applications. For example, in an application, the identities can play the functional roles as the targeted figures, the locations, or the means. From the perspective of representation, identities are elements of the environment and can characterise the environment in the same time. From the perspective of applications, identities can play the roles of wholes and parts. As wholes, they have their own characterisations for being identities. They can have contents of their own, which can include material components and internal parts (e.g., internal organs for an organism). As parts, they are the elements to define the large spatial context and can be used as tools or means for reaching other targeted objects.
On structural and formal constraints on ontological kinds

Different ontological kinds of identities mean their distinctive existences in the world. The precise existences of identities in the world determine that the identities are not only functionally meaningful, but also formally distinguishable in terms of their representation from others. From the structuralism’s point of view, there are two senses of the ontological natures as the constraints on representation, called structural constraint and formal constraint respectively.

Structural constraint: The structural constraint is about the inherent constraint from the state of cognitive structure on representation. The possibility of an explicit representation of an identity which is a member of an ontological-kind is constrained by the developmental level and stage of a cognitive system. Specifically, there are two senses:

Firstly, at a given state of cognitive structure, certain ontological distinctions can be made explicit but others are not. It is often about whether certain refined ontological distinctions of identities can be made. For example, objects and substances may not be explicitly differentiated in the sensorimotor period, even though this distinction can be implied in the different sensorimotor schemes which can be applied to these different kinds. An object can be explicitly differentiated as a member of physical kind, organisms, or a person of the social environment.

Secondly, at a given state of cognitive structure, certain ontological existences can be represented, while others cannot. The structural constraint is associated with the possibility of explicit cognition of certain identities. The identities which are recognised (functionally and structurally) earlier are those in the common sense world. The identities in other smaller or larger spaces are recognised rather late. For example, the identities in the D-space cannot be represented until in a reasonably developed fourth level cognitive system.

Formal constraint: An ontological nature constrains the exact form of a representation. While identities are classified into members of ontological-kinds because of their own existences and their functions, the different forms for the representation of different ontological-kinds can also be used as an empirical rule. That is, the formal criterion on ontological distinctions is related to the observation that there are different forms of representation for identities of different ontological-kinds (Humphreys and Forde, 2001).

Indeed, the structural constraints and the forms of representation should be treated separately. The formal characterisation of identities is about the development of the exact forms for the representation of identities. The forms of representation are constrained by the cognitive and
conceptual structure on the one hand, experiences with *identities* and *core-domain situations* on the other hand. Chapter 8 will be devoted to the discussion on various factors as constraints on forms.

**On relational information of identities for ontological distinctions**

The objective relations between and among identities are important for the *ontological distinctions* of identities as well as the objective understanding of these identities. These relations are learned and defined within certain complex situations. For identities within such a situation, there are a few different kinds of relations between and among identities, such as *spatial relations*, *temporal relations*, *functional relations*, *causal relations*, and *relations of states*. However, these objective relations are either the properties of the environment in general (e.g., spatial and temporal relations), or they are relevant to the ontological distinctions of identities, or they are simply the properties of identities. The level of differentiation is both the factor of natural existences and the choice with functional consideration.

**Functional relations and relational properties**: The *functional relations* of identities in the general sense are the part-whole relations or container-contained relations which are involved in defining a *state* of a representation system (see Section 4.3). Identities in different spaces can be distinguished into different *core-domains* and *ontological kinds* because of the patterns of functional connections. Specifically, identities in different spaces which bear part-whole relations (e.g., an identity with its contents) or container-contained relations (e.g., an identity in its contexts) to each other are sorted into different core-domains. In a conceptual system of representation, there are core-domains in different spaces. These core-domains can be related non-randomly to each other because the identities which are studied as figures in core-domains bear part-whole relations or container-contained relations in the physical world. The identities in the larger space often define the contexts of the identities in the smaller space. These identities (which are figures studied in their core-domains) are identified as of different *ontological natures* because of their functional relations to identities in other core-domains.

*Identities of spatial-features* (which are *natural units* on different scales) are important to define an environmental state at time. For the representation of an identity itself, there are the instantiations of *part-whole* or *container-contained relations*. However, for any one of such “identities”, when its relations to other “natural-units” are studied and involved in defining the
state of an environmental setting, such part-whole or container-contained relations do not necessarily link *natural-units* as belonging to different ontological-kinds. Rather, the part-whole relations or container-contained relations as important *relational* or *structural properties* which are knowledge of *identities* to support different cognitive functions. Two cases may be differentiated: The first refers to the case where an identity is examined in the *spatial context* of its core-domain. This spatial context can have multiple objects which bear *spatial relations* to each other. There may also be the *whole-part* relations between the overall state of an identity to the distinctive features of its boundary or to its *internal parts*. While such *spatial relation* and *whole-part relations* can play certain functional roles to the process of identifications or re-identification, they do not necessarily contribute to the ontological distinction of the identity. There is the second case where an identity contributes to the definition of a *spatial context* which goes beyond that of its *core-domain situation*. That is, while the *natural-unit* (which is a natural-unit on a scale) is identified as a *component* for this spatial context, it is either a *particle* which contributes to the “material” content of such a spatial context (e.g., a person to the study of a geographical region) or a general *constraint* (e.g., a person as the container for the *cells*). In this case, the identities on the opposite sides which are connected by the part-whole relations or container-contained relations do belong to different sub-domains of a core-domain.

**Causal relations and causes of existences:** The *causal relations* are defined as one kind of *transformations* in the environment. They are often involved in applications where the transformations overtime are to be modelled. For identities in the *common-sense-space*, they belong to an ontological-kind because they can be interacted differently. However, they also belong to a particular core-domain because they can bear certain distinctive *causal relations* when they interact with each other. For example, for physical objects, they can interact with each other when they meet and the result can be explained by the knowledge of the *causations* for such interactions.

To make further ontological kinds of identities, the patterns of *causal knowledge* learned for identities in the *common-sense-space* can be applied to study the identities in other spaces (where the direct observations may be restricted), as implied in the proposal of *structural mapping* (Gentner, 1983; Gentner and Markman, 1995). Identities can be differentiated based on their *causes* of existences, either natural *cause* or *artefacts*. For identities with natural causes, however, they can be further differentiated. For example, for *natural systems* in the environment, the *conditions* (i.e. the environmental contexts) for the emerged phenomena are consid-
CHAPTER 7. ON THE NATURE AND SYSTEM OF ONTOLOGICAL-KINDS

...ressed as the causes for them. For animates or organisms in general, their causes of existences are from other individuals as parents. Indeed, the causal transformations in general can be relevant for the further distinctions of identities. However, this relevancy exists only when there are the integration of different situations from different space into a generalised domain (e.g., the area of physics in scientific understanding) and then further specialisations of such a generalised domain. Identities in different spaces are then differentiated into the corresponding scientific domains with the general causal constraint is applied. However, there are differentiated causal laws. For example, there are different causal laws for physical entities or phenomena which can be defined on different scales. There are the Newtonian physics for objects in the common-sense-space, the quantum physics for the small world, and the physics for cosmology for the large space.

Relations of states: There is another kind of objective relations which can be defined over two states of an identity or a spatial context. The changes of states of an identity over time are often called processes. Such a process is relevant to describe identities, in particular, those in the large-spaces. However, to study the natural systems in the large-space, there are both the changes of states of the natural systems and the changes of conditions (i.e. spatio-temporal contexts of identities). The sudden changes of states are often called events. For the emergence of certain natural systems or phenomena in Geosciences, the study is either to describe the events or to understand the causal conditions (i.e. the causes). The study of natural causes or conditions for the emergences of natural systems and phenomena has been an important topic in natural sciences.

To study natural systems, a set of variables are often used to describe the states. The changes of states can be modelled by mathematical functions over the measurements for these variables. However, these mathematical functions as models can have different semantics. Specifically, for spatial-features in the large-space, while processes and events are often taken as important properties associated with identities, they can correspond to the relational properties of two different natures. The processes correspond to the functional relations as properties of identities, which involve the measurements to describe precisely the states of the natural phenomena. The states at different times can be measured with the same set of variables. The processes are modelled by the changes of such states. The events correspond to the causal relations as properties

That is, the changes of states as properties, which are important for the re-organisation within an attribute dimension, see Section 8.4.
for describing the interactions of identities with others\textsuperscript{6}. The causal relations are defined with the measurements which describe the conditions for the emergences of the natural phenomena.

### 7.3 On systems of ontological kinds in cognitive systems

The study of ontological distinctions of spatial-features and the study of a system of ontological-kinds for spatial-features are both important for the practical purpose to design of a new SISystem. The situation-based theory can provide a unified account for both issues. The theory is important not only because there is a system defined by the different ontological-kinds of spatial-features, but also because that the representations for different ontological-kinds of spatial features be treated separately.

In this section, three issues will be further discussed. Firstly, the distinctiveness of the cognitive theory in understanding of ontological-kinds of spatial features will be discussed in comparison with the studies of ontological kinds in SISciences. Secondly, the system of ontological distinctions of spatial-features as figures in the common-sense-space will be covered. Thirdly, the system of ontological distinctions of spatial-features as locations in the environment, which is directly relevant for the study of the environment, will also be discussed.

Two points should be noted. Firstly, the thesis has focused on the cognitive principle for understanding their distinctions (including the nature of the complex kinds in the large environmental space). The set of ontological kinds is the by-product of the secondary importance to the purpose of this thesis. Secondly, although the ontological-kinds of identities in the common-sense-space and large-space are treated separately, these two sets of “natural units” share a considerable overlap. The formal schemata developed for the representation of complex objects in the common-sense-space can be adapted for the representation of identities in the large-space\textsuperscript{7}.

#### 7.3.1 On the study of ontological-kinds of spatial-features

The ontological distinctions of spatial-features are crucially important for the representation theory of SISystems. In this subsection, firstly, a brief review of the studies of ontological-kinds of spatial features in SISystems will be discussed. Secondly, the general positions on the

\textsuperscript{6}That is the background part of a situation in case with natural system.

\textsuperscript{7}The generic formal schema for the representation of any identities was discussed in the second subsection of Section 4.3 and the first subsection in Section 6.3.
cognitive understanding *ontological-kinds* studied in this thesis will be given. The differences between this cognitive understanding of *ontological-kinds* and those in conventional studies will be emphasised.

**On ontological-kinds of spatial-features studied in SIScience**

In SIScience, the study of ontological-kinds of spatial-features is a crucial issue for the representation theory of SISystems. A study of representation often starts with the two basic assumptions on the ontological nature of the world (Chrisman, 1978; Couclelis, 1992; Peuquet, 2002). Following the *object-view*, the world is filled with objects which have boundaries. Following the *field-view*, the field of substances can be studied with continuous properties in space-time. The two *world views* directly influence how spatial features are modelled in a SISystem, and consequently how a SISystem is to be designed and implemented in order to accommodate either the *objects* or the continuous properties of the world. The resulting SISystems have *vector* or *raster* or both kinds of spatial data models and can support the representation of *objects* in *vector* format and *fields* in *raster* format (Worboys, 1998).

However, in the recent literature of SIScience and SISystem, the searching of a new representation theory for SISystems has been an important topic (Goodchild et al., 2007; Usery, 1993; Raper, 1996; Mennis and Peuquet, 2000; Schuurman, 2006). On the one hand, there are the practical concerns with the representation in current SISystems. There are not only the needs of 3D representation (Raper, 1989) and handling the changes of representation overtime (Langran, 1992; Frank, 1998; Hornsby and Egenhofer, 1997, 2000), but also the issue of dealing with scales (Oosterom and Schenkelaaars, 1995; Goodchild, 2001) and inherent fuzzy spatial boundaries (Burrough, 1996) for some kinds of spatial features.

On the other hand, there is also the theoretical concern which aims at the adequate of *object* versus *field* views of the world for modelling *spatial features* in the large scale environment (Smith and Mark, 2001; Smith, 2001). In comparison with the objects in the common sense world (such as physical artefacts and animals encountered), spatial features studied in the large scale environment are rather complex (Smith, 2001). For one thing, they often have complex *internal structure*, and the change of scales can be a significant theoretical concern given it may bring the change of identities totally. For example, a city has buildings, and these are in complex configurations to define the physical aspects of a city. For another, spatial features can often
get involved in different contexts of applications. Here, the change of contexts can imply the changes of the functional roles of a spatial feature and correspondingly different representations models (i.e. involving different attributes). For example, a person contributes to the collection of aggregate data over a census tract and the aggregate data is further involved in defining a pattern in the socio-economic landscape. The spatial-features like these are complex kinds, whose representation cannot be accurately captured simply by a geometrical boundary. Indeed, the different ontological natures of spatial-features should be studied and the semantics behind the geometrical boundaries in the representation of SISystems should be treated explicitly.

**The cognitive perspective for the ontological distinctions of identities**

Understanding the ontological-kinds of spatial-features in the large scale environment and the system of the ontological-kinds of spatial-features are both important for SISystems and SI-Science. This thesis provides a situation-based cognitive perspective to understand the system of ontological-kinds of spatial-features, which includes the ontological-kinds of spatial-features in the large scale. In comparison with current studies of ontologies in SISciences (e.g., Fonseca et al. (2000, 2003); Kokla and Kavouras (2001); Frank (2003); Grenon and Smith (2004); Tomai and Kavouras (2004)), there are four clarifications regarding ontological-kinds in this thesis.

Firstly, there is a system of ontological-kinds of identities and it can be explained by the development of a cognitive system. Each of the ontological-distinctions of identities whose representation can be supported by the fourth-level cognitive system can be employed to study the environment. The identities of a distinctive ontological-kind can be studied separately in their core-domains or application-oriented domains. The form of representation can be developed relatively independently from those of other ontological-kinds. While the system of ontological-kinds will be applied to the study of the environment, the representation of the environment is also constrained by this system. In other words, the system of ontological-kinds has implications on what kinds of environmental situations can be represented and how accurate the representation can be which depends on the representation and knowledge of individuals and their core-domains.

Secondly, the inherent functional dimension is taken into consideration for these spatial-features to be treated as belonging to different ontological-kinds. These spatial-features in Zubin spaces do not just define the environment of a person. They have their distinctive func-
tional values (such as buildings for shelter and schools for education of the youths). While there may be different formal schemata for identities of different ontological-kinds, they are specialised from the generic formal schema for identities. For modelling different ontological-kinds, the formal subtypes for characterising situations in general can be assimilated. This means different ontological-kinds can share the same formal structure for descriptions, e.g., the configuration of objects in A-space versus the configuration of landmarks in B-space.

The configuration is a formal type, which can be applied to study natural-units of different natures. Formally, the configuration of the internal parts for an object shares the same formal structure with the configuration of objects in A-space for a location (Humphreys, 1983; Bremner, 1985). The configuration of objects in A-space share the same formal structure for the configuration of landmarks in B-space as environmental settings (Tversky and Hemenway, 1984). There are also the configurations of these environmental settings or neighbourhoods to describe towns or cities which are spatial features in C-space. However, the configurations of parts for objects and configurations for environmental settings or towns may be understood as for the descriptions of the internal contents of identities. The formal schemata for the representation of identities in larger space can also include the descriptions of the figures and their even larger contexts, although these may be less developed.

Thirdly, there are two kinds of restrictions which are often associated with the study of these identities. On the one hand, there are issues of the accessibility to the figures and perceivability of properties to study these spatial-features in the large-space as figures. The restricted accessibility means they may be learned from learning their internal components first. Then, the pictures of the wholes can be constructed. While the states of some identities at a time can be directly observed by using the sensorimotor modalities, the states of other identities are either constructed (e.g., buildings), inferred (e.g., the ore deposits), or defined (e.g., social patterns). Since the states of identities in the large-space are described by the configurations of internal components, the development of representation and knowledge often depends on the ontological natures of these components which define the configurations (i.e. physical objects, buildings, or people). The configuration of building in B-space can be studied when the explicit configuration of objects in A-space can be achieved.

On the other hand, these spatial-features may be studied with formal definitions and then

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8 See Section 6.3.
9 See Section 4.2.
their states in space-time can be examined. Such a case directly depends on the capability to provide formal definitions. These definitions often are applied to study certain ontological-kinds of identities (e.g., natural systems which are studied as 4D entities). However, the ontological distinctions should take into consideration the natures of the properties which are used in definitions (e.g., physical properties and social-economic properties are of different natures). This is relevant for the perceivability of the values of these attributes. In short, for an identity as an individual which belongs to an ontological-kind, the representation is constrained not only by its ontological nature, but also by the state of the conceptual system of its core-domain.

At last, there is a fundamental departure of this thesis in understanding the ontological-kinds of spatial-features from those in current SISciences. In SIScience, the studies on ontologies have emphasised on formal definitions for different ontological-kinds which are considered ontologically prior. Different models of individuals will be the direct instantiations of these definitions. In this thesis, the ontological-distinctions are based on their existences in the world and the functional need to study these identities. They are not distinguished simply based on the formal descriptions for their representation (e.g., configurations). The functional values of identities (to the concern of a person and to other objects in the same or different spaces) are taken into consideration in the first place. Different ontological-kinds can be associated with different formal schemata (e.g., natural systems and environmental settings can be defined differently). However, the knowledge of ontological distinctions of identities can be adaptive. The formal schema adapt with the adaptation of its core-domain and the accumulation of knowledge of core-domain situations.

7.3.2 The ontological-kinds of figures in the common-sense-space

The system of ontological-kinds for identities in the common-sense-space will be discussed in this subsection. For identities in the common-sense-space, which are distinctive in that they can be the targets of actions directly, cognitive development can be associated with the increasingly refined ontological distinctions of identities.

There are four levels of ontological differentiations of identities in the common-sense-space. These ontological distinctions are mainly associated with the differences in terms of the complexity of structural descriptions. There are also distinctive patterns regarding the causal relations of the identities themselves. For identities in the common-sense-space, the most important
ontological distinctions include *stuffs* versus *objects*, *container* versus *contained*, *simple objects* versus *complex objects*, *physical objects* (i.e. non-living things) versus *organisms* versus *people*, and *natural objects* versus *artefacts*.

**Ontological kinds of figures in Level-1 & Level-2 cognitive system**

In the **first-level cognitive system**, two kinds of *ontological distinctions* can be achieved. One is the *self* versus the *environment*. The other is the distinction of the environment in terms of *figures* versus *ground*. However, this second ontological distinction is implicit. The *figures* are portions of the environment which can be acted upon. They can have distinctive parts or materials. The *ground* means two things. One refers to the *surface* (e.g., floors) which can support the self or other objects. The other refers to the general *context* of the environment for all the possible situations where the identity as a figure may be involved.

Identities can be differentiated into *stuff* versus *object* kinds (the two kinds of figures). However, in the very early stage of cognitive development, there are only the sensorimotor based implicit differentiations of *stuffs* and *objects*. One distinctive attribute for objects is the
The explicit distinction of objects with clear boundaries from substances (or called stuffs) is perhaps achieved until Stage IV of the sensorimotor period. According to Piaget, there is the object permanency in the minds of infants when they are about 10 months old. This is about a structural change for the cognitive systems. The empirical data from the studies on object permanency (e.g., Bremner (1985); Mareschal et al. (1995); Munakata (1997, 1998); Thelen et al. (2001)) can support the claim that a significant structural change happens at this period of time. Such a change is not only about an object being understood as an objective existence in the world, but also about the conceptual organisations where identities can be differentiated into substances versus objects. In later period of development, this ontological distinction, which is originally applied to the identities in the common-sense-space, can also be applied to study the identities in the small and large spaces.

However, in stage III of sensorimotor period in Piaget’s study, there is an important function-based ontological distinction of objects into the container-kind (e.g., milk bottle) versus the contained-kind (which can be substances or objects). However, the ontological distinction of objects into container and contained kinds also takes into consideration of different shapes of objects. The container-kind requires distinctive shapes (a concave in 3D) in order to fulfil the functional specification.

In the second-level cognitive system, there is the explicit ontological distinction of object versus stuff, which is based on both formal and functional considerations. Having a clear boundary is not the sufficient property for distinguishing an object from the stuff. An identity which has a boundary can still be treated as stuff. For example, a chunk of cheese is made in a shape, however, it is still considered as stuff. The thing with the stuff is that, from the functional perspective, the shape does not matter much. The functional consideration means that this ontological distinction is not only about the clear boundary, but also whether the boundary is functionally meaningful. The boundaries of objects are understood as important properties.
because of their functional implications. An object is differentiated from the stuff because there are distinctive boundary parts for an object, such as a cup has the body in the shape of a container and a handle. The association of functions with distinctive boundary parts also implies different action schemes can be applied to the objects when they are to be interacted with.

In this Level-2 cognitive system, however, there are two important function-based distinctions of natural-units. One refers to the distinction of identities into targets, means, and locational cues. In Piaget’s theory, infants in Stage V and Stage VI of the sensorimotor period can make such functional distinctions. Identities in the common-sense-space are directly relevant for the actions of a person. However, in an application, they can play different functional roles of being the targets, locational cues, or means. The locational cues indicate where a target can be found. The means are objects used as tools for reaching a target. A target is the goal that is to be reached and acted upon by a person for satisfying the biological needs (how, to use a tool, it has to be reached first and thus they can be the temporary target). Identities of different ontological natures can perform these functional roles differently. For example, organisms such as animates can be the targets, such as food. However, animates may not be the good locational cues for other targets, since they are not fixed to locations and their own positions can often change. Physical objects can be the targets and tools. Physical objects of the container-kind are also good locational cues. These containers are often placed in certain larger and fixed containers, e.g., a box is put in a cabinet in a house. These large containers are relatively larger and could not be handled in hands or shifted into different places easily.

The other function-based distinction of natural-units in the environment corresponds to the identities as 1) the figures, 2) the portions or parts for the contents of the figures, and 3) the contexts for the figures which can refer to either the containers or locations defined in terms of the collections (Markman, 1983) or configurations of objects (Bremner, 1985). The natural-units for the contents and contexts can be studied in their own right in this and later stage of cognitive development. There is also the change from the egocentric to allocative representation of the environment in Piaget’s theory (Piaget and Inhelder, 1956; Bremner, 1985).

The last ontological distinction of identities by the end of second-level cognitive system is the simple versus complex objects. A simple object does not have the separated internal content and the boundary. A simple object is either a container or a contained object. A complex object need to have a container and contained as two components in one entity. It has a boundary and an internal content as two distinctive components. For complex objects which can have
multiple *internal parts*, the *internal parts* can also be treated as *attributes*. The *natural-units* which function as the *internal parts* of *complex objects* can be identities in their own right. The *internal parts* can be represented in the primitive forms (e.g., as single points) or with detailed descriptions (such as with the attributes for *states*). They often bear *causal relations* to other internal parts which contribute to the processes and behaviours of *complex objects* as wholes.

**Ontological kinds of figures in Level-3 & Level-4 cognitive system**

In the **third level cognitive system**, there are the *ontological distinctions* of *physical objects*, *organisms*, and *people* (Carey, 1985; Keil, 1989a; Wellman and Gelman, 1998). In a sense, all objects in the *common-sense-space* can be treated as *physical* ones. However, the *physical objects* can be further differentiated. This level of ontological distinctions of objects in the *common-sense-space* is closely related to the development of *core-domains* emphasised in cognitive literature. The distinctions of *core-domains* are often based on the studies of concepts of different *ontological-kinds*, including *animals*, *non-living things*, and *people*. These ontological distinctions of objects are psychologically meaningful.

For the biological concern of a person, these ontological distinctions of objects in the *common-sense-space* can be based on the different manners the identities can be interacted with by the person. The spatial properties are often important for the reliable categorisations and re-identifications of any objects (Smith, 1989b; Humphreys and Forde, 2001). However, the distinctions of *ontological-kinds* require other criteria and conditions, such as, the possible *self-initiations of actions*, different kinds of *movement patterns*, *functional properties*, and the characterisation of *causations* regarding the patterns of interactions of the individuals themselves. On this **third-level cognitive system**, however, the functional characterisations of identities are not only about their relations to the needs of a person, but to other identities directly (e.g., the relation of a predator and preys). Indeed, there are also the distinguished kinds as *systems*, *organisations*, and *core-domain situations* of *core-domains* in following development. These are identities of complex kinds with consistent internal structure and coherent patterns of behaviours. They are also contexts and constraints for the involved parts.

The structural distinction of *simple* versus *complex* objects is important for the further distinctions of identities of *core-domains*. Physical objects are either the *simple tools* (e.g., chairs or kitchen utensils) or *complex machines* (e.g., television, vehicles, or computers). Animates
and people are both complex objects with *complex internal structures*. To study the complex object, their *internal parts*, the *causal relations* of the *internal parts* to each other, and their contributions to the overall behaviours of the complex objects are all important, which can be achieved at the end of the second stage and the start of the third stage (Carey, 1985). The study of the material contents may also be required in order to understand the “internal structure” and behaviours of the objects in normal and abnormal circumstances\(^\text{10}\).

In the **fourth level cognitive system**, an important ontological distinction for objects in the *common-sense-space* is about *natural kinds* versus *artefacts*. For *natural kinds*, which can be simple or complex objects, the causes of existence are from the processes in nature. The *natural kinds* are embedded in the complicated causal and functional relations of identities in the world. For *natural kinds*, from *simple* to *complex* objects, there are the increasingly detailed *internal contents*. For *artefacts*, the cause of existence is man-made. The artefacts fulfil the functional expectations of people. There are man-made physical artefacts (e.g., simple tools or complex machines). However, even with complex internal structure, artefacts are often well-defined and have fixed *internal structures* which can be complex. Artefacts can be identities in different spaces (e.g., *buildings* and *dams* in B-space). This distinction of natural kinds versus artefacts is relevant to the domain distinction of *natural sciences* versus *applied sciences* or *engineering* (see Section 5.3).

Regarding the **four-level cognitive systems**, more ontological distinctions are applied to the *natural-units* in the smaller and larger spaces. For example, there are *spatial-features* of different *ontological-kinds* in the four Zubin’s spaces of the environment. These *natural-units* in the large space are not only the attributes of the contextual kind for identities in the *common-sense-space*, they are also studied in their own right with distinctive kinds of attributes for their representations. There are also the re-organisations of core-domains into corresponding scientific domains and further development of sub-domains or super-domains\(^\text{11}\).

\(^{10}\)For example, the study on cell levels for the organisms, and atoms and molecules for the physical properties of the material in artefacts.

\(^{11}\)However, the set of individuals covered by the studied *ontological-kinds* of identities in psychology does not precisely match to the set of objects studied in the contemporary scientific domains of physics, biology, and social science, e.g., the identities in the domain of biology can include both *animals* and *plants*. 
7.3.3 The ontological-kinds of locations in the large environmental spaces

From the cognitive perspective, spatial-features as natural units in the environment can also belong to the category of locations, either the locations of the person or the contexts of other objects (such as figures which are biologically distinctive to a person). These spatial-features traditionally studied in the application domains of SISystems and they are the characterisations of the ground in nature (e.g., water for a fish). To study these “spatial-features” as locations in the environment, the formal subtypes have been discussed earlier\(^\text{12}\) However, the formation of an ontological-kind also requires other criteria, including functional consideration and the natures of the substances within the situations as locations.

The identities as locations in the environment are further differentiated into the four Zubin spaces. The set of spatial-features can include the smaller objects in the common-sense-space, such as those objects in A-space and B-space, as well as those in the larger C-space and D-space. However, although the attribute of the sizes of identities can be used as an index or a cue for the discussion of ontological-kinds of identities in these spaces, it is not the criteria for the ontological distinctions. On the one hand, identities in different spaces are of different ontological kinds even though they may share the same formal model of the internal structure. The identities of different ontological kinds in one space only bear distinctive functional relations to identities of certain other spaces. On the other hand, identities in one of the four Zubin spaces are further sorted into different core-domains or application-oriented domains in their corresponding space. These are treated as belonging to different ontological-kinds. Identities of different ontological kinds in one space can be differentiated based on the physical properties and other characterisations of the natural-units themselves.

**Ontological kinds of identities as locations in A-space and B-space**

Spatial-features in A-space are closely related to our daily life. These spatial-features in the A-space of the environment can either be substances, or objects with boundaries, or configurations of objects. Substances refer to things like water, rocks, and other materials. Substances in solid shapes, such as rocks, can be used as locational cues. Objects in A-space can be the figures, tools, or locational cues. They can be differentiated into physical objects, living things, or people. The majority of the physical objects are artefacts. These objects in A-space in general

\(^{12}\)See the second subsection of the Section 4.2. Also see Figure 4.2 and Table 4.1.
are not very good locational cues. However, the configuration of objects at a time can define a location with robust structure. The container kind objects which can be used for holding things can be reasonably good locational cues. When there are multiple objects of A-space, the configurations of these objects can define locations rather robustly. For the concern of environmental representation, the locational cues, containers, and the configurations of objects in A-space are three important subtypes of the ontological-kind of locations.

The collections of objects can form another distinctive kind in A-space. A collection can include different items. These different items themselves are neither too small nor too large and can be handled in hand. The collections of objects or stuffs can be held in some sort of containers which can then be treated as wholes when they were picked up (Wierzbicka, 1984). That is, the collections as wholes can also be handled collectively in one round, such as spoons and forks being held together in one hand. A collection can be formed based on that the common action can be applied to the objects in a collection, such as chopping and kicking. The global categories studied by Mandler (2000a) are some categories in nature. However, the collections of objects can also be defined based on other criteria. For example, there are collections of objects because these objects are in close spatial proximity (Markman, 1979; Markman et al., 1980; Markman, 1983), such as the collection of tables and chairs as furniture. There are superordinates, such as kitchenware, which are collections of items in certain spatial contexts. The collections of objects are also formed because they are embedded in certain events (Nelson, 1986), or share a functional goal (Barsalou, 1983, 1985, 1991) and a person interact with these items in sequences in order to reach the goal.

Spatial-features in B-space can include large independent spatial features (e.g. landmarks, buildings, houses). In the B-space environment, the spatial features as objects often have larger sizes which do not allow them to be manipulated in hands. There may be some spatial-features with natural causes (e.g. caves), but in most cases, objects in B-space are man-made artefacts. For the study of the environment in B-space, from the consideration of sizes only, there is a range of spatial-features can be included into the set of spatial-features in B-space. The emphasised spatial-features are the kinds like landmarks, buildings, fences or barriers, road segments. They are fixed to the ground and are important locations of people and their properties in space.

However, these spatial entities can be differentiated into different ontological kinds because of their functional roles and formal structures. Landmarks are locational cues in B-space. In-
deed, *landmarks* is a functional category. Although there are dedicated constructions as landmarks, such as monuments, it can refer to any entity which can characterise a location or marking a place. Distinctive *buildings* can be landmarks in B-space. However, buildings can belong to the *container-kind* and can be associated with functional roles for being the shelter of people and other objects. As containers, they are functionally similar to the natural ones such as *caves*. However, they are also complex artefacts. Apart from *landmarks*, other functional kinds of *spatial-features* can include *fences* and *barriers* for blocking the flow of people or other objects on the one hand, *road segments* for facilitating the traffic.

From the consideration of size only, a *vehicle* should also be an identity studied in B-space. However, the *ontological-kind* for a *vehicle* is rather complex. They are artefacts in nature and are produced with the consideration of distinctive functions. However, they are also physical systems with complex internal structures. To treat a *vehicle* as a distinctive *ontological-kind*, there are a few considerations. Firstly, a vehicle as a tool in B-space for shifting people or stuffs. In most cases, it can be distinguished from the simple tools because of the complex structure of a vehicle. Functionally speaking, vehicles are similar to other small tools in A-space in terms of its relations to the concern of an ordinary user. For example, as a complex tool, a car can be manipulated by a person in the case of driving. From the point of view of a car driver, a car can be treated as a simple object to be acted upon by a driver. However, they are treated as complex physical systems and studied by the experts who design, make, and maintain them. The different views of the same identity can give different representations for the same entity. Secondly, a vehicle is a B-space entity. They can be the *containers* and locations of people (e.g. sit in a car) or other objects. As a container, it is functionally the same as a building. However, buildings are usually fixed to specific positions over rather longer times. Cars are not fixed to locations. Thirdly, from the consideration of the *internal structures* of a vehicle, it is often a complex *physical system*. In this sense, it is the same as a *television* or a *computer* which are also complex physical systems. However, a vehicle is a distinctive kind of existences in B-space. Televisions or computers are objects in A-space because of their small sizes.

The third *ontological group* of *spatial-features* in B-space refers to the *configurations* kind. For example, there are the road networks, which are configurations in formal structure. The configurations of buildings are also formally the same as the configurations of objects in A-space. The configuration of landmarks and road segments define the internal structure of a city environment. The landmarks or road segments are spatial-features themselves in B-space.
which can be partially perceptually examined. In order to get a full view, a person can walk around it. However, the configurations in B-space are often about locations of people and their activities. That is, the configurations of buildings are often involved as the components for the environmental settings of different kinds, such as households, schools, hospitals, and local government buildings. To study environmental settings of different kinds, two cases are to be differentiated. One is about the configurations of buildings in the physical sense. The other is the associations of such configurations with social institutions. The configurations for different environmental settings are also important for defining spatial-features in C-space, such as a city. A city can be described in terms of configurations of landmarks or the aggregation of some neighbourhoods. However, there is always the social dimension to study a city. For being a real kind, its existence has a natural and a man-made cause (Boyd, 1991; Millikan, 2005).

**Ontological kinds of identities as locations in C-space and D-space**

For spatial features in C-space, there are a few ontological-kinds, including natural landscapes, simple regions, natural systems, configurations, administration boundaries, social-economic patterns, and complex ecological systems. There are two more factors to differentiate spatial-features as natural units in C-space into different ontological-kinds. Firstly, these different ontological-kinds mean they have different corresponding formal schemata for their representations. Secondly, in differentiating identities in C-space, there is also the consideration of whether their definitions can include physical objects, organisms, people, or their combinations.

The majority of the ontological distinctions for spatial features in C-space are for understanding the natural physical environment. Spatial features are not necessarily restricted to the existence on the surface of earth, but can be extended to both beneath and above it. Regarding the spatial features in C-space in the physical environment, the ontological-kinds are 1) the locations in C-space for spatial-features in B-spaces (e.g., the built-up area of a city in terms of the configuration of buildings, or the transportation networks on the state level which is defined in terms of the configuration of road segments); 2) the partitions as simple regions for characterising the earth surface (e.g., the differentiations of soil types and different landscape types, e.g., mountains, valleys, rivers); 3) distinctive natural systems of the natural environment (e.g., ore deposits for mineral resources or water catchments) which are relevant to the study of the physical environment; 4) there are phenomena or events which are natural systems in nature but
they are functionally crucial to the life of an organism or a person and those of a population (e.g., floods, earthquakes, forest fire, volcanic eruptions, tornado, and the change of coastlines over time). For these spatial features in the C-space, the accurate descriptions of their states are directly relevant to their representations in SISystems. However, the condition of existences and processes are also important research issues. Such knowledge can be included in the formal schemata for the representation of these spatial-features.

There is also the region-kind spatial-features to characterise the environment with a formal subtype of a region. They are characterisations of the earth surface and different areas can be characterised with a set of variables. The variables are from one of the domains, such as the variables to describe the physical or the social environment exclusively, thus they are also called simple regions. The first group refers to a simple kind of region for the physical environment. For example, in geography, there are types of land use into generalised categories for large scale maps. In geology, there are the so called provinces which are the regions for partitioning the earth defined with geo-chemical characterisations. The two examples of regions are defined with physical variables only. The simple regions, such as land-uses or soil-types, are often taken as spatial-features in C-space.

The second group refers to spatial patterns studied in social geography. Spatial patterns (e.g., patterns of crimes) for certain occurrences are defined with the occurrences of certain types of people. However, the study of such a pattern can involve spatial features on different scales. For example, the study of the epidemic pattern of a disease is about the spatial pattern in C-space which is defined with the occurrences of people who have the diseases in a particular time period. Such a pattern may involve spatial-features in B-space if the emphasis is to examine the kind of environmental settings (such as a part of the city) where a case can be easily found. A spatial pattern can also involve spatial-features in D-space if the emphasis is to study the social-economical causes.

Apart from spatial-features which belong to the physical environment or simple social patterns of occurrences, there are two other groups, which correspond to the environmental situations which are defined involving identities from the biology or social domain respectively. However, such systems or organisations often attached to certain physical environment. For example, there are ecological systems, such as the habitats and the niches of a species studied in ecology. There are also social organisations (e.g., the neighbourhood or other social organisations of different but specific functions) in the social environment.
The last ontological-kind for spatial-features in C-space is about the social environmental boundaries or the environment of a human being. They are the complex environmental settings in nature and can be defined with considerations of both physical and social variables. For example, there are settlements of different sizes, from villages, towns, cities, to metropolitans. They are relevant for the study of the human environment in C-space and urban development in human geography. The complex systems may be considered as identities in C-space if only these patterns or individual existences are defined over the scale for identities in C-space (e.g., a particular urban environment). However, they are spatial-features which bear close relations to the study of regions in D-space. There are complex interactions of humans with the physical, biological, and social environment. To study natural units of this kind, both physical and social variables are taken into descriptions.

Spatial features in D-space belong to the kind of complex regions because they are the “containers” for humans, their activities, and all the artefacts they have created. However, the contexts of a person can be variously defined which extend into different spaces. Thus, regions as the contexts of a person can be defined on different scales and in different spaces. The environmental settings in B-space can be understood as regions. There are also regions which are defined in the C-space which can include neighbourhoods, cities as wholes, census tracts, and electorates. However, regions are often understood as special situations in the environment which are the (indirect) contexts of a person. They have extended from the cities in C-space to reach to the geographical regions where ethnic groups of people live and there are countries and other large scale administration boundaries. Spatial-features as regions in D-space are often restricted to refer to these ethnic regions, political boundaries, or other social-economical patterns appeared in the large scale environment.

As contexts of a person, these situations are complex ones and each of the situations can have at least two parts. One is the figure and the other is the ground or the container of the figure. As the container of a figure, the background region can also be defined differently if there are other identities which can be distinguished from the ground. Indeed, there are two reasons which render the study of a region much complicated. Firstly, those identities which are involved in the ground part can be defined over different scales. A geographical region can involve identities which bear spatial, temporal, functional, and causal relations to each other. A region in D-space can also have internal structure defined with spatial-features on different scales. For example, to study the demographic patterns and regions studied in social geography,
census tracts are taken as the units for being the data supports. However, a census tract itself is an aggregate of individual data. Usually, “regions” in D-space do not pose direct constraints on the activities of a person in daily life. To the life of an individual person, the relevance of changes in the ground part of regions exists only indirectly. However, these large scale environment can be variously defined and involve identities in the smaller space.

Secondly, a geographical region, such as a country, can be described or defined with attributes from physical, social, and economical dimensions. Geographical regions in general may be taken as the environment characterised with social organisations of different kinds which are strongly attached to land. These identities in D-space can be defined with physical variables, social variables or both. That is, the environment in general can be differentiated into the physical environment, biological environment, the social environment, or their combinations. The region kind of spatial-features, in particular those in D-space, may be restricted to those which involve the combinations of the physical, biological, and social environment. Inside a region, there are complex relations of physical entities, other organisms, people, and natural resources.

7.4 Summary

The chapter addressed two main issues. Firstly, it restated the realist’s position that the nature of ontological-kinds of identities refers to the existence of the identities in the world. While the distinction of identities into ontological-kinds is ultimately determined by their existences in the world, there are also cognitive criteria for understanding different ontological-kinds. The functional roles, structural constraint, formal characterisations, and objective relations were discussed for developing the empirical cognitive rules of ontological-distinctions.

Secondly, the structural constraint of an ontological-kind on representation is directly associated with whether or not an identity can be explicitly represented at a particular level and stage of cognitive and conceptual development. The difference between the study of ontological-kinds in this thesis and ontologies in SIScience were clarified and emphasised. The chapter also discussed separately the system of ontological-kinds of identities which are figures, i.e. targets of the actions of a person, and the system of ontological-kinds of identities which are location kind, i.e. the characterisation of the ground.
Chapter 8

On ontological nature as the constraints on the descriptions of identities

8.1 Introduction

For modelling the representation of identities, there are both the structural and formal constraints to be taken into account in the first place. Indeed, for the representation of identities, the system of ontological-kinds and the formal schemata of ontological-kinds are two theoretical issues to be addressed by a cognitive theory. Practically, the former is related to the specification of an information architecture with the constraint that a system of ontological-kinds for identities should be supported. The latter is relevant for studying the formal constraints of ontological-kinds and their core-domains. This chapter will focus on the formal constraints on identities. The four factors, kinds, levels, details, and forms, will be discussed.

Section 8.2 will provide an overview of the constraints from the conceptual structure upon the representation and knowledge of identities. For the models of identities with attributes, vertically, there are four conception levels. Horizontally, there are three functional components of representation. They are representations from sensorimotor experiences, the knowledge of the boundary conditions, and the knowledge structured in formal schemata to support inferences of attributes for different applications. These components should be treated separately. However, they are integrated in applications. Issues related to the knowledge of boundary conditions for basic-level-categories were also discussed.

Section 8.3 covers the constraint from the state of a core-domain on the formal schemata for the knowledge of identities. The representations are determined by the ontological nature of identities and states of core-domains which are constrained by the development of conceptual systems and their applications to the core-domains. Regarding the knowledge of identities in terms of formal schemata, three factors, kinds, levels and details will be discussed. These con-
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Constraints are important for understanding the states of possible models of identities and potential adaptation of the models.

Section 8.4 is about the factor forms on the knowledge of identities. The factor of forms is about the exact forms which can be given to the interpretations of the attributes involved in the representation of identities. The attributes which are involved in the descriptions of identities are of different ontological natures. There are also different ways to interpret the attributes.

8.2 On representation and knowledge of identities in conceptual structure

The representation of an identity in mind is inherently constrained by the development of a cognitive and conceptual system as a whole. The constraints are from the structural changes as well as experiences of other identities. The constraint of ontological nature of an identity on the representation of identities can be differentiated into structural and formal constraints. The structural constraint of the cognitive system is about, at a given state of a cognitive system, whether or not the existence of an ontological-kind can be explicitly represented in its own right. It is directly relevant for whether an identity can be studied explicitly in the context of a specialised core-domain and as a member of an ontological-distinction. For further understanding the structural constraint from the conceptual system of a core-domain, the effects from the vertical and horizontal dimensions of conceptual systems will be studied. These are the focused points in this section.

8.2.1 Conceptions of identities in the conceptual structure

For the concern of modelling conceptual structure of a core-domain, there are two kinds of relations which are to be maintained: Vertically, there are four conception levels (see Figure 4.5) and the relations of conceptions on different inclusive levels for the same identity must be kept. The conceptions of the same identity on different inclusive levels can be related to

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1 See Chapter 7.
2 See Sections 4.4, 6.2, and 6.3 for the discussions of these two dimensions of the conceptual structure for situations in general, for the development of causal knowledge of a core-domain, and for the development of representation of an identity within a core-domain.
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each other. A range of attributes can be involved in the representation of an identity. Some are relevant for sorting an individual into an ontological-kind, others for a basic-level-category, or the particular individual.

Horizontally, on each of the four conception levels, there is a set of classes for the identities to be classified into. Ideally, these different classes on each of the conception levels should be mutually exclusive from each other. This mutually exclusiveness should be applied to the relations of different ontological-kinds, the relations of different basic level categories, the relations of individuals in space-time, and the relations of states of identities (at a time) in an environmental state (however, states of identities from different spaces can bear topological relations to each other). The different groups on one conception level are made mutually exclusive to each other for the efficiency in sorting the states in the environmental input.

To handle the relational constraints from the conceptual system, the separate models for the representation of identities in terms of states and transformations, the knowledge as the boundary conditions on different inclusive levels, and the knowledge of formal-schemata on different conception levels are crucially important.

**On maintaining the relations for an identity in the conceptual structure**

The vertical and horizontal dimensions to understand the conceptual structure of a core-domain are established in the development and applications of the core-domain. Generally, identities and causal knowledge of core-domains are to support the models of applications where the identities are involved as elements. Vertically, the states of existences (which are yet to be identified) in the environmental input have to be sorted into classes on each of the conception levels. Horizontally, there are causal rules as knowledge of the boundary conditions. They involve the associations of relevant attributes and use them for classification. These causal rules for identities may adapt, in particular with a changed set of basic level categories.

Two processes are to be taken into consideration in order to maintain this connection of conceptions on different inclusive levels for the same identity. Bottom up, in processing the perceptual input and with the knowledge of boundary conditions for identities on different inclusive levels, the state of an identity at a time is discriminated, identified as an individual which is also a member of an ontological-kind (i.e. identification), categorised into a basic level category (i.e. categorisation), identified as a distinctive one and sometimes re-identified as a
new state of an old individual (i.e. re-identification). This whole process of identification is differentiated into several steps.

However, in most applications, classification is not the final target. It is only for establishing the conditions for the inferences of knowledge. Top-down, when the state of an identity is sorted as belonging to a member of an ontological-kind, the general knowledge about the ontological-kind can be inferred (including the knowledge of other individuals as members of them). When the state is recognised as belonging to a particular individual which had been learned in the past, other states of the individual and the different descriptions of states of the individual can also be associated. The (recalled or inferred) knowledge of an identity can support other applications of the identity.

There are not only the formal schemata for the knowledge of the identity on different inclusive levels, but also the inherent relations of such knowledge since the state of an identity can be classified into a group on all four different inclusive levels. From the ontological-kinds, to basic-level-categories, to individuals, and states of the individuals, there are increasing kinds and number of attributes to be added. The understanding that an identity belongs to a particular ontological-kind can lead to the understanding of the formal schema with the sorts of attributes for the identity. The knowledge of identities on the more inclusive levels can support the inferences on what can be the added information for categories and individuals. The formal schema of an ontological-kind constrains the exact representation of an individual, i.e. with relevant attributes for the representation of the identities.

For an application, both processes are involved. On the one hand, to schedule an application, it will depend on the knowledge of ontological-kinds, basic-level-categories, or individuals. Thus, the instances of such ontological-kinds, basic-level-categories, or individuals can be judged on whether they can satisfy certain expectations. The physical contents and spatial characterisations of identities often determine the functional roles. The inferences of certain properties can be based on the knowledge of ontological-kinds and basic-level-categories, other identities which are members of the same group, and the past states of a particular individual. On the other hand, the involvement of an identity in an application will depend on locating it (thus the knowledge of its location or the common locations of its kind can be used directly) and the processing of the state of an identity in the environment. The state will be assimilated to an individual as a member of a category. If the state is re-identified as the new state of a known individual, the past states of the individual can also be involved to assimilate the new state in
the environment.

### 8.2.2 Individuals as members of basic-level-categories and ontological-kinds

Regarding an individual, there are two senses. Firstly, an individual means a particular existence in space-time which can be examined in sensorimotor modalities directly. It can be linked to the representation of a sequence of states and transformations over certain periods of time. Each of the states can be described with a set of attributes for it as a figure, the content, and context of it. Secondly, an individual can also be known as a member of a kind and inherit the properties belong to the kind. Regarding the explicit knowledge of an individual, the knowledge of *boundary conditions* and knowledge of *formal schemata* should also be treated as two separate components. The knowledge of *formal schemata*, i.e. the *causal conditions* on different conception levels, stores the information to support inferences.

Below discussion will cover the *formal schemata* for individuals and *boundary conditions* for basic-level-categories. The knowledge in terms of *formal schemata* for individuals should be treated separately from the formal-schemata for ontological-kinds and basic level categories. The knowledge of formal-schemata for ontological-kinds and of basic-level-categories will be studied in Section 8.3. Within the context of a core-domain, regarding the causal rules for setting the *boundary conditions*, the knowledge of *boundary conditions* for classification into basic-level-categories should be treated differently from the knowledge for identification and re-identification of individuals.

#### On knowledge of individuals as existences and members of classes

The knowledge of individuals has two components. These two components of an individual should be treated separately. One links to the representation of an identity as being a particular individual in situations in space-time. As a particular, an identity refers to a *natural-unit* which is an independent existence in its own right. The other is linked to the knowledge of an identity as a member of an ontological-kind and a basic-level-category. The knowledge of an ontological-kind and a basic-level-category allows the identity to inherit all the general knowledge about such a kind and a category.

An identity as a 4D existence can have a unique distinctive position in space-time, i.e. exists
in space and lasts over time. The *representation* of an identity is essentially determined by the development of cognitive structure and sensorimotor experiences with the identity. The representation of an identity starts with the conception of it as an objective existence in the world (i.e. object permanency). The knowledge of an identity as an individual in space-time is associated with the representation of a sequence of *states* in spatial contexts at different times and various kinds of *transformations* of this identity (e.g. processes and distinctive events). The state at a time is described which can involve different aspects of it. It has a particular boundary in space-time. The *knowledge* of an identity can include certain situations in the world as its contexts. The representation can be in the form of raw data, or in the processed forms. For example, the shapes are described in Geometrical forms and the representation has become the knowledge of an individual. In short, these states and transformations can be described with different levels of details. If an identity is re-identified, the knowledge of it as a particular individual accumulated in the past can be incurred and used for cognitive functions if required.

As a member of an ontological-kind and of a basic-level-category, the formal schemata of an individual can be constrained by the formal schemata of its ontological-kind and its basic-level-category. An individual can inherit the formal schemata. For example, the knowledge of physical properties to support applications can be derived from such general knowledge. While the *formal schemata* for the representation of identities as individuals can be derived from the sensorimotor experience directly, it is also compromised by the formal schemata for an individual from the instantiation of a kind. The latter will constrain the perceptual examination and consequently the representation of the individual.

However, the representation of individuals also contributes to and constrains the understanding of an ontological-kind and a category in that the empirical knowledge of an ontological-kind or a category is learned by generalising the representation of all identities which are members of an ontological-kind or a category. Such a position agrees with the cognitive theories which propose the representation of a category can be about the examples or prototypes (Brooks, 1978; Rosch, 1978; Nosofsky, 1992). The representation of a category can point directly to the examples in the world, or they are associated with the perceptual based representations of these examples. The representation of these examples either stay as *individuals* or are generalised into a *prototypical form*. Regarding the formal schema for the representation of a basic-level-category, it is also a specialisation of the formal schema of an ontological-kind.

There is a third case associated with the knowledge of an identity. That is, an individual is
often associated with a set of attributes or properties for its descriptions. This case is possible when children can learn in a language environment. The language descriptions for the representation of individuals can be used for classification. In cognitive literature, there is a second type of examples and prototype based theories (Smith and Medin, 1981). In this group of example-based or prototype-based theories, examples and prototypes are described with properties and attributes. That is, the representation of identities (as examples) is in terms of descriptions with information about the figures, contents, and contexts. According to Smith and Medin (1981), the descriptions of examples or prototypes can include both defining and characteristic attributes. However, the descriptions with attributes may be better considered as the knowledge of identities or categories in terms of formal schemata, which can support inferences and further applications.

Another issue is that these examples in descriptions are often known as members of certain ontological nature. This means that only certain knowledge about the individual can be relevant and thus described (Dienes and Perner, 1999; Millikan, 1998b). The properties of an individual which are meaningful for the concern of applications of the identity are collected under the direct influence from the knowledge of an ontological-kind. The development of knowledge of identities is studied in their corresponding core-domain and among other members of an ontological-kind. The knowledge of an identity as an individual is a member of an ontological-kind and linked (i.e. there are pointers) to an ontological-kind at least, and sometimes a member of a basic-level-category of its core-domain. The basic-level-category which an identity may be assigned to often depends on the state of knowledge of the core-domain. The set of basic level categories can change when there are more experiences and conceptual re-organisations.

**On knowledge of boundary conditions of categories**

The knowledge as causal rules supports the identification, categorisations, and re-identification of an identity as a particular. The causal rules in nature are about the knowledge of the boundary conditions for these classes (which are within certain contexts, e.g., basic-level-categories are within the context of an ontological-kind). It refers to the models of the relations from attributes, to ontological-kinds, to basic-level-categories, to individuals. The knowledge of attributes of identities can be involved for these cognitive processes. General issues related to the development of causal rules for boundary conditions of different groups on the conception of
categories will be briefly discussed.

The different conceptions on the same level for different groups of identities can be associated with sorting them into mutually exclusive groups, however they are not the boundary conditions. The knowledge of boundary conditions of the groups of identities is to facilitate the classifications of identities into the classes on each of the conception levels. There are always two sides in developing such causal rules. One is from the empirical sides where such rules are derived from the generalisation of the examples which belong to a class. The other is from the functional rule which expects mutually exclusive class for sorting the states of individuals at all levels of conceptions.

The knowledge of identities in terms of causal rules refers to the boundary conditions which are pragmatic ones, rather than defining these groups either. Thus, the development of basic-level-categories, which are not only mutually exclusive but with highest cue validities and category validities, will also be emphasised. Regarding the boundary conditions for different groups on the same inclusive level, firstly, the attribute dimensions will be searched in order to find the one which can have different values for different groups. That is, the causal rules will include the attributes which maximise the differences of identities in the different groups. Secondly, these causal rules, which will divide the identities into a set of groups, can change. If there are different values for the alternative groups along an attribute dimension, these values can be used as the rules for categorisation. The mutually exclusive relations of different groups on the same conception level can also be maintained because different values for different classes.

While categorisation can be based on similarity to the known example, the meaning of the rules in rule-based systems is about the boundary conditions for distinguishing categories. Indeed, in rule-based theories, the emphasis is on the cognitive function of categorisation, rather than representation. However, the rules are probability rules rather than logical ones. They are based on the descriptions of the examples of categories. That is, the rules are empirically based and learned in different manners in different theories. In the context of this thesis, they are boundary conditions for basic level categories of an ontological kind. The finding of a relevant attribute dimension and searching for the different properties for the reliable categorisations of identities is an inherent constraint on representation. This idea is the same as the idea proposed by the neo-essentialist’s theory (Medin and Ortony, 1989; Gelman, 2004). The formal

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3Such as either in enhanced associations (Estes, 1986) or in an explicit category rules (Bruner, 1957) which test different criteria systematically.
schemata for such a kind of knowledge of a category emphasises distinctive features, either parts or properties. The usefulness of such features can be evaluated depending on their functional effectiveness. Thus, the development of an efficient categorisation rule is often determined by all identities to be sorted as well as what are other categories which are to be differentiated from each other.

The use of concepts in Piaget’s studies is often interpreted as about necessary or sufficient properties (Sigel, 1983). However, it is about the capability to develop the rules (with sufficient properties) and conditions (to necessary properties). In the context of sorting identities of an ontological kind into mutually exclusive basic level categories, the intensional definition is possible. In this context, a concept is about the properties that the members within a category must have and the members of other categories do not have. It is a functional understanding. There are different attributes which are emphasised and included in the rules for the boundary conditions. They are defining attributes in that the attributes which are possessed by the members of a basic level category are not the same as those in other basic level categories, even though all these basic level categories can share an even large number of properties.

8.3 On factors as constraints on the formal schemata of identities

A formal schema is essentially about what kinds of domain-specific attributes can be involved to study identities of the core-domain. Attributes which are included in the formal schemata of representation are because of their existences and their significant cognitive values of uses. The knowledge of identities in terms of formal schemata are constrained by their ontological natures and the development of knowledge of their core-domains, which will be discussed separately.

Specifically, three kinds of constraints will be discussed, which are called the factors of ontological-kinds, levels, and details. The constraint of an ontological-kind is an inherent constraint on the representation of individuals from their existences. The formal schema of an ontological-kind, which is the knowledge of such existence, has direct implication on what information can be given to the identities which belong to an ontological-kind. The last two are from the states of core-domains on the representation of individuals.
8.3.1 The constraint from the ontological natures

The factor of ontological-kinds as the constraint is a complex issue. In the general sense of ontological-kinds as the constraint, the representation of an identity is inherently constrained by its ontological nature in that ontological nature constrain the possible sensorimotor experience with such an identity as a member of an ontological-kind. An identity belongs to an ontological kind whether or not the ontological-kind for the identity may be known explicitly or not. An explicit idea of ontological-kinds for identities of spatial features is an important cognitive achievement.

In the specific sense, the knowledge of an ontological-kind for an identity implies the possible form of representation for the identity (Millikan, 1998a) and different patterns of inferences of properties (Keil, 1989a). Thus, the study of the constraint of ontological-kinds is important for the purpose of constructing models of identities. The formal schema of an ontological-kind is the constraint on the contents of representation of an individual in terms of what kinds of information can be involved to define an identity which is a member of an ontological-kind. The knowledge of an ontological-kind is about the formal schema which can be applied to all identities as members of the ontological kind. However, the formal schema as the knowledge for an ontological-kind can be further enriched to represent basic level categories and individuals.

The knowledge of ontological-kinds in terms of formal schemata

The ontological-nature poses the important constraint on the representation of identities. Three issues related to the formal schemata of ontological-kinds should be clarified. Firstly, the knowledge of an ontological kind is a different issue from the knowledge of the criteria of the ontological distinctions. The nature of ontological-kinds and cognitive rules for the distinctions of ontological-kinds were discussed earlier\(^4\). The knowledge of an ontological-kind means a formal schema which pose constraints on what kinds of attributes can be applied to study an identity as a member of the ontological-kind. There are different formal schemata for different ontological-kinds. This knowledge of a particular formal schema can be inferred once identities are classified as belonging to an ontological-kind.

Different understandings of criteria for ontological distinctions may result in different sets of ontological-kinds. In this thesis, the ontological nature of an identity is about the distinctive

\(^4\)See Section 7.2.
existence of an identity in a spatial-temporal scale. The natures and locations of such identities mean that they bear distinctive functional relations to a person or other identities in the environment. The rules for sorting identities into different kinds are explained by cognitive factors. The explicit distinctions of ontological-kinds can be known when there are different patterns of representation for their representations (Humphreys and Forde, 2001). However, while the empirical cognitive criteria can be used for the classification of ontological-kinds, the ontological-kinds of identities are determined by the nature of existence. The different formal schemata of representation are not the causes for ontological distinctions. It is the existence which poses constraint on what form of representation can be given to the identity.

Secondly, the formal schema of an ontological-kind is also a different matter from the formal schema for the representation of an individual. If an ontological-kind is taken as a category, each of the individuals which are members of the ontological-kind can be seen as an example which can be pointed to. The knowledge of an ontological-kind in terms of a formal schema bears a close relation to the representation of identities as individuals (which are members of the ontological-kind). The formal schema is directly associated with the possible sensorimotor schema to experience these examples. However, the knowledge of an ontological-kind in terms of a formal schema is not a generalisation of the representations of individuals, but an inherent formal constraint on the representation of all individuals as its member by prescribing certain kinds of information can be available while other kinds are not (Millikan, 1998b). Even if none of the examples has been learned, the general formal schema as the constraint can still exist.

The representation of an individual as an instance of the formal schema of an ontological kind is in the sense that it shares the general pattern for all identities of the same ontological-kind, but there are also extra characteristics belonging to the individual. For example, while the formal schema of an ontological kind can have three components with descriptions for figures, contents, and contexts, the formal schema of an individual can have extra components added to it, such as there are smaller parts (e.g., cells) for the internal parts (e.g., organs) of an object (e.g., an organism). For the representation of an individual, it is constrained by the formal schema of an ontological kind (which is indeed a constraint applied to all identities as members of the ontological-kind).

Thirdly, the kind of relationship between the formal schema of an ontological-kind to the formal schema of an individual is significantly different from the relationship between an ontological kind and the individuals as the instances of it in current literature of knowledge rep-
representation and in the study of ontologies in SIScience and SISystems. In such studies, for the representation of an ontological kind, a fixed formal schema is constructed, which can be derived from the generalisation of the empirical knowledge of the individual examples. The representation of an individual is a simple instantiation of the formal schema as the definition of an ontological kind. The relationship between an ontological-kind and an individual is a simple is-a relation.

In this thesis, an ontological-kind and an individual which is a member of the ontological-kind bear the relationship between a container and a contained element. For one thing, identifying the ontological nature of an identity is a different issue from assigning a formal schema for it. The knowledge of the formal schema for an ontological-kind can change, but the ontological nature of an identity can stay. For one thing, the specification that there is a distinctive ontological-kind for certain spatial-features (which means adding a distinctive node to the model of cognitive structure) is a different issue from the specification of a formal schema for all identities which can be sorted into this ontological-kind. For another, while the formal schema of an ontological-kind and the formal schema of an individual bear certain inherent relations, this relationship is a different kind, rather than a simple instantiation of a definition. While in general, the formal schema of an ontological-kind constrains the development of the formal schema of an individual (which is a member of the ontological-kind), it can also be specialised into the formal schema of an individual by adding new components to it, such as by adding new information about parts of a part.

8.3.2 The constraint of core-domains in terms of levels and details

The constraints from core-domains on the representation of individuals are termed factors of levels and details. The factor of levels on the representation of an identity is directly related to the development of a set of basic-level-categories for a core-domain. The factor of details is about the representation and knowledge of individuals which are studied in different situations and applications.

The constraint from the development of basic-level-categories

The representation of an identity is developed within a core-domain. The development of the set of basic level categories of a core-domain for the identities is an important factor. The
representation of an identity is influenced by the knowledge of it as a member of basic level category of a core domain.

Identities in a core-domain can be sorted into their basic-level-categories. Identities within a basic-level-category will share more perceptual and functional similarities than the identities from different basic-level-categories but of the same ontological-kind. Once an identity can be properly categorised, the representation of an identity is constrained directly by the basic-level-category it belongs to. The knowledge of a basic-level-category includes the properties which can allow their accurate categorisation. For an identity as a member of a basic level category, certain knowledge (i.e. relevant attributes and properties) about the identity can be reliably inferred from the general knowledge of the basic-level-category or from other members which belong to the same basic-level-category (Rips, 1990; Sloman, 1996). The inferred knowledge about it can allow the judgement on whether it can be included in various kinds of applications.

The set of basic level categories for a core domain is important index for the state of representation and knowledge. However, the development of basic level categories and the adaptations of the set of basic level categories for identities are possible, which are influenced by three factors. Firstly, they are influenced by the direct experience of identities of the same core domain. This is either because there are the increased numbers of identities of the same core domain which are to be differentiated and represented. Or there is the enriched set of information about these identities with the adoptions of new technology (for example DNA techniques for studying species of organisms). The set of basic level categories is contingent upon the exact experiences with identities of core domains and the core domain specific situations. The exact set of basic level categories and the boundaries of basic level categories of identities are constrained by two functional constraints.

Secondly, it is about distinguishing all the identities which are experienced and the examination of all applications where these identities have been involved and will continue to be involved. Thus, the suitable organisations of representation can support categorisations and meaningful inferences in order for the identities to get involved in similar applications. The re-organisation is for fast retrieval of the knowledge about them. The quality of the conceptual system of a core domain lies in its capability to minimise the effects from the potential changes. However, the current knowledge of identities may be updated when the changes are to be assimilated in their core domains with a new set of basic level categories. The change of conceptual structure may also be related to conceptual re-organisations with more levels added.
CHAPTER 8. CONSTRAINTS ON THE MODELS OF IDENTITIES

Thirdly, the exact set of such basic level categories is related to the experiences with a number of identities in a core domain which are learned with certain functional expectations. The experiences are related to two functional constraints. One is that the set of identities in a core domain which are perceptually examined should be perceptually distinguished efficiently. The other is that these perceptually differentiated identities should be functionally distinguished as well. Basic level categories are with highest cue validities and category validities. However, regarding the category validities, it is not only about reliable inferences, but also functionally meaningful inferences. The development of the conceptual systems of a core domain can be driven by the factor of experiences only when new distinctive individuals cannot be assimilated into the existing set of basic level categories. This reorganisation is usually based on the consideration of the distinctive physical and spatial properties.

On the details of representation of individuals

An identity is a particular existence in space-time. The factor of details is associated with two sets of representations. Firstly, the factor of details is related to the representation of an individual identity as an existence which appears in certain situations in the world in the past experiences. There are descriptions of the identity structured in its formal schemata.

Secondly, the constraint of details is related to the knowledge of the identity which can be involved in different uses and applications. The representation is developed in a situation as the direct context of the identity. Such a situation as the context for an identity can be defined in terms of multiple identities which bear certain spatial, temporal, functional, and causal relations to each other. The knowledge of an identity can include more or less information about such situations. These situations themselves can be differentiated into those restricted to the core-domain situations and others. The four kinds of category systems can be involved to represent such situations\(^5\). The representation of these complex situations themselves can also have direct implications on representing further applications.

The representation of identities as existences in space-time can be quite different from the representation of them which is needed for particular applications. In an application, only certain information will be necessary. The suitable form of representation of an identity is to be

\(^5\)See Section 6.3.
judged in the context of applications. In a sense, the ontological nature of an identity in representation in mind and the ontological kind an identity is treated as in a particular application shall be distinguished. An object may be treated as a different ontological-kind in a particular application. For example, the objects with boundaries may be treated as stuffs if only the values of the physical substances is emphasised. In a navigation task, a biological entity can be treated as a physical object to avoid collusion with. A person is a physical object, an organism in biology, a member of social groups, and a sort of “particle” for the census tract in demographic studies. The ontological differentiation of spatial features is to be studied and is meaningful only when the representation of an identity in a core domain should not be confused with the representation of the identity in an application.

8.4 On modelling knowledge of identities with attributes

For the representation and modelling identities, the issues are what kinds of attributes can be associated to what identities as well as how these attributes can be interpreted formally. The first issue is not only about that identities of different ontological-kinds can have different kinds of attributes, but also about how the attributes of the same identity are differentiated and associated with the formal schemata for the conceptions on different inclusive levels of the same identity\(^6\). The second issue is about the constraint of forms on the representation of identities. Attributes of different natures can have different formal interpretations. In this section, these two issues for the models of identities will be further discussed based on theories on the adaptation of the attribute structure for the representation of identities.

8.4.1 On data schemes for modelling identities with attributes

The structure of attributes develops to support the representation and knowledge of identities. Firstly, the distinction of attribute dimension versus the values along an attribute dimension is emphasised. The dimension of an attribute defines a domain. The values of attributes are recorded differences along an attribute dimension. Two other distinctions of attributes, integral

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\(^6\)The generic formal schema for the representation of all identities was first formed in Section 4.3 and it was also discussed in Section 6.3. The differentiated formal schemata for different ontological kinds were examined in Section 7.3 and Section 8.3. However, conceptions on different inclusive levels are also associated with distinctive formal schemata.
versus separable (Garner, 1974) and feature versus dimension kind of Garner (1978) will also be discussed. The perception of values and the conceptions of attribute dimensions are of different processes. For developing attributes, indeed, the two mechanisms of changes can be applied. One is from values to an attribute dimension. The other is from attribute dimension to the re-organisations of values.

Secondly, Garner’s theory of attributes allow the relational link of conceptions on different inclusive levels of an identity to be established. The attributes in the formal schemata for ontological-kinds constrain the attributes in the basic-level-categories as well as in the individuals. While the representation of identities can be learned directly from experiences with the identities, the selected attributes which are to be examined are constrained by knowledge on different inclusive levels. The selection of attributes for an identity will be constrained by the knowledge of the ontological-kind, the basic-level-category, the individual, and the past states or other information about the individual.

**On attribute dimensions and values along an attribute**

The representation and knowledge of identities involve attributes, which are special kind of categories. Attributes are relevant for different cognitive functions, such as re-identification of identities and supporting reasoning for applications. There are a few distinctions of attributes in cognitive literature, which should be covered here for understanding the structural changes.

Firstly, the dimension of an attribute and the values along an attribute dimension shall be differentiated. Formally, an attribute dimension (e.g., colour) is about a domain. According to Garner (1974), the attribute domains can be differentiated into two kinds, integral and separable. An integral attribute is a domain where a value is defined in a space involving several dimensions working together, such as colour involves hue, brightness, and saturation. The change in the length of an object can lead the change in thinness, such as studied in Piaget’s conservation task (Elkind, 1969). A separable attribute is a domain which is relatively independent from other attribute dimensions (such as weight). Regarding the description of identities, if an attribute is involved as a domain, it is often relevant for the representation and differentiation of identities into ontological-kinds and basic-level-categories, such as the attribute of shapes as a dimension is relevant for the representation of objects with boundaries.

The values of an attribute (e.g., red) is about the position of a property in the space of
an attribute dimension. According to Garner (1978), based on the values of attributes, the attribute can also be differentiated into two kinds, the *component kind* with values of *presence or absence* and the *dimension kind* which can have multiple values (e.g., very long, long, medium, short, very short) or numerical values. Regarding the descriptions for identities, the component-kind attributes are more relevant to categorisation which classifies identities into basic-level-categories. However, the different values of the dimension kind are often relevant for indicating either different individuals or changed states of the same individual. That is, the *state* in perception can be conceived as of a new individual (which is a member of a kind) or the new state of an old individual.

There are two developmental cases, the development of attributes and the development of properties. Regarding the properties of identities, the process can start with the perceptions of the differences in values and then the conception of an attribute dimension. That is, the values along the attribute dimension which can be perceived, then the attribute dimension is conceived later, such as textures and weights. For different objects, they may have different values along the same attribute dimension, which can be examined directly. The different values along the same dimension are derived in comparison with each other directly and the significant differences can become explicit properties for a set of individuals.

The different values can also define the attribute dimension as a domain, for example, from the exact colours such as red, green, and blue, to the understanding of colour as a domain. However, once the attribute dimension is conceived, there can be the adoption of a standard unit for the comparison and derivations of different values. This is about one aspect of the re-organisation of an attribute dimension. There is another way the values of an attribute dimension (from a perception) can be assimilated into the attribute system. That is, different values of an attribute dimension are not only sorted into an order, but redefined. Using *colour* as the example:

- In one case, there are a few colours which can be selected as the reference points (Berlin and Kay, 1969; Rosch, 1973). More colours can be defined in terms of these reference points, such as the combination of blue, yellow, and green to define the whole range of colours.

- In the second kind of re-organisations, the *integral* attribute is further differentiated into a

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7 By then, the language names for such properties can be designed for them.
few independent dimensions, for example, the dimensions of hue, saturation, and brightness for studying colours. These independent dimensions are then used to re-define values of the integral dimension.

The process of re-organisation with attribute can also start from the formal schemata for identities with the selection of attribute dimensions first, and then the values along the attribute dimensions are examined. These distinguished values along certain attribute dimensions are then re-define the differences of identities. For example, for physical substances, there are commonly examined properties as textures and colour. This relation of attributes-to-substances is a general one which can be applied to study substances in different scales, such as in the studies of physical and social environment in the large-space. The physical or social patterns can be defined with certain attribute dimensions.

The second kind of cases is different which has the starting point with the conception of identities as figures, with contents, and contexts. An internal part for the contents of identities is essentially an attribute of component-kind. Then, the differentiations of the identities can be carried out, which are along the two perspectives with distinctive sets of attribute dimensions. One is the component-kind for identities, either distinctive features or parts of the shapes, contents, and contexts. The other is about the states and transformations which are applied to these three components. This is the case when a component refers to a feature which can either be present or absent. This component itself can also become a dimension-kind when the precise descriptions of the component are required (e.g. different shapes) are involved for distinguishing and sorting the states to individuals.

**On re-organisation of attributes for conceptions on different inclusive levels**

For the concern of modelling, apart from different formal-schemata for the representation and knowledge of identities of different ontological-kinds, there are also different formal schemata for the conceptions on different inclusive levels, but of the same identity. These formal schemata on different conception levels are associated with the inferences relevant to the corresponding conception levels once an identity can be reliably categorised into a group belonging to the corresponding conception level.

Indeed, the process from the perception of the state of an identity, to the recognition that it belongs to a particular individual, often goes several steps (Humphreys and Forde, 2001;
Goldstone, 1998). The formal structures for the two kinds of explicit knowledge of identities (i.e. the knowledge of causal rules and causal conditions respectively) which can be generally defined in terms of the relations of attributes-identities or identities-attributes are both involved.

Starting from the state in perception, there is the preliminary call of the ontological-kind for the identity (e.g., substances versus objects). Then, there are inferences and further identification of it into one of the core-domains based on the examination of its figures, contents, or contexts (if all of these are applicable). The categorisation of an identity can be based on examining the boundaries or internal structures. However, the set of basic-level-categories or categories is correlated with the developmental state of the conceptual system of the core-domain. The nature of the core-domain implies whether there are further distinctions of sub-domains or sub-situations first, then the development of basic-level-categories within these further differentiated contexts.

For the purpose of categorisation, if the conceptual system is well-development, the categorisation can be based on the rules which specify the boundary conditions for categories of identities directly, which are often the distinctive features unique to one category. However, in the general case of development, the partonomies for the representation of identities can be involved (within a core domain, the simple and complex entities are differentiable). The categorisation stops at the point when the identity is categorised into one of the basic-level-categories or the descriptions with part-whole relations do not provide further gain or have reached the functional goals. The further re-identification is about the understanding of an identity as a particular in a certain position in space-time. That is, there is the recognition of a state in the perceptual input as belonging to a known identity. This identity can have past states and certain transformations which were learned in the past. Such knowledge can be used to register this new state (e.g., in image processing) and to study further the changes along the time dimension (e.g., in the study of natural systems in geosciences).

Indeed, the conceptions on different inclusive levels are about setting the contexts for the further identification or re-identification. Being identities, they are the primary properties of the environment from the biological perspective. With different ontological-kinds, there are increasingly detailed distinctions of the environment. From an ontological to the individuals of the ontological-kind, there are increasingly detailed descriptions for the three components as figures, contents, and contexts. The formal schemata for basic-level-categories of a core-domain must inherit the formal schema of their ontological-kind. In the meanwhile, they also have
added components, such as more functional distinctions of the figures with distinctive features (and the changes in forms do contribute to the understanding of biological classes), internal structure with increasingly detailed levels which study the parts (i.e. the parts of a part), or the larger or the refined distinction of contexts where the individuals are usually constrained (e.g. habitats, niches, clans, kinships, or families).

The study of attributes as values versus dimensions is important for understanding the representation or knowledge of identities as individual. The knowledge of an identity is about it as a member of an ontological-kind, a member of a basic-level-category, and a particular individual in situations in space-time. The ontological-kind of an identity is determined by its location in different spaces as well as the properties of the identity which can be differentiated by the distinctive sensorimotor experience with it. Empirically, the differences in terms of the three components of figures, contents, and contexts can be used for the identification of an individual into an ontological group.

From the knowledge of an ontological-kind to the knowledge of it as a member of a basic-level-category, the differences are often described with increased number of attribute dimensions in the representation schemata. The basic-level-categories can include more component-kind attributes, such as parts, which can be defined on different scales (e.g., from parts in A-space to the particles in the increasingly smaller space). Regarding a dimension-kind attribute, the values can be modelled differently (e.g., a shape as an attribute dimension can be described with a point, with distinctive features, or with a precise shape defined in Euclidean Geometry). Regarding the set of basic-level-categories within a core-domain, they themselves can be differentiated with the patterns defined with attribute dimensions.

For the knowledge of individuals, both the dimensions and the values of attributes can change. For an individual of a core domain, the general pattern as the configuration defined with the attribute dimensions can stay. However, a component-kind attribute can be changed into a dimension-kind for the accurate description. There can be single or multiple dimensions, which are involved in differentiating states of individuals within the context of an ontological-kind or a basic-level-category. When such attributes are involved in the representation of a state of an identity at a time, the specification can include values along different attribute dimensions (either component-kind or dimension kind). Depending on the number of identities within a core-domain, the distinctions along an attribute dimension can be detailed or coarse (i.e. related to the factor of details).
While the distinctive values along certain attribute dimensions are used for the description of a state. However, there is the possibility that different states at different times can belong to either the same identity or different identities. The re-identification of a state as belonging to an old identity is not based on the physical or spatial properties of the figures or contents, but rather on their ontological nature, possible changes, and the attributes of their locations at different times.

8.4.2 On interpreting attributes for the models of identities

The factor of forms on the representation and models of identities will be discussed in this subsection. There are two main points. Firstly, the system of attributes which are involved in the descriptions of identities will be discussed. The attributes are about the figures, the contents, and the contexts of identities on the one hand, the states and transformations which can be applied to the study of the figures, the contents, and the contexts of identities on the other hand. The second discussion is about the two different ways attributes can be interpreted. Different models of an identity are related to whether the attributes are in language codes or modelled in mathematical forms. If the attributes are described in a language, the issue is about how the attributes which are involved in the descriptions can be interpreted in logical-mathematical forms. For attributes of different natures, they can be interpreted in distinctive ways formally. However, the interpretation of attributes can follow the second order isomorphism (Shepard and Metzler, 1971; Shepard, 1987) and the prototype theory (Rosch, 1983).

On differentiating attributes into different kinds

Generally speaking, when a system of attributes for the representation of identities is to be proposed, there are three issues to be taken into consideration. Firstly, it is about the structure defined by the different kinds of attributes which are involved in the representation of identities. Specifically, it is about whether the attribute dimensions are independent to each other or they bear complex relations to each other. Secondly, it is about whether or not the attributes can be perceived directly, thus, they can be associated with the developed perceptual modules as described in (Fodor, 1983) for the purpose of differentiations. The third issue is that the natures of the attributes. Attributes of different natures often require different mathematical forms for their formal interpretations.
In this situation-based theory, the understanding of attributes for the representation of identities is on two dimensions. In other words, the different attributes for the representation are defined in a system of two perspectives. On the one hand, there is a generic form for the representation of all identities, which have the figures, contents, and contexts as the three components. The formal schemata for identities of different ontological-kinds are differentiated in terms of whether there are further differentiations for each of the three components which can be included in the representation scheme. In particular, what degrees of details in the descriptions for these components are included, i.e. how many levels of parts in the partonomies for the contents, how may distinctive features of the boundaries defined on different scales, and what kinds of contexts the identities can be involved in as elements.

On the other hand, there are the attributes for the descriptions of states and transformations aspects of identities. However, states and transformations are applied in two steps for developing the representation of identities. On the first step, states and transformations are applied to the study of identities as figures. An individual as a figure is a 4D existence and can have different 3D states at different times. For the study of an identity as a figure which exists in 4D, it has a shape at a time, physical properties, textures for its substance, surface characterisations if it is an object on the one hand, the processes and behaviour patterns over time on the other hand.

On the second step, states and transformations are studied for the content and context of an identity. The study of the contents and contexts are also based on sensorimotor examinations. For the content of an identity, there can be different substances with properties and internal parts. For the context of the identity, there can be variously defined situations which contain the identity. The context can be defined either in the absolute terms, such as with geo-coordinate systems or in relative terms in terms of other identities which bear spatial and temporal relations to the identity which is in the focus of the study (Golledge, 1993). Depending on how the context (the part of a situation excluding the identity of interest) is defined, it may be possible to further differentiate it. Generally, the contexts of an identity can be differentiated into the domain-specific situations and those larger and often more complex situations which go beyond the core-domain.

For the descriptions of identities, states and transformations for figures, contents, and contexts can provide the increasing detailed information for the identity. The states of any natural-units at a time are defined with spatial properties and physical properties. The spatial properties
of objects can include \textit{shapes, boundaries} and \textit{locations}. The shapes for figures are defined in 3D or 2D Geometry. Spatial properties can also include \textit{configurations}, which can be the configuration of \textit{boundary features}, the configuration of parts for the \textit{internal structure}, and the configuration of other identities as elements for the \textit{external contexts}. Depending on the ontological natures of identities, the \textit{internal structures} can be defined differently, so can the \textit{external contexts}. \textit{Ontological-kinds} can be distinguished in terms of the patterns of such configurations as well as how many levels of part-whole relations. The attributes of \textit{transformation-kind} can include \textit{processes, events}, and \textit{causal relations}. The \textit{causal relations} can refer to the \textit{relations} of parts to the processes and behaviours of the wholes and the \textit{causal relations} when identities interact with each other. These different types are more or less relevant to different core-domains.

To the issue of interpretation, this distinction of attributes into those for \textit{states} and \textit{transformations} is important. On the one hand, the attributes for states and for transformations are independent of each other and handled in separate perceptual modules in the visual systems (van Essen et al., 1992; Milner and Goodale, 1995; Norman, 2002). On the other hand, this distinction is important for formal interpretations of the attributes in mathematical forms. States and transformations kinds and their subtypes respectively are different kinds of attributes. This means they can be associated with different formal interpretations in modelling. For physical properties, they can be coded in numbers. For a shape of an object, it can be described with a single point, distinctive \textit{boundary features}, the \textit{configuration} of \textit{boundary parts}, or in geometrical \textit{shape}. The configuration can be a pattern definable in Topology as well as described in Geometry. For processes, there are mathematical functions. For events, they can be represented in terms of relations of two states. For causal relations, they can be represented in terms of a system which can be formally modelled in mathematical simulations.

\textbf{On interpretation of attributes following the second order isomorphism}

The representation of an identity can also be in different forms because of the different interpretations of these attributes of different kinds, i.e. the kinds of attributes in the descriptions of \textit{states} and the representations of different \textit{transformation kinds}.

Firstly, for modelling in mathematics, the explicit differentiation of \textit{properties} as values and \textit{attributes} as dimensions is important, given attribute dimensions refer to domains. The properties mean the values along the attribute dimensions. For example, a shape can mean a
dimension, the exact shapes in terms of circles and rectangles are properties.

Secondly, attributes in the representation of identities can be interpreted in mathematical forms of numbers, geometrical shapes, and functions in the absolute sense\(^8\). Attributes of different ontological-kinds, such as properties, configurations, shapes, processes, events, or causations, can be interpreted by different formal mathematical structures. Physical properties can be represented in numerical values. The states in space can be represented with single points or complex shapes. The transformations associated with an identity can be different kinds, such as processes and causal interactions the identity has been involved. These can be formally modelled in functions or relations.

Thirdly, the attributes can also be interpreted following prototype theory (Rosch, 1978, 1983). That is, the values along an attribute dimension can be defined in terms of its distances to the prototype and other typical examples. Not only the representation of one identity as a whole can be defined in terms of its distance to the prototype, but also the value of an attribute dimension is also defined in terms of its distances to the values of reference points. That is, the interpretation of attributes for modelling identities can follow the prototype theory.

This prototype theory for identities of the same kind or the different values along an attribute dimension means that the distinction can be made based on the similarities and differences between and among identities, rather than searching a complete copy of all information and the pursuit of truth values. This also means, generally speaking, the principle of second order isomorphism (Shepard and Metzler, 1971; Shepard, 1981, 1987, 2001) is adopted to understand how the representation of an identity in mind can be realised (see Section 2.3) and how to interpret the values of an attribute dimension. The principle of second order isomorphism is also directly related to understanding how to construct the models of identities with attributes.

The better application of this principle of second order isomorphism has to take into consideration that the representations of identities are to be studied within their core-domains. The ontological-kinds and basic-level-categories are important to handle the differences in component-kind attributes. Within the context of an ontological-kind and a basic-level-category (of a core-domain), this second order isomorphism can be integrated with the prototype theory (Rosch, 1978, 1983). Individuals can be distinguished based on the different values of different attribute dimensions for their states.

\(^8\)However, a detailed study on the interpretation of attributes of different kinds for representation of identities is irrelevant for this thesis which focuses on structural constraint.
8.5 Summary

The explicit knowledge of identities is constrained by the development of the conceptual system of a core-domain. There are four level conceptions and the distinction of representation versus knowledge for identities. The knowledge of identities is about the *boundary conditions* and *formal schemata* of identities to support inferences. These constraints should be taken into consideration for the models of identities.

The conceptual constraints mean that two components for the knowledge of identities are to be separated. One is about their existences in the environment and the knowledge can be associated with a sequence of states at different times and transformations over time. The knowledge of identities is also about them being members of ontological-kinds and basic-level-categories. The causal rules are about the boundary conditions of ontological kinds, basic-level-categories, and individuals in space-time.

The *formal schemata* for identities on different conception levels were explained. The constraints of *formal schemata* from the *ontological-kinds*, *levels* and *details* for knowledge of identities were also discussed.

The factor of *forms* on different representation of identities is explained in terms of different interpretations of attributes. The attributes are distinguished into those for the *states* and for the *transformations*, with each of them having several subtypes. The changes of attribute dimensions and values can explain the conceptions different inclusive levels for the same identity. Different kinds of attributes can be modelled differently in mathematics. However, attributes can also be modelled in terms of distances to reference points following second order isomorphism.
Chapter 9

Discussion

9.1 A Piagetian figurative theory of representation in mind

This thesis has been devoted to studying the representation of the concrete environment in mind. Generally speaking, the biological principle was adopted to understand the representation in mind. A situation based Ontology of the world was proposed in order to develop a figurative theory of cognitive development and conceptual systems. A situation-based theory of conceptual structure, the development of the representation and knowledge of identities, and the constraints on the representation of identities was presented.

9.1.1 The biological principles for representation in mind

The biological principle in understanding representation in mind is adopted explicitly (Chapter 2). There are three positions, which mark the departures of the new theory from the current studies in its general understanding of the representation:

Firstly, regarding what the representation is about (Section 2.2), the new theory follows Millikan (1998a). It emphasises the representation in mind is about the category of substances as natural units in the world, which include stuffs (e.g. milk), individuals (e.g. Mother), and real kinds (e.g. dogs). This is fundamentally different from current cognitive theories of representation with their emphases on the representation of categories. However, Millikan’s basic position was extended.

Secondly, the new theory adopts the functional principle in understanding the nature of representation (Section 2.3). The psychological representation is for the functional purpose of re-identification of Millikan (1998a) of interesting natural units of the world. The thesis has provided a systematic account where the functional principle is applied to understanding the different aspects related to the representation and its development in mind. The second order isomorphism of (Shepard and Metzler, 1971; Shepard, 1987) was also adopted explicitly for
understanding how the representation of identities can be realised.

Thirdly, the new theory extends Piagetian structural principle in understanding the cognitive system (Section 2.4). The representation in the brain systems, cognitive systems, and conceptual systems were explicitly differentiated. The distinction of structure and the contents for representation in Piaget’s theory was kept. While the essence of Piaget’s abstract characterisations of structure (Piaget, 1971) was kept, a figurative account on structure as the constraint on representation was given. It has also provided a systematic account of the different understandings of the term structure in representation theories.

9.1.2 The situation-based theory of cognitive and conceptual structure

The idea of situations as 4D units of substances in space-time was introduced (Section 3.2). This general idea of situations was then applied to provide a figurative re-interpretation of Piaget’s theory of cognitive development and the Piagetian constructionist’s theory of conceptual systems of representation and knowledge (Section 3.3).

A situation-based re-interpretation of cognitive development

A situation based understanding of the development of cognitive and conceptual systems was given. An explicit distinction of cognitive versus conceptual structure was made (Section 2.4). Four levels of cognitive systems and four stages of conceptual systems were discussed (Section 3.3).

Levels of cognitive systems: The four levels of cognitive systems can be differentiated based on the different kinds of situations whose representation can be supported. The environmental situations which can be represented have changed over the development with increased details and complexity. The complexity of the situations which the cognitive systems can represent increases from those of single identities in the common sense world (Level 1); to situations involving relations of identities and representation of parts and locations for identities (Level 2); to situations involving causal relations of identities in interactions and differentiated core domains in the common sense world (which are based on causal relations of different kinds, i.e. physics, biology, common sense psychology, and social science, Level 3), to the representation of arbitrary situations in the world and core-domains in the smaller and larger spaces other than the common sense world (Level 4).
**Stage of conceptual systems:** The stages of conceptual systems are differentiated based on the development of different forms for the representation of identities. It is also correlated with the support for different sets of ontological distinctions of spatial features\(^1\). For the development of conceptual systems, both domain general and domain specific kinds of changes were covered. Different *stages* of conceptual systems are based on the different forms of representation for identities, which are studied within core domains. However, for identities of different ontological kinds, the development of representations can follow their separate routes and reach different stages.

For objects as figures in the common sense world, the first stage (*Stage 1*) is associated with the general change from implicit representation to explicit representation of objects. Here, there is the ontological distinction of *objects* with boundaries and *substances* without boundaries of themselves in the common sense world. The second stage (*Stage 2*) is associated with the explicit representation of not only identities, but also the boundary parts and collections of identities which define locations in the common-sense world. The third stage (*Stage 3*) is associated with explicit representation of identities within the context of core domains in the common-sense space. There are not only the explicit distinction of categories and individuals of identities, but also the representation of internal parts which are associated with distinctive functions and causal relations to other parts. The fourth stage (*Stage 4*) is associated with the development of basic level categories, taxonomies, and intensional definitions of basic level categories.

Indeed, with the idea of situations and the re-interpretation of Piaget’s cognitive development, a few positions regarding the fourth level cognitive system and fourth stage conceptual system can be spelt out, which are directly relevant for the design of a new information architecture of SISystems. Firstly, the figurative understanding allows Piaget’s *structure-d-ensemble* to be defined. Specifically, the state of a conceptual system can be defined with 1) part-whole relations of identities from different core domains, 2) the part-whole relations of “identities” within core domains, and 3) the part-whole relations of “identities” in applications\(^2\).

Secondly, this thesis has provided a systematic discussion on the specialisations of domains, including the specialised core-domains and application-oriented domains for the environment\(^3\).

\(^1\)See Section 7.3  
\(^2\)See Section 4.3 for the overview of *structure-d-ensemble*.  
\(^3\)See Chapter 5.
It also has provided a realist’s position in understanding the *ontological nature* of identities and the system of ontological distinctions supported by the mature cognitive systems⁴.

The fourth level cognitive structure should be followed for the information architecture of SISystems. It can support the representation of a system of core-domains and application-oriented domains on the one hand, the representation of a system of ontological distinctions for identities relevant to SISciences on the other hand⁵.

### A situation-based theory of constraints in conceptual structure

The idea of *situations* was also used to provide a principled understanding of the constraints of *core-domains, ontological-kinds, and applications* studied in cognitive literature on the representation of categories of *spatial-features*⁶. The distinction of these three kinds of situations allow the flexible treatment of identities in the environment, the development of *representation* and *knowledge* of them in core-domains, and the application of such representation and knowledge⁷.

Firstly, the situation-based theory explained three special kinds of situations, namely, *core-domains, ontological-kinds, and application situations*. The contexts of an identity in terms of situations in the world are to be differentiated from the constraints on the development of *representation* and knowledge of *identities* in the mind. As contexts for identities in the environment, these situations are the *contents* of representation themselves which are supported by the cognitive structure as well as the *constraints* on the representation of identities. A spatial-feature as a *natural-unit* in the world is both a member of an ontological-kind and an element of a *core-domain situation*, which are important constraints on the development of representation of categories studied in cognitive literature.

Secondly, to understand the development of *representation and knowledge* of identities, there are vertical and horizontal dimensions as the second level structural constraints. **Vertically**, there are conceptions of *identities* on four inclusive levels, i.e. for *states, individuals,*

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⁴See Chapter 7. The development of a cognitive system is correlated with the support for a system of ontological distinctions of identities.

⁵See the discussions in Sections 5.3 and 7.3 for the system of contents supported by the fourth state of cognitive structure.

⁶See Section 4.2

⁷See Chapters 5 and 6 for issues related to core-domains. See Chapter 7 for issues related to ontological-kinds. See Section 5.4 for modelling applications.
categories, and ontological-kinds\(^8\). During the periods of the cognitive development, there are different levels of conceptual organisations which correspond to the explicit distinctions of the conceptions of identities on the four inclusive levels. Then, once an identity is identified as a member of an ontological-kind, there will be another direction of conceptual re-organisation which contributes to the development of basic level categories and category systems\(^9\).

The meaning of ontological natures, the cognitive criteria for making ontological distinctions, and the general understanding of the structural and formal constraints on the representation of identities were systematically explained\(^10\). The development of basic level categories and four kinds of category systems are emphasised for the development of conceptual re-organisations of core domains. The development of a set of basic level categories for identities of a core-domain and the representation and knowledge of basic level categories are important constraints on the representation and knowledge of individuals. The development of basic level categories is correlated with the further development of the second type of taxonomies and intensional definitions\(^11\).

**Horizontally**, apart from the issue of domain specialisations, the study also covered the development of domain representation and knowledge on the one hand, the understanding of the constraints of core-domains on the representation and knowledge of identities and on modelling applications\(^12\). The horizontal development is correlated with the development of a system of causal knowledge of different kinds, including the causes, causal rules and causal conditions of inferences, causal mechanisms, causations, and causal theories and laws, and causal constraints.

The *cause* is about the process which accounts for the existence of an identity and the psychological recognition of such an existence\(^13\). *Causal rules* and *causal conditions* are associated with the knowledge of identities on different inclusive levels for two families of functions\(^14\). The *causal rules* refer to the states of representations for individuals or categories which are used to assimilate the inputs from the environmental states. *Causal conditions* are about the levels of knowledge for inferences once the states of identities in perception can be classified into

\(^8\)See Section 4.4 for the overview and Section 8.3 for further discussion
\(^9\)See Section 6.3.
\(^10\)See Chapter 7.
\(^11\)See Sections 4.4, 6.3, and 8.3.
\(^12\)See Chapter 6.
\(^13\)See discussions in the first and second subsection in Sections 4.4.
\(^14\)See Sections 4.4 and 8.3.
certain groups. For example, the distinctive physical and spatial properties of identities can be inferred which are relevant for the functional uses of these identities. Or processes and events of identities are inferred which are relevant to an organism to make corresponding decisions of actions. Causal mechanisms, causations, causal theories, and laws are the understanding of domain specific interactions or transformations of complex core-domain situations\textsuperscript{15}, and the general causal constraint for regulation and adaptations\textsuperscript{16}.

### 9.1.3 The situation-based understanding of cognitive contents

This thesis adopts the view that there is a common mental structure for representing the natural units. However, it extends the category of substances to include those natural units in the small and large spaces and developed an elaborated account of the representation and knowledge of identities based on Piaget’s identity rules and current cognitive studies on constraints of representation. Two kinds of cognitive contents were studied in detail. One is the development of representation and knowledge of core-domains. The other kind of cognitive contents is the representation and knowledge of identities.

On representation and knowledge of core domains

The structure-d-ensemble in Piaget’s theory can be defined in terms of supporting the explicit representation of a system of domains. The fourth level of a cognitive system is correlated with the kind of specialised core-domains and application-oriented domains for the environmental studies\textsuperscript{17}.

The different theories of domain specificities can be unified in the situation-based theory. Firstly, the situation-based theory can explain the specialisation of core-domains and application-oriented domains and the development of representation and knowledge of the core-domains in one principled approach\textsuperscript{18}. Secondly, the constraints of ontological-kinds and causal theories of core-domains can be explicitly differentiated\textsuperscript{19}. The core-domains as representation units in mind are developed to better serve the functional demands. Thirdly, the states

\textsuperscript{15}In Sections 4.4, 6.2 and 6.3.
\textsuperscript{16}See Sections 4.4 and 5.4.
\textsuperscript{17}See Section 5.3.
\textsuperscript{18}See Chapters 5 and 6 respectively.
\textsuperscript{19}See Section 6.2 and Chapter 7.
of representation and knowledge of core-domains are meaningful in their own right for modelling these core-domains. The representation and knowledge of core-domains are applied to modelling new applications and can adapt in the context of applications. Thirdly, core-domains are also important constraints on the accurate representation of applications on the one hand, the knowledge of identities on the other.

For understanding the states of core-domains, their constraints, and modelling identities of core-domains, two distinctions should be emphasised:

1. The distinctions of domain representation versus domain knowledge. The constraints of domains on the representations of identities come from the ontological natures of identities within the corresponding core domains on the one hand, the domain distinctive kinds of causal knowledge on the other hand. The system of causal knowledge of core-domains, i.e. the representation and knowledge of various transformation kinds for core domains were also studied.

2. The distinction of conceptual structure versus the contents of a core domain. The two structural constraints, which are shared by all core-domains, refer to the development of a set of basic level categories and the four kinds of category systems. However, the state of a core-domain is also constrained by the experiences.

On representation of identities of ontological kinds

Firstly, the structure of the whole in Piaget’s theory can also be defined in terms of supporting a system of ontological kinds. The representations of identities, which are inherently members of certain ontological kinds, are constrained by their ontological natures. The thesis also presented a systematic understanding of the nature, cognitive criteria of ontological distinctions, and the structural and formal constraints of the ontological natures on the representation and knowledge of identities.

Secondly, the structural constraints of ontological kinds is about the possibility of explicit knowledge. It means whether certain identities can be explicitly represented and studied in their own right. The state of cognitive structure is about supporting the representation of a
particular system of ontological distinctions for identities of spatial features. The four levels of conceptions for the representation of identities observed in empirical studies were taken explicitly as the structural constraint on the representation and knowledge of identities. The distinction of representation and knowledge of identities is applied to the four conception levels. Based on these positions, the four kinds of formal constraints on the representation of identities can be explained and should be treated separately for the purpose of modelling.

Thirdly, the formal constraints on the representation of identities are relevant for understanding the differences in descriptions for identities. These constraints are named kinds, levels, details, and forms. The factor of kinds is about the constraint from the ontological natures on the development of representation from sensorimotor experiences. The ontological nature of existence inherently constrains the sensorimotor experiences with the identities. The factor levels correspond to the constraints from the set of basic-level-categories and the representation of basic-level-categories. The intensional definitions for basic-level-categories are possible. However, the set of basic-level-categories for a core domain may change over time. The factor of details corresponds to the constraints from the knowledge of other individuals and states of the four category systems. They constrain both the representation of individual identities and the representation of core-domain specific complex situations.

The factor of forms is related to the development of different formal schemata for identities of different ontological-kinds on the one hand, the re-presentations with attributes in languages or mathematical forms on the other hand. A generic formal schema for the representation of an identity includes the descriptions for three functional components, the figure, the content, and the context. The three functional components are emphasised differently for different ontological kinds. The constraint from the states of core-domains can be reflected in the more or less detailed descriptions for the three components (i.e. hierarchical distinctions of boundaries, contents, or contexts) for basic level categories of their corresponding core-domains.

For the interpretation of the attributes in the descriptions of identities, two positions were clarified. One is the explicit distinctions of attribute dimensions versus values. This is for

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24 See Section 7.3.
25 See Section 8.3 and 8.4.
26 Section 7.3.
27 See Sections 6.3 and 8.3.
28 See Section 8.4.
29 See Section 8.4. But also studied in Sections 3.3, 4.3, 6.3, and 8.3.
understanding the specialisations and generalisations of the attributes which are involved in the descriptions of identities on different inclusive levels. The other is that, for the concern of formal interpretations of the attributes, the attributes involved in the representation of identities were differentiated into those for states and transformations which can be applied to study the three functional components as figures, contents, and contexts. The interpretation of attributes for identities can be based on absolute measurements and mathematical forms as well as the distances to reference points.

9.2 On the contributions of the new theory of representation

The research in this thesis is classified into the domain of SIScience, since it is in the domain of SIScience where the research problem is raised. For modelling spatial features in SI systems, there are both theoretical and practical concerns. This thesis was devoted to address a theoretical concern, namely a new representation theory in mind on how to represent the identities of spatial features. This is a necessary research issue since the current problems with SISystem are caused by the state-of-the-art map or images based conceptual models in its core, and thus cannot be addressed by these conceptual models.

While a theoretical study always has downsides, there are particular difficulties and risks faced by the study in this thesis. The writing of this thesis has been disadvantaged in the first place by the topic. It is a great challenge to write about an idea as complicated as the one in this thesis. One of the main reasons is that the study has touched upon the fundamental understanding of Ontology and Epistemology. Further, any theoretical understanding is always associated with certain presumptions in understanding representation itself. Researchers who hold different philosophical positions and take different presumptions on representation may have starting points fundamentally different from the positions held in this thesis. For example, if a behaviourist’s understanding of representation is taken, it will be hard for the theory in this thesis to make sense. However, other difficulties with this thesis are because of the multidisciplinary nature of this study. It demands the readers to be considerably familiar with the domains of SIScience and cognitive studies. Both domains are rather complex in themselves. Nevertheless, the study has presented a situation-based unified account on the issue of representation of identities of spatial features in the human mind.
9.2.1 A contribution to the understanding of representation in mind

A biological understanding of representation should be followed because the human brain belongs to an organism which has gone through a long history of evolution. The thesis contributes a theoretical understanding to the domain of cognitive studies by providing an unified theory of representation in mind. It clarified the functional and structural principles of representation and development and integrated a range of theories in cognitive and developmental literature.

On a biological understanding of representation in general

This theory in this thesis can be contrasted with other cognitive theories of development and representation on a few accounts. It has several departures from the current literature on representation in general.

Firstly, the representation is not about coding, but to service basic biological functions of re-identification. The representation of identities is studied by exploring the cognitive literature of representation, not the language descriptions.

Secondly, following Millikan and Piaget, the representation in mind focuses on individuals, not categories. This fundamental position of the new theory can explain the innate theory of Spelke (1994, 1998). Both theories can agree upon understanding of what the representation in a biological system is about, i.e. about the category of substances in the world, which is an innate prescription. However, the two are also different. The innate theory tends to adopt a continuous theory regarding the changes of representation in mind with accumulation of attributes. The new theory is a constructionist’s theory. It has adopted the Piagetian positions of the structural change of a cognitive system as well as the qualitative changes in the form of representation of identities. Further, the conceptual structure as the constraint on representation can include and support the representation of categories and their relations.

On integrating cognitive theories of representation

The situation-based theory has provided a unified account of cognitive systems of representation. It is based on the essence of Piaget’s the theory of development and identity rules. However, it has also integrated other developmental theories and cognitive theories of representation from a few perspectives.

Firstly, a developmental perspective is followed in understanding the development of repre-
presentation. However, a figurative re-interpretation was given based on the basic understanding that identities are in situations in space-time. The form of representation changes from the representation in terms of direct actions and action schemes in sensorimotor period, to the representation as an independent existence (i.e. the development of object permanency), to the representation of identities in terms of their relations to others, to the further development of representation within the context of specialised core-domains in the period of conceptual representation\(^{30}\). Regarding the form of representation, this thesis has integrated the idea of representation re-descriptions (RR model) of Karmiloff-Smith (1986, 1992) which emphasised the change from implicit to explicit and different kinds of explicit representation.

Secondly, for the concern of representation of identities, the theory has studied both the representation and the constraints of representation. The developmental changes of these two were understood in a Piagetian general framework of cognitive development. The representation of an identity is influenced by the development of cognitive and conceptual structure on the one hand, the domain representation and knowledge on the other hand. The level of a cognitive system in development is relevant for whether a particular ontological kind of identities may be learned or not. The cognitive development allows the explicit representation of identities of a certain ontological kind. The stage of development of the conceptual systems in a core-domain influences the forms of representation of the identities in the corresponding core-domain. That is, the constraint on the forms of representation of identities come from the development of conceptual structure in general and state of representation and knowledge of core-domains.

With this unified account of contents and constraints, the new theory can integrate a range of current cognitive theories of representations. On the one hand, the different understandings of the identity rules (Brainerd, 1978) can be accounted, i.e. the representation of individuals (Elkind, 1969) and the representation of categories (Bruner et al., 1956; Smith and Medin, 1981). On the other hand, it can also assimilate the different theories which emphasise constraints on representation, including the constraints of ontological kinds (Keil, 1989a), the theory theory (Carey, 1985; Gopnik and Wellman, 1994; Gopnik, 1996), the neo-essentialist’s theory (Medin, 1989; Gelman et al., 1994; Gelman, 2004), the context theories (Murphy and Gelman, 1985), and the theories which emphasises the effects of uses upon the representation of categories (Ross, 1997, 2000).

Thirdly, the developmental changes of the forms of representation were understood in the

\(^{30}\)See Section 3.3 and Chapter 6 mainly.
Piaget’s general idea of identity rules. For identities within a core-domain, there are also constraints from the two structural dimensions. Vertically, the conceptions of identities are differentiated into four inclusive levels, namely, the ontological-kinds, basic level categories, individuals, and states of individuals at different times\(^{31}\). Horizontally, three functional understandings of the mental structures for identities were distinguished. That is, there are functional components for representation, knowledge of boundary conditions, and knowledge of inferences on each of the four conception levels for identities\(^ {32}\).

The structural and functional principles have led to three conceptual organisations within a core-domain. Firstly, it is about the representation of an identity in terms of its states and transformations on the one hand, the knowledge of it as an objective existence in situations in the environment and serving various functions in applications on the other hand. Secondly, there is the development of a set of basic-level-categories. Thirdly, there is also the development of four kinds of category systems for the representation of core-domain situations. Regarding the form of representation, the three positions can explain another kind of developmental changes observed in the theory of Vygotsky (1986). Namely, for the development of meanings of concrete nouns, there are the changes from pointing to the example, to descriptions, to intensional definitions for categories of identities. Different representation theories of categories can be integrated, such as the rule based theories (Bruner et al., 1956) and examples and prototypes (Smith and Medin, 1981)\(^ {33}\).

### 9.2.2 Contributions to SIScience and SISystems

Based on the study of a range of cognitive theories, this thesis has provided a unified theory on the representation of spatial features in the human mind. The new theory also contributes to the domain of SIScience and SISystems since the new theory can provide a unified approach and possible solutions to the current theoretical issues raised in the research of SIScience. The new theory will be the new basis for the development of the data model of a new general purpose SISystem.

\(^{31}\)See Sections 4.4, 6.3, and 8.3.

\(^{32}\)See the first subsection in Section 4.3 and see Sections 6.3 and 8.3 for the general discussions.

\(^{33}\)See Section 8.2.
A theoretical contribution to the SIScience

The study on a theory of how spatial features are represented in mind contributes to the research on the foundation for SIScience and SISystems. For SIScience to become a distinctive scientific discipline, it requires a coherent theory (Goodchild, 1992, 2004; Goodchild et al., 2007). This thesis has made such an effort to provide a new perspective and unifying principle for the studies in SIScience. It has contributed a situation-based Ontology and a situation-based figurative re-interpretation of Piaget’s theory of cognitive systems can be given. Such a theory is parsimonious, consistent, and comprehensive.

Firstly, the thesis presented a situation-based view of the world. It has four main advantages over current theories of Ontology adopted in SIScience. 1) It allows the simultaneous and unified treatment of spatial and temporal dimensions of natural units in the environment. 2) It allows the unification of the atomic and field view of the world (Couclelis, 1982, 1998a). Spatial features as 4D existences are special kinds of situations which are defined over certain spatio-temporal resolutions and extensions. Objects and fields of substances are two specialised situations with heterogeneous and homogeneous contents respectively. 3) The understanding of the contexts of identities in terms of situations. 4) The distinction of a few primitive situations based on both structural and operational considerations.

Secondly, a realist’s position is adopted in understanding categories. Identities in the world are differentiated from the descriptions in mind for the psychological understanding of the identities. The psychological representation is not about an exact copy, but for functional purposes. 1) The representation of a spatial-feature as a 4D existence can have different states at different times and can be associated with distinctive transformations over time. The descriptions about figures, contents and contexts for spatial features can all be involved. These attributes are used for their psychological differentiations. 2) The knowledge of a spatial-feature is not only about the representation of it in situation, but the understanding of its location and properties which allow them to be involved in different applications. 3) This view of Ontology and the realist’s theory on representation can also provide a foundation for the systematic discussions on the concepts of domains for SISciences and the nature of ontological kinds of spatial features.

Thirdly, the representation of identities is studied in the contexts of core-domains and ontological-kinds, which restricted the adaptations. On the one hand, the identities of spatial...

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34 See Sections 3.2 and 4.2.
features in the world can be differentiated into different core-domains. The representations of identities are studied in core-domains. 1) Both representation and knowledge of core-domains and the representation and knowledge of identities with core-domains are to support functional needs of modelling applications. 2) There is a cognitive principle in understanding domain specialisations and the system of core-domains for identities relevant in SIScience. 3) For representation of identities in core domains, the development of basic level categories and category systems for core-domain situations with two or more identities were studied. 4) The representations of identities with attributes in core-domains and in particular applications were differentiated.

The theory has provided an answer on how to represent identities as natural-units of different ontological-kinds in the world. 1) There is the cognitive principle in understanding of ontological kinds of spatial features and the system of ontological kinds. 2) Different ontological kinds are associated with different formal schemata as constraints for the representation of identities which belong to their ontological groups. 3) The constraint of ontological nature on the development of representation of identities is in terms of sensorimotor experiences with them. 4) The development of core-domain with identities of distinctive ontological nature also constrain the development of the knowledge of identities as members of basic level categories and as particular individuals with detailed formal schemata as constraints for assimilating the states of identities in the environment.

At last, the theory shall be able to deal with other theoretical concerns of representation in current SISSystems. For example, the scale effect should be associated with changes of core domains in different spaces. The distinction of partonomies for identities in a core domain versus in applications is also important. Regarding the hierarchies and organisations, partonomies for identities, taxonomies for categories, event structures with hierarchies and contingency of events, and the causal knowledge on different levels of abstractions and generalisations were all

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35 For the constraints of applications on core-domains, see Sections 5.4, 6.2.
36 See Chapter 5 for the development of the system of domains of the environment.
37 See Chapter 6 for the rules of domain specialisations, the development of domain representation versus knowledge and their constraints on the representation, and the structure and contents of core-domains.
38 See Sections 6.2 and 6.3 for the constraints of applications on the development of representation of identities in core-domains and the representations of particular applications respectively.
39 See Chapter 7 for the nature of ontological kinds, the cognitive principle for ontological distinctions of spatial features, the system of ontological kinds, and formal constraints of different kinds on the representation of identities.
explained. These are applied to the representation of domain specific identities and situations. Regarding the problem of indeterminate boundaries of representation (Burrough, 1996), there is the realist’s position and functional principle on boundary conditions for spatial features as individuals and their states at a time. The boundary of the state of an individual is related to its ontological nature and its states at other times. The boundary of a basic level category of identities is studied within the context of a core-domain. It is determined not only by the generalisation of its examples, but other identities to be distinguished in the core-domain. It is the result of conceptual reorganisation and the same process also explains the development of category systems in core domains.40

On the design of information architecture of SISystems

By providing a structuralist’s theory on how spatial features are developed and represented in mind, the thesis can explain rigidly the structural constraints of four levels for the representation of identities. The description given to an identity is constrained by the state of cognitive structure, the state of conceptual structure, the state of domain representation and knowledge, and the demand of a particular application. These structural constraints are to be considered for the development of new information architecture of SISystems.

Firstly, the state of a cognitive structure is definable with part-whole relations of identities. The fourth level cognitive system can support two sets of part-whole relations. One is the part-whole relations of core-domains. The other includes the three kinds of part-whole structures for the representation of identities within a core-domain.41 The system of core-domains and application-oriented domains and the system of ontological distinctions for identities were also studied.42

Secondly, the state of a conceptual structure which constrains identities can be understood from vertical and horizontal dimensions. Vertically, there are conceptions of four inclusive levels which are relevant to the development of representation of identities. Horizontally, there is a system of causal knowledge which constrains the forms of representation. These two dimensional constraints contribute to the specialisation of core-domains and application-oriented

40See Section 6.3 for understanding the conceptual system of identities within core domains.
41See Sections 3.3 and 4.3.
42See Chapters 5 and 7 for the development of domain specialisations for identities and the development of the system of ontological distinctions of identities.
domains on the one hand, the systems of ontological distinctions of identities on the other hand\textsuperscript{43}.

Thirdly, the constraint from the experience with situations can be differentiated into two kinds, either with the focus on core-domains or on identities in core-domains. The constraints of core-domains on the representation and knowledge of identities are in terms of the set of basic-level-categories and the states of the four kinds category systems, including core-domain specific system of causal knowledge\textsuperscript{44}. The constraints of ontological nature on the representation and knowledge of identities are in terms of sensorimotor experiences and the state of the core-domains definable with a set of basic-level-categories and states of four kinds of category systems\textsuperscript{45}.

At last, the models of identities are constrained by the knowledge of \textit{formal schemata} which can be applied to the representation of identities of different ontological-kinds. It is also constrained by the interpretation of attributes in the descriptions. The generic \textit{formal schema} for the representation of any identities can include three aspects, 1) the representation of states and transformations; 2) the descriptions with states and transformations for three functional components, namely, the figures with boundaries, the internal contents of the figures, and the external contexts of the figures, 3) the development of increasingly detailed descriptions for the three components. The functionally suitable \textit{formal schemata} of identities are correlated with the states of three part-whole structures for identities in core-domains. The constraint of the attributes in the \textit{formal schemata} comes from their different ontological natures, which constrain the ways these attributes can be modelled formally. However, for the models of an identity, both the \textit{formal schemata} and the interpretations of attributes can change over time\textsuperscript{46}.

\textsuperscript{43}See Section 4.4 for the overview of these structural constraints. See Sections 6.2 and 6.3 for these two dimensions on the development of representation and knowledge of core-domains. See Section 8.3 on these two structural dimensions on the representation of identities.

\textsuperscript{44}See Section 5.3 for the system of domain distinctions which are supported by the mature cognitive systems. Also see Section 6.3 for modelling the conceptual structure of core-domains.

\textsuperscript{45}See Section 7.3 for the system of ontological distinctions of identities which are supported by the mature cognitive systems. See Sections 8.3 and 8.4 for the systematic study of the formal constraints on the representation of identities which are of certain ontological nature.

\textsuperscript{46}See Chapter 8.
CHAPTER 9. DISCUSSION

On modelling representation, knowledge, and applications in SISystems

If the situation-based theory is followed in the design of a SISystem, in principle, three families of practical issues can be addressed. The advantage of the new information architecture is its flexibility. The architecture can integrate models for the representation and knowledge of identities and the causal knowledge of core-domains. It facilitates the representation of applications of different kinds by providing the primitives for constructing the models. It also allows the adaptation of the different models in localised contexts.

On modelling identities: An individual is a distinctive unit of existence in the world as well as in the information architecture in its own right (i.e. permanency object in mind). With each of the individual spatial-features as a single node, the theory can address four kinds of practical concerns in modelling identities.

Firstly, there are different formal constraints on the modelling of identities from their ontological nature. Further, there are four kinds of formal schemata for ontological-kinds, basic level categories, individuals, and states. They are all relevant for the representation of an individual, but are treated relatively independently. The independent treatments are necessary since they adapt in different conditions and follow different mechanisms.

Secondly, the theory can address the practical concerns regarding the possibility of 3D representation for spatial features and dealing with time for the potential changes of identities. The identity as an individual is clearly differentiated from the states of it at different times. The formal schema for an identity allows the list of states of the same identity at different times as well as the distinctive transformations of the identity which are observed in the environment.

Thirdly, in this new information architecture, there are separate treatments of the representation and knowledge components of an identity. The separate components for representation and knowledge can provide the possibility to assimilate both the physical measurements and mathematical models on the one hand, codes in language for various kinds of concepts on the other. For each identity, the exact representation of the identity is determined by two factors. One is the knowledge of it as a member of a category (i.e. with the specification of a formal schema). The formal schema of an identity is a direct instantiation of the formal schema for the basic level category the identity belongs to or the formal schema for the ontological-kind the identity belongs to. In the second case, the formal schema is a direct generalisations of the formal schemata for the representations of other individuals of the ontological-kind. The other is
the exact measurements with values along a set of attributes of the formal schema. These values define the state of the formal schema (i.e. with the values along several attribute dimensions).

Fourthly, the knowledge of rules for categorisations and knowledge of identities which allow inferences and support decision making regarding the involvements of identities in different applications are treated as different components. The development of basic level categories in core domains is also emphasised. Theoretically, the basic level categories are important for allowing the adaptation of representation and knowledge of core-domains. The re-organisations of categories can lead to a new set of basic level categories to be developed and the further distinction of the core-domain situations may also be required. For these sub-situations, the four category systems can be applied for developing the representation and knowledge of them. Practically, it also allows the integration of the models of categories derived from different cognitive theories of representation. Whether the intensional definitions for the categories can be found or not, the empirical rules (either the rule-based theories or similarity based theories) can be used for categorisations. With one set of basic level categories, the specifications of formal schemata as the knowledge of different categories are possible which allow the efficient assimilation of information about identities as members of the category.

**On integration of processes and reasoning:** Apart from the direct relevancy of the theory on the representation of identities as individuals in SISystems, there are other theoretical possibilities. For example, the information architecture can support the separate modules for different core-domains and application-oriented domains. Thus, the knowledge of other kinds can also be assimilated into the general information architecture, in particular domain specific category systems and knowledge of transformation kinds. There are the different kinds of category systems for representation and knowledge of core-domains. The formal structures of category systems are differentiated from the exact states of these category systems in core-domains. The knowledge of processes, events, causations, and more abstract causal theories and laws can also be assimilated. For example, processes can be associated with the identities of spatial features as properties. The relevancy of domain knowledge is indeed directly for addressing the practical concern to integrate models for complex processes, which are associated with the changes of complex situations defined with multiple identities over time. Events and causations may be more or less relevant as knowledge of different core-domains for identities of spatial-features. The development of causal knowledge of different kinds, including causations, causal theories, and causal laws can be handled in the context of core-domains.
**Modelling applications with states and transformation**: The representation of environmental situations in general can also be supported. It can be defined with *states* at times and *transformations* over times. The environmental state at a time links to the representation of maps and images directly. The state can be defined in terms of spatial relations or configurations of states of spatial features (which are recognised in the state). The identities which define the state can be of the same or different ontological-kinds in the same or different spaces. The transformation aspect can be modelled from both the global and localised perspectives. The global transformation is in terms of the change of states at two times (e.g. from $T_1$ to $T_2$). The localised understanding is in terms of the integrated effects from the transformations as *processes, causations, and events* over shorter period of time within the range between $T_1$ and $T_2$. These transformations are associated with individual identities or certain *core-domain situations* treated as wholes. This generic idea on modelling situations can be specialised to address the various representation demands from the application areas of SISciences.

**9.3 Final remarks**

This thesis presented a cognitive theory of the representation of spatial-features in mind. Perhaps, the theoretical proposal has opened a Pandora’s box, which leaves many more questions than it has answered. Nonetheless, it has provided an argument for a principle which allows following studies from cognitive literature to be integrated.

A unified theory on the representation of spatial features is one of the most crucial theoretical issues to the research in SISystems and SIScience. The study of the representation theories in mind have revealed the information architecture for SF-SISystems to be further complicated, not simplified. The increased complexity is related to the constraints from the complex cognitive and conceptual structure on the representation of spatial-features of different ontological natures and from the states of representation and knowledge of core-domains and application-oriented domains on the exact forms of representation.

Although the value of such an integrated theory on the representation of spatial knowledge stands in its own right, the future work is about formal specification and implementation of a SISystem following the discussions of such an integrated theory in this thesis. The theory has prescribed the constraints upon the design of information architecture of SISystems and models of representation and knowledge components of different kinds. The models to
be constructed can include the representation and knowledge of identities, core-domains, and application-oriented domains. If the implemented SISystem can follow these structural and formal constraints outlined in this thesis, it shall be a flexible system. If the models of identities of different ontological kinds and models of core-domains and application-oriented domains are sufficiently accurate, the new SISystem can have a wider range of applications. With an implemented SISystem, the practical usefulness of the synthesised theory can be tested in the real world applications.

All in all, the theory in this thesis should be taken as a tentative first effort instead of the final say in the matter. Is there any possibility of designing new information architecture for SISystems which is based on the environmental representation in the mind of a human? Yes, there certainly is. It depends on how the topic of representation shall be understood and the structural issue for representation shall be handled. The thesis is devoted towards such an ultimate goal. Hopefully, future efforts shall prove it to be a success.
Glossary

**Attribute**  Refers to the categories which are involved in the descriptions of identities. They are also used in categorisations and re-identifications. Attributes are of different ontological natures. For example, there are attributes called physical properties, spatial properties of shapes, boundary parts, internal parts, processes and behaviours. Attributes can also be differentiated based on the formal models for their representation. For example, a shape can be described in geometrical form. A process can be modelled with a function. However, the values of an attribute can also be defined in terms of distances to a reference point.

**Attribute dimension**  The dimension (e.g. colour) of an attribute is about a domain. According to Garner (1974), the attribute domains can be differentiated into two kinds, *integral* and *separable*. An integral attribute is a domain where a value is defined in a space involving several dimensions working together, such as colour involving *hue*, *brightness*, and *saturation*. A *separable* attribute is a domain which is relatively independent. Regarding the descriptions of identities, the contribution from an attribute as a domain is whether an attribute dimension is relevant for the representation and differentiation of identities (e.g., into ontological kinds).

**Attribute values**  That is, the values along an attribute dimension. For example, the value of an attribute (e.g. red) is about the position of a property in the space of an attribute dimension. According to Garner (1978), the attribute values can be differentiated into two kinds, *component kind* with values of presence or absence and *dimension kind* which can have multiple values (e.g. very long, long, medium, short, very short) or numerical values. Regarding the descriptions for identities, the contribution from the values is often related to the identification and categorisation which sort identities into specific categories.

**Basic-level-categories**  The term *basic-level-categories* in this thesis refers to a set of categories which are cognitively salient. In this thesis, *basic-level-categories* are studied within
the context of a core domain. The basic-level-categories are mutually exclusive in that every identity in a core domain should be, in theory, sorted into one of the basic-level-categories. In cognitive studies, a basic-level-category is associated with high cue validity and category validity. The former means they are associated with distinctive features for categorisation. The latter implies the inferences of the properties can be reliable once an identity is categorised as a member of a basic-level-category.

**Categories** In this thesis, categories refer to the collections of identities of spatial features which share certain conditions, such as structural and functional similarities. A category is formed for the purpose of retrieval of the set of identities of spatial features which are members of the category and their general characteristics. The representation of a category is thus also closely related to the representations for the set of identities, either in terms of examples or a prototype.

**Category of substances** The category of substances in this thesis follows Millikan (1998a). It refers to the natural units in the world, including stuff (e.g. milk), individuals (e.g. Mum), and real kinds (e.g. people). The meaning of substances in this use is more generic in comparison with the use of it by GIScientists when the Ontology of the world is discussed. In GIScience, as an ontological kind, the term of substances is in contrast with objects which have boundaries. In discussing this ontological contrast made and emphasised in GIScience in this thesis, the terms stuffs versus objects are also used for identities in the common sense world and the terms field versus objects for spatial features in the large space.

**Causal conditions** The term causal condition or conditions in this thesis is used to refer to the group of transformation processes from identities to properties of the identities. It is about retrieval of information or inferences of properties, locations, processes, or behaviour patterns of identities. The inferences can be based on the representations of identities on different inclusive levels. The retrieved information can then be used to support other cognitive functions, such as attributions of causes, causal explanations of normal or abnormal behaviours, planning of actions and informed decision making on new projects.

**Causal rules** The term causal rules in this thesis is associated with different cognitive processes. The causal rule of identification refers to the process where a natural-unit in the
world is explicitly represented as a distinctive existence in the world, e.g. a member of an ontological-kind. The *causal rule* of categorisation refers to the criteria for sorting identities into a basic-level-category in a core-domain. The *causal rule* can also be associated with the process of re-identification where a new state of an identity in the environment is recognised as belonging to a particular identity. The last sense of *casual rules* is about empirical relations studied in science for explaining certain phenomena.

**Causal systems** The term *causal systems* in this thesis refers to the concrete domain specific situations, which can be either natural or man-made. In these domain specific situations, identities within the situations bear certain causal relations in interaction. The situation itself can be treated as a whole in terms of its internal coherency and behaviour consistency. An example of a causal system can refer to a complex machine. However, there are also natural physical systems.

**Causation** The term *causation* is used in a specific sense to refer to the patterns when two identities, usually objects, interact with each other. There are different patterns when two objects, two organisms, or two people can interact with each other. The distinctions of such patterns are important for defining the core domains of physical objects, biology of individuals, and social domain of people.

**Cognitive systems** A cognitive system is the part of the brain system which is relevant for processing the inputs from the environment and controls the actions upon the environment. A cognitive system exists in the brain of an organism. The state of a cognitive system is determined by the development of the brain and the past experience in the environment. Cognitive systems view the environment in terms of what the environment can *afford* to an organism and the *actions* and *action schemes* which can be applied upon the environment. In a cognitive system, representation of an identity is in terms of the generalised and specialised action schemes applied to the identity. The recall of actions is either activated by percepts of certain properties, or results of mental operations.

**Conceptual systems** A conceptual system is the part of the cognitive system which is relevant for the representation of the environment. Conceptual systems view the environment in terms of *substances, relations, processes*, and *events*. The representation of an identity is in terms of its similarities or differences to other identities. There are different structures
for the representations of categories and individuals. The state of a conceptual system is constrained by the state of a cognitive system. However, a conceptual system can be re-described with symbolic systems and realised in media other than the brains.

Core-domains A core-domain refers to special situations in the environment which have identities belonging to a single ontological kind and have distinctive causal knowledge. Core-domains are associated with distinctive spatio-temporal locations. For a core-domain in the common-sense-space, it is defined by the distinctive interaction patterns when two objects in the close neighbourhood interact with each other. For a core-domain in the small or large space, it is also defined by the distinctive causations and part-whole relations to other core domains.

Identities of spatial features The term refers to the “natural units” in the world, i.e. the “existences” of things in the environment. The terms spatial features and identities of spatial features are used interchangeably, and they are closely related to the term the category of substances in (Millikan, 1998a). However, the term identities of spatial features can include not only stuff, objects, and real kinds, but also other natural units in the larger or smaller spaces, such as those geographical entities or phenomena. Further, the use of the term an identity in this thesis shall not be confused with the descriptionist’s understanding of the term. In the latter case, the meaning of an identity is restricted to some sort of “description(s)” which is supposed to allow the tracking of a thing as the same overtime.

Immediate situations Identities are in situations as contexts. An immediate situation for an identity is about the situation which contains the identity only. The very nature of immediate situations for identities determines the ontological natures of the identities. However, identities of ontological-kinds in different spaces are defined differently. When such situations for identities are in the common-sense-space, the identities within such situations are functionally distinctive to the concern of a person. They can also bear certain functional and causal relations to a targeted object by a person. When they are in the small or large spaces, they have fixed functions as parts or wholes for the objects in the common-sense-space. They are also structurally distinctive in that the situations are in spaces which are on different scales.

Ontological-kinds of spatial-features The term ontological-kinds (of spatial-features) refers
to the functionally and structurally distinctive existences in the world. Functionally, different ontological kinds are fixed with functions to the biological needs of a person and other identities. Structurally, different ontological kinds refer to spatial-features which have distinctive structural properties such as with clear boundaries, or they are in situations in different spaces. The developments of representations of identities in mind are inherently constrained by their different ontological natures. The ontological-kinds of spatial-features as distinctive existences in the world shall be clearly distinguished from the formal logical-mathematical structures which can be used for their representation and modelling.

**Situations** The term refers to the spatio-temporally framed substances in the environment. A situation in the environment is a 4D unit of substances, which can be defined either in terms of the spatio-temporal coordinates or in terms of its internal contents. A situation can be simple (i.e. contains a single identity) or complex (i.e. contains multiple objects which are in simple or complex relations). Situations can be in different spaces and play different functional roles to the concerns of a person. From the cognitive perspective, a situation is learned via its states at times and changes of states over time. The state of a situation can be defined by the states of spatial features in complex relations.

**Spatial features** Spatial features refer to the distinctive units of substances in the environment, often called *spatial entities* or *phenomena*. They are defined over specific resolutions and extensions. They exist in space, have substances and sometimes parts for their contents, and bear spatial relations to other spatial features in a large context. They last and can change their states over time. Some of them can have clear boundaries, which distinguish them from either the background or other spatial features which share the boundaries with them.

**Sub-domains** Refer to application oriented domains which deal with specialised *core-domain* specific situations. A sub-domain has a coherent internal structure and consistent behaviour patterns. There are two kinds of sub domains. One is about the specialisations of a *core-domain* which often take different locations, e.g. geology and hydrology can be taken as two sub domains of the *core-domain* for natural systems. The other is engineering versus physics of natural objects.
Super-domains Refer to application-oriented domains which are complex situations in the environment with multiple identities from different core-domains. The situation can be treated as a whole in that it has a coherent internal structure and consistent behaviour patterns. There are two kinds of super-domains. One is about the complex situations which can have different causal mechanisms working in coordination inside the situation, such as ecological systems. The other is about the generalisation of core-domains in different spaces, and these core-domains are considered as sharing the same causal mechanism or causal law. For example, a social study can include domains which study on the level of individuals and kinships, studies of social organisations of different kinds, demographic studies of patterns of various kinds based on aggregate data (i.e. census tracts), and geographical regions.
Bibliography


BIBLIOGRAPHY


Table 1: First level *cognitive system* versus *conceptual system*

<table>
<thead>
<tr>
<th>Cognitive systems (0-10 month)</th>
<th>Cognitive systems at (0-1 month): the <em>self</em> and the <em>environment</em>. Cognitive system (up to 10 month): the <em>self</em>, the <em>stuff</em>, and the <em>environment</em></th>
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</thead>
<tbody>
<tr>
<td>Conceptual systems (10 months - 4 years roughly)</td>
<td>Representation of simple identities of objects or substances. Before stage IV, identities are understood implicitly with properties and actions upon them. After stage IV, explicit representation of identities are possible. The explicit representation of an identity has two senses. One is the explicit representation where an object is an existence in a location at time. The other is about the explicit conception of an object in terms of its properties and functions (by the end of the first phrase of pre-operational period). The ontological distinction of identities, i.e. substances/stuff/field-kind versus object-kind identities with clear boundaries can be understood by the end of this stage. The distinction is implicit when shapes of objects can be perceptually defined in Stage II of Piaget’s sensorimotor period. However, the ontological distinction should become explicit when boundaries of objects can be explicitly understood in association with functions by the end of the first phase of Piaget’s pre-operational period. Objects can be further differentiated into their corresponding core-domains later.</td>
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</table>
Table 2: Second level cognitive system versus conceptual system
Cognitive systems

Self, identities in situations, the rest of common-sense-space. Associated with fast learning of language names for concrete

(after 10 months)

nouns for objects, locations, and parts as well as names for physical properties (e.g. colour), spatial properties (e.g. shapes,
sizes), and functional properties (e.g. associated with names of sorting objects into functional groups).

Conceptual
tems
years)

(after

sys-

Relations of identities in space and in time can be represented and explicitly known. In Piaget’s sensorimotor period, the

2

relations are implicit which can be represented as embedded in the actions where a child interacts with the objects in sequences.
However, in this second stage of the conceptual system, spatial relations are represented explicitly. Temporal relations of
objects are also understood in children’s representation of events (Nelson, 1986).
There are two levels of functional distinctions of identities in the environment. First, identities can be differentiated into three
functional groups of targets (or figures), means, and locational cues. Second, apart from objects as figures, there are also
functional kinds for the contents (e.g. samples or portions of material, boundary parts, and internal parts) and contexts (e.g.
ground marked by distinctive landmarks, containers, and spatial locations defined with configurations of objects) of the figures.
The representation of simple kind spatial locations with multiple objects in a visual perceptual field starts to develop at stage
V of Piaget’s sensorimotor period (Bremner, 1985). However, the conceptual representation of a location is limited (Piaget and
Inhelder, 1956; Siegel and White, 1975). Those locations which require the configurations of views from different perspectives
are possible. For example, children of Piaget’s pre-operational period usually have difficulties to represent the environment
from others’ perspective (i.e. they often fail Piaget’s three mountain task). The representation of spatial locations for a larger
scale environmental setting is often route-based. The configuration of landmarks for a large scale environment can be constructed in the concrete operational period (Piaget and Inhelder, 1956).


### Table 3: Third level cognitive system versus conceptual system

<table>
<thead>
<tr>
<th>Cognitive system (after 4 years)</th>
<th>Conceptual system (after 4 years - 11 or 12 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self, identities (in core-domains), core-domains (as distinctive units of representation), and the rest of the environment. Representation of spatio-temporal frame and large scale environmental settings in concrete terms. The development of serial operations and basic skills in sorting objects into mutually exclusive groups.</td>
<td>Conceptual development is proliferate. For representation of identities: 1) they are not only existences in their own, but as members of different ontological-kinds and to be studied in their context of core-domains (Keil, 1989a). Identities are explicitly differentiated into core-domains. 2) The representation of the large environmental settings (i.e. the configurations of locations within and for a larger location) (Piaget and Inhelder, 1956; Hirtle and Jonides, 1985; Hirtle and Heidorn, 1993; Hirtle, 1995). 3) Conceptual reorganisation with distinction of individuals and categories (Piaget, 1962). Identities are not only described with properties and contextual information, but also sorted into groups based on different criteria. The criteria change from focusing on single property or spatial locations, to adopting multiple dimensions. The category systems in a language and culture also contribute to, not determine, the process of this re-organisation. For causal knowledge and core domain: 1) The distinctions of causal relations of identities from other types of relations, understanding of simple physical machines and the complex causal mechanisms of biological functions (Smith et al., 1985; Carey, 1985). 2) Core-domains for objects in the common-sense-space become distinctive and independent units of representation. The explicit distinction of core-domains for objects can be based on explicit knowledge of different patterns when identities interact with each other. However, there are also further developments of domain specific causal theories. 3) The core-domains can be defined by the domain specific identities and their relations on the one hand, as distinctive units of representation and knowledge in their own right on the other hand.</td>
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</table>
Table 4: Fourth level *cognitive* and *conceptual* development

| Cognitive system (after 11/12 years-) | The *self, identities* (in core-domains), *core-domains* in *common-sense-space*, *core-domains* in situations in other spaces, and the *environment*. The representation of any situation is theoretically possible, but the accuracy depends on the development of *causal knowledge* of core-domains. There are further specialisations and generalisations of *core-domains* and development of *application-oriented* domains. Formal spatial-temporal frames for situations can be defined in terms of *coordinate systems* (Piaget and Inhelder, 1956). In Piaget’s studies, children can have hypothetical thought and systematic testing of hypotheses. Formal systems of logic and structure of mathematics can also be developed (Brainerd, 1978; Phillips, 1981). |
| Conceptual system (after 11/12 years-) | 1) For objects in the *common-sense-space*, they can be sorted into classes. There are different kinds of category systems. There are taxonomies for core domains in terms of individuals, basic level categories, and ontological kinds. There are possible intensional definitions for basic level categories. There are further generalisation and specialisation of super-ordinates and subordinates, which are associated with events or locations.  
2) *Identities* in the even *smaller* and *larger* spaces are represented. These identities can be studied in their own right. However, from biological perspective, these identities in the smaller or larger spaces are of distinctive ontological-kinds. They are either the *parts* for *contents* (e.g. *cells* or *organs* in an animal) or *elements* of *contexts* (e.g. *buildings* and the *environmental settings* in larger scale) of the *figures* which bear closer functional relevance to a person. |