Propositions

attached to the thesis
A Knowledge-based Computational Approach to
Architectural Precedent Analysis

Nan Fang

(1) The work by Coyen *et al.* (1990) (*Knowledge-based Design System*) is advocating a shallow expert system reasoning approach on design of artifacts which resorts solely to natural language representation.

(2) From a computational point of view, design by analogy and learning by analogy share the same elements in their general structure but have different input and output patterns.

(3) If we use one framework to compare the various research projects carried out in the AKS group (Architectural Knowledge Systems) at Delft University of Technology, this framework must include five levels, i.e., case study, cognitive modelling, computational theory, computing algorithm, and hardware implementation. Each single project covers two or more levels; no project covers all the levels.

(4) The core of applying a computational approach to a theoretical study is that you have to define input and output unambiguously.

(5) It is not accidental that some architectural design methods, such as the "pattern language" by Christopher Alexander, are methodologically very beautiful but have not demonstrated results in design practice that are beautiful enough.

(6) The application of computers in architecture has so far reduced little employment in design practice; but it has certainly increased many jobs in design research.

(7) To impose an order on society and environment is constantly a general motivation in all architectural design actions, whatever the order is.

(8) While architectural designers aim at imposing an order on human life, architectural theorists aim at imposing an order on designs.

(9) As in architectural design, the most difficult work in architectural research is to define a problem rather than to solve it.

(10) If one is unable to write about his/her research subject in a fairly nontechnical way, it could be that he/she does not know the subject as broadly and as deeply as he/she should.

(11) The contrast between Oriental synthetical mode of thinking and Western analytical mode of thinking can be exemplified by the contrast between the use of chopsticks and the use of fork, knife and spoon in dining.

(12) Writing a thesis in architectural theory is analogous to drawing a circle which must pass through four or more given points without knowing if all the points are actually on a circle.

(13) Religions are like drugs. They can maintain the health of a society; but they can also be abused to destroy a society.

A KNOWLEDGE-BASED
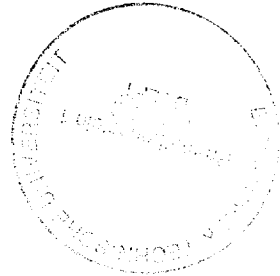# COMPUTATIONAL APPROACH TO
ARCHITECTURAL
PRECEDENT ANALYSIS

A KNOWLEDGE-BASED COMPUTATIONAL APPROACH TO ARCHITECTURAL PRECEDENT ANALYSIS

Proefschrift

Ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
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Dit proefschrift is goedgekeurd door de promotoren

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To Ling and my parents

On the cover is the plan of the King City of Zhou, showing an ideal model of city in ancient China, recorded in *San Li Tu*. Under the title of each part is a portion of an old map of Beijing City in the Qing dynasty, recorded in an atlas made in ca. 1750. Under the title of each chapter is an ancient Chinese character, which means *Gong*, or palace, inscribed on bones or tortoise shells remained from the Shang dynasty (ca. 17~11 century B.C.).

Preface and Acknowledgments

This work is generally concerned with the question *How can precedent knowledge be used in architectural design computation?* Specifically, the work investigates how plans of architectural precedents could be analyzed so that some characteristics of their spatial organization can be represented and used for generating new designs.

In architectural design practice, generating new forms on the basis of precedents is a common approach. Yet, it has not received enough attention in design computation research until recently. Presently, understanding the use of precedent knowledge in design and describing it with a computational theory is still a major challenge in research, even though some computer programs have been hastily produced for the purpose of utilizing precedent knowledge in automated design generation. This work is regarded as an effort to address that challenge.

The work is part of a collective research project, Artificial Intelligence for the Intelligent Architect (AIIA), which is carried out in the Architectural Knowledge Systems (AKS) research group of the Faculty of Architecture, Delft University of Technology. The general objective of the project is to improve architectural design methods by studying and applying methods founded in the area of Artificial Intelligence (AI). The ultimate goal of the AIIA project is the development of an intelligent architectural system, Intelligent Architect, for automatic generation and evaluation of design solutions which satisfy specific programmatic requirements.

In carrying out the research and preparing the thesis, I have received the help and encouragement of many people. First of all, I would like to

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Part III The representation of domain knowledge

7. From Drawing to Structural Description

8. Frame-directed Spatial Categorization

Chapter 1
Introduction

Precedent knowledge is an important aspect in architectural design practice, but it is only beginning to receive widespread attention in design computation research. The challenge, for such research, is to produce a description that reflects the characteristic features of precedent knowledge and the way precedent knowledge is used in design and at the same time respects requirements of computation.

Non-computational description of precedent knowledge and its use in design has often been provided by architectural theorists and educators. How far the accounts could be made computational is indeed a debatable subject. On the other hand, some computer-oriented work in architecture has produced computational models or even operational programs by suppressing some crucial aspects of precedent knowledge, or simply ignoring the importance of precedents.

The objective of this work is to develop a framework for the use of architectural precedent knowledge that combines both architectural and computational perspectives.

1.1 Architectural precedent analysis and its computerization

Architectural precedent, in this work, means a preexisting building or other built environment[1] that may be used as an example for the current design action. Although in many architectural designs the example may not be a built environment, the work is confined only to the examples that are built environment. In this work, "architectural precedent" and "architectural precedent analysis" are also simply called "precedent" and "precedent analysis". An architectural precedent may be a real built environment or the document of a built environment.

Why precedent

Using precedent in making professional judgement has long been an established method in law and medicine. In actuality, using precedent in design decision making has been an important approach in architecture as well, although it was not seriously explored until Collins (1971) discussed architectural judgement by analogy with legal judgement.

Generally speaking, most architectural design actions are inspired and/or constrained, in one way or another, by precedent (Hancock, 1986; Clark & Pause, 1985; Rapopport, 1990). We have several reasons for that:

(1) The architectural problems are typically ill-defined; some desired characteristics of a new building are often difficult to be specified in the sense that there is neither definite means to achieve them nor clear criteria to evaluate them. This often leads to connecting the description of the characteristics to some precedents which are known for having the characteristics at least to a satisfactory extent. In other words we "borrow" the means and criteria from the precedents to specify our problem.

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[1] The term *built environment* is used after Habraken (1982). It is a generalized concept of the rooms, the buildings, the urban sectors, the cities, etc. A built environment is an artifact, but it has a peculiar property, that is, people can stay or move in/around and perceive the spaces of it.

(2) In some design tasks, we often hope to keep the historic continuity of the site where the new design stands. In this case, we need to select some of the distinctive characteristics from the preexisting environment and to realize them in the new design.

(3) In design, we often solve a new problem by referring to some previous solutions so as to reach a new solution efficiently. This is often referred to as analogical or heuristic method of problem solving, which involves in matching the characteristics of a new problem with the characteristics of a precedent solution.

Yet, a precedent, either a real built environment or its document, can not serve directly for a design action before it is *analyzed* in terms of its characteristics and with respect to the specific design task.

Why precedent analysis

The characteristics relevant to a design task often cover only one or several aspects of a precedent and that may not be shown by the precedent itself or be explicitly described by the document. For example, if we are told that an old house is good for privacy and might be used as an example for a current design work, we need first to analyze why it is good for privacy and maybe we conclude, say, that it is because of the use of small windows. That using small windows can achieve privacy, however, may not be already written down as a rule. We have to do some analysis before we get the conclusion.

Moreover, even if some rules are documented and they are relevant to the design task, they may not be able to be applied directly to the current design task for this or that reason. For instance, in the above example, probably the small windows are not applicable to the current design because of other constraints, such as natural lighting or desired composition of facades. If so, then we have to find other possible reasons causing these privacy and subsequently arrive at some new conclusions.

Finally, assuming that all the relevant rules are found and we may apply them to the current design, there is still a problem: How can we synthesize them *efficiently* into a new design? This third situation is very

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common in architectural design, because usually many important characteristics of the architectural precedents have been documented in detail or known by the designers through their education. Yet, when these precedents are to be used in a particular situation, they are still found difficult to be put together.

In short, a prerequisite to using architectural precedent knowledge is an adequate analysis of the precedent in terms of its characteristics and with respect to the specific design task. Precedent analysis can be generally defined as a process of explicating characteristics of a precedent according to some known characteristics of it.

The nature of precedent analysis: example-based learning

Precedent analysis is in fact a process of acquiring new knowledge from examples; and this process requires the application or re-organization of some preexisting knowledge. Because of this, precedent analysis can be viewed as a process of *example-based learning*. Example-based Learning is to derive new knowledge according to some given examples and instructions; its purpose is to reorganize predefined rules or specify a general concept so as to improve the performance of a problem-solving system (Carbonell, Michalski & Mitchell, 1983). Precedent analysis, as will be argued, is structurally similar to a learning process that combines both inductive learning and deductive learning. This assumption leads the work to develop the computational framework of precedent analysis on the basis of machine learning paradigms, some well-established theories in Artificial Intelligence.

Precedent analysis has some features common with *diagnosis*. They both start from some known performances of a system, and aim at finding the causes of those performances; they both need special knowledge to conduct the reasoning; but they are not identical. The precedent analysis studied in this work concerns the analysis of all kinds of performances, whereas diagnosis is usually applied only to systems with unsatisfactory performances, such as the dampness in buildings or house structure problems (Oxley, 1981; Seaquist, 1980).

Precedent analysis can also be compared with the process of *analysis in design* defined by Rosenman (1990). Analysis in design is "the process of taking a description of a building element and deriving values of its performance." The precedent analysis studied here is primarily a reversed process, i.e., taking a performance and deriving a formal description related to this performance.

Precedent analysis and design computation

To study precedent analysis from a computational point of view is an urgent task in design computation research. This claim is made out of several reasons.

First, since the computer entered architecture it has long been fettered by the paradigm that architectural design is a pure analytical process without the need of precedent knowledge (Tzonis, 1990). The use of precedents has thus long remained only as a topic of non-computational research.

Second, in recent years, integration of precedent knowledge in design computation system has received some attention. But as in the other architectural design computation researches, it still lacks "a demonstrably sound, comprehensive, rigorously formalized theoretical foundation upon which to base practical software development efforts" (Mitchell, 1986). Of course, the construction of such a theoretical foundation is beyond the capacity of a single research project like this one. But the attempt made by this work is definitely contributing to the development of the theoretical foundation.

Third, some computation-oriented work has developed a number of techniques that might be used for the representation of architectural precedent (e.g., shape grammars, see Mitchell, 1990). However, most of these techniques are hardly satisfactory with respect to the needs of precedent analysis because of their limited capacity in morphological description or incompatibility with the descriptions of other aspects of built environment (e.g., operation and performance).

Finally, some recent discussions on the use of architectural precedent have been inspired by Artificial Intelligence (e.g., Coyne, *et al.*, 1990;

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Gero, 1992). These studies have suggested some prominent concepts and useful clues to the computerization of precedent analysis, though, they need to be extended by further investigations taking into consideration some important aspects of cognitive competence relevant to the representation of architectural domain knowledge.

To further understand the importance of precedent analysis and its computerization research, let us review briefly the development of computation in architecture.

1.2 Computerization in architectural design: a brief review

In the early 1960's, the computer entered into architecture with three remarkable events which defined roughly three major lines along which architectural computation tools and theories have been developed.

One of these events was the appearance of SKETCHPAD (Sutherland, 1963), which allowed an engineer to produce line drawings on an interactive graphic terminal, and manipulate the drawings on the screen through light-pen and keyboard. The system pioneered the development of computer graphics, resulting in tools for drafting and visualization currently used by many designers. This use of computers, however, is very limited; because it does not affect the actual process of design, except by reducing the time required to communicate the design ideas (Orr, 1985). Even though many of today's graphic systems can generate impressive 3D building models, they are still viewed as merely another medium, taking the place of physical scale models, for the representation and review of design solutions (Harfmann, 1987).

Another event in the early 1960's was the occurrence of a system for specifically architectural applications (Newman, 1966). Besides providing stored standard modular building elements for a user to assemble a plan on the screen, the system was able to produce a list of room areas of the plan

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automatically, compile a schedule of the material used, calculate the heat loss from the structure and assess the lighting levels. This was the beginning of using computer in performance analysis, or design evaluation—another line of computerization. The application along this line has been quite successful as well, especially in environmental analysis (Reynolds, 1987); but it is still regarded by many as beyond the centre of interest of computerized design, that is, design generation.

Computerized design generation is the third major line of computerization in architectural design. This was started by two important works, i.e., Chermayeff & Alexander's *Community and Privacy* (1963), and Alexander's *Notes on the Synthesis of Form* (1964). These works, having introduced the computer, also brought in to architecture an *analytical paradigm*: generation of a design required little domain knowledge as constraints in advance; design was viewed as a quantitative, combinatorial problem defined by the matrix of elementary requirement interactions plus a few restricting rules, a problem which could always be solved through numerical calculation (Tzonis, 1990).

The analytical paradigm dominated the early computerized design generation research, which resulted in various architectural plan generation techniques generally known as Space Planning or Space Allocation (Grant, 1983; Tzonis, 1990). The problem to be solved by these techniques can be typically expressed as: "Given a list of rooms, dimensional constraints on their areas and extensions, and topological constraints on interconnections of rooms or their access to open air, find: one or more floor plan(s) composed of the rooms so as to satisfy the constraints." (Galle, 1986). Solutions to the problem are usually searched for by exhaustively enumerating all the possible plans satisfying the constraints or by means of mathematical models of optimization.

Yet, few of these techniques, including some with marginal modifications, could be satisfactorily applied to design practice because they were neither effective nor efficient as expected. If computationally manageable they were reductive in their conception and led to poor products—thus ineffective. If they were enriched by a higher degree of complexity they led

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to long cumbersome computations or "combinatorial explosions" impossible to handle with available computers—thus inefficient (Berwick, 1971).

After many attempts and failures, it was finally realized that the problem was not with the computers and mathematic algorithms used, but with the analytical paradigm of architectural design itself. To improve the computer application in design generation, the only way was to break through the old paradigm and look for a new one (Tzonis, 1990).

Currently, a new paradigm is being formed: architectural design is a knowledge-based process. It assumes: to realize computer aided design generation, strong constraining structures have to be employed in advance in generating or manipulating designs; architectural precedent knowledge has to be introduced in the design process; the computer has to be used as an instrument to carry out reasoning and symbolic inference.

The new paradigm, developed under the influence of AI (Artificial Intelligence) theories and techniques, leads many researchers to the development of *automated design systems* capable of producing either automatically or interactively complete designs from scratch. How far this can be achieved eventually is indeed still a question arguable both technically and philosophically; but at least some work has shown the merits of the efforts, such as the development of expert systems (Reynolds, 1987). More important, such development requires more in-depth studies on the formalization of architectural knowledge, and it is, in turn, pushing the development in architectural theories and education. For example, in the past years, we have seen many efforts in the formalization or re-formalization of architectural knowledge, such as pattern languages (Alexander, 1977), design typology (e.g., Argan, 1963; Moneo, 1978), the classic canon (Tzonis & Lefaivre, 1986). A re-examination on these formalisms from a computational point of view, would largely deepen our understanding on them.

AI and architectural design computation
Compared with the early computation paradigm that treated architectural problem-solving merely as numerical calculation work, AI theories, which deal with symbolic reasoning, are more appropriate for studying architec-

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tural thinking. Reasonably, design computerization can be developed by making use of some well-developed frameworks and methods in AI. However, this does not mean that AI theories, developed mostly in non-architectural fields, can be directly applied to solving architectural problems.

A pre-requisite to any AI application is *knowledge representation*, i.e., how to capture the important aspects of a knowledge domain and represent them in an appropriate form for manipulation (Winston, 1992). Yet, the knowledge representation systems developed with general purposes are mostly unable to be used directly in the architectural domain. This is partially because of some peculiar properties of built environment, and partially because of the nature of architectural design thinking. Therefore, applying AI methods we must develop architectural domain-specific representation systems which fit the frameworks and methods developed in the non-architectural fields.

This principle, as will be seen, is precisely followed by this work: the computational approach to the precedent analysis is formulated by analogy with machine learning, a well-developed AI theory; but the representation system for the approach is devised by referring to characteristics of architectural spatial recognition.

1.3 Research framework

This work attempts to develop a theory for the use of precedent in architecture with the goal to implement this theory in a computer-based system. More specifically, the work presents a computational approach to the use of architectural precedent by designing the structure of a knowledge-based computer system, ARPRAN (ARchitectural PRecedent ANalyst).

ARPRAN
The task of ARPRAN is to produce a pre-parametric description of spatial organization that accounts plausibly for a given performance of built environment according to the plans of some precedents known for having

that performance. The output of ARPRAN is expected to be used by a design system.

The "pre-parametric description" denotes the description of the architectural forms at a highly abstract level. It is borrowed from and corresponds to the concept of *pre-parametric design* (Ulrich, 1988): design at the level of detail of a blackboard sketch rather than at the level of detail of a construction drawing. In architecture, pre-parametric design can be roughly defined as the design that specifies only the gross spatial organization of a built environment. The specification level for pre-parametric architectural design and the correspondent precedent analysis will be further discussed.

That ARPRAN will operate with pre-parametric description is due to the nature of the architectural design and the precedent analysis. Architectural design on a pre-parametric description level is an important stage in the whole design process (Lin & Protzen, 1993). At this stage some global, qualitative design objectives are synthesized; whereas such objectives are often difficult to be specified without relying on precedent. Therefore, to produce a useful specification for those global, qualitative objectives is a major reason why precedent analysis need to be performed.

As will be further discussed, the main features of the computer systems serving for architectural design are dictated by the characteristics of architectural design. The fundamental ability required of a computer system like ARPRAN is not to "solve" problems by producing a single "correct" answer. Instead, the requirement is to produce *plausible* answers according to given domain knowledge. Plausible reasoning is characteristic to precedent analysis as well as design thinking (Polya, 1954; Simon, 1973; Roozenburg, 1992).

The design of ARPRAN

The work focuses on three basic issues in the design of ARPRAN: (1) the domain problem ARPRAN deals with, (2) the specific computation task being addressed, and (3) the representation system used in the computation. The development of the computing algorithm as well as the implementation of ARPRAN is beyond the limits of the work.

This methodological decision follows Marr's (1982) distinction between the three different levels at which an information processing device could be described. According to Marr, the top level requires a *computational theory*, which is to specify in formal terms the domain problem the device deals with, the information that may be available, and the information required to solve the problem. The middle level, called *representation and algorithm*, has to do with the various ways the required information could be represented and the necessary calculations made. Finally, the bottom level, *hardware implementation*, describes the actual implementation of a given algorithm in some computer hardware. The description of ARPRAN in this work lies somewhere between the top and the middle level.

The level of specification of ARPRAN in this work is analogous to the usual task of an architect: he designs a building but does not necessarily construct it. Similarly, the work specifies ARPRAN to a certain degree only: the general principles, the major procedures of the proposed approach, as well as the representation system used in the approach are outlined as comprehensively as possible or necessary, but the finer details of their implementation, including the precise computational tools that may be used, are considered only in brief and in abstract. To use architectural terminology, the work describes the *design* and not the *construction* of ARPRAN. Designing ARPRAN at computational theory level is a research strategy similar to that used by Koutamanis (1990) in the development of a computer vision system for architectural plan recognition.

1.3.1 Defining the use of architectural precedent

The first issue in the computational theory of an information processing device is to define the domain problem. This issue is tackled by the work in two parts. The first consists of a presentation of a design case study, which aims at understanding the use of precedent knowledge in a real design situation. The second is a critical review of some available representation

systems for architectural space; the review aims at evaluating problems as well as potentials of those systems with respect to reconstructing the precedent analysis method implied by the case study.

As mentioned earlier, architectural precedent analysis is closely related to a design task. While architectural design includes a very broad class of problems, this work is focused quite narrowly on one category of domain problem: urban renewal design—designing new buildings in the old urban fabric. This choice is made to highlight the use of precedent knowledge. In this type of design, one usually needs to use precedents not only as heuristic means to identify new solutions analogically (Winston, 1992; Tzonis, 1990), but also as a constraint for keeping the historic continuity of a place (Hancock, 1986).

To understand the role of precedent knowledge, the work begins with the study of a successful design case—the design of the "new courtyard house" in Beijing's old city. This design case serves two particular purposes in the research.

First, it is a methodological device used for clarifying several basic issues concerning the use of precedent in design: the concept and elements of precedent knowledge, as well as the role the precedent knowledge plays in design. For this purpose, the case study is undertaken with a prior assumption, a general model of architectural precedent knowledge, which has been derived from some previous theoretical works and which can provide a satisfactory account for the case study. In other words, we can say that the case study is aimed at specifying the general model of precedent knowledge in order to apply the model to the development of a computation system.

Second, several precedent analysis sub-problems extracted from the case study and the knowledge related to the analysis are also used as examples in specifying the computation task of ARPRAN. It can be said that the initial version (or the research version) of ARPRAN is intended to *reconstruct* the process in which the designer in our case study analyzed the precedents. The reconstruction here does not mean to simulate a designer's thinking in real time; rather, it is aimed at producing a reasonable and

potentially generalizable model of representation and inference by referring to a specific actual design situation. Some important methodological considerations underlying such a case study will be given in the next sub-section.

Once the design case is analyzed in rough manner, several available representation systems are reviewed in reference to their capability of accounting for the design case. The systems reviewed include topological representations of plan, rectangular dissections of plan, shape grammars, zoning diagrams and schemata of classical architecture. They can generally be classified as computational and pre-computational systems for using, describing or analyzing built environment. These systems are selected for review because they had already widespread applications in architecture in representing spatial organization of built environment.

The systems reviewed have been developed each within a specific problem domain and with a specific goal. Seen from this vista they may be regarded as efficient and effective. In this work, however, the systems are evaluated in respect to two criteria, both of them are derived from the case study. The first is their capacity of conveying information which is necessary to the representation of some spatial concepts found in the case study. The second is the possibility of integrating the systems into a reasoning approach towards the use of precedent, which is characterized by correlating the representation of built environment with a design objective, as we can see in the design case study.

Through this critical review of the "state of the art methods," the characteristics of the approach to be developed are defined. The work finally develops a new approach to the use of precedent in design which comes closer to the one emerging out of the case study.

1.3.2 Why a case study

All of the major ideas in this work are initiated and developed on the basis of the design case study. This is mainly because precedent analysis is closely related to design; whereas architectural design is application-oriented and

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diverse in nature, hence it is difficult to talk of an "architectural design problem" abstractly. The case study, however, allows one to specify the design and the analysis task and to focus in depth and in detail on the domain problem without loosing applicability.

The case-study method

Case-study is a research method widely used in many different disciplines, especially the social and behavioral sciences. Case-study refers to the description and analysis of a particular entity (object, person, group, event, state, process, or whatever). Such singular entities are usually natural occurrences with definable boundaries, although they exist and function within a context of surrounding circumstances. The case studied is usually seen as an instance of a broader phenomenon, as part of a larger set of parallel instances. A case-study is thus often used to demonstrate a "typical" or "representative" state of affairs or to illustrate a range of phenomena. A case-study may also prompt further, more wide-ranging research, providing ideas to be followed up later (Bromley, 1986; Orum, Feagin and Sjoberg, 1991; McNeill, 1985).

A case-study may deal with a single case or a handful cases, depending on the field of inquiry. Sometimes a single case is enough for the investigation of a category of situations; but sometimes within a given field of inquiry there may be family resemblances between different cases, hence several cases are studied in a comparative framework. In both circumstances, the "case" must be described and analyzed with some presuppositions. In this respect, a case-study is not exhaustive in its description and analysis of a situation; it is selective in the sense that it addresses itself to some issues and ignores others.

The advantage of case-study, as Orum *et al.* have addressed, is that it is an in-depth, multifaceted investigation, enabling holistic studies of complexes, permitting insights into human motivations. Case-study is a *qualitative method* and is in contrast with the *quantitative methods*, which are often based on collecting data from large number of samples. The difference between case study and the quantitative investigations of a large

number of cases can also be analogous to the difference between deductive learning and inductive learning (see Chapter 6 for explanation of learning). The case-study method can be understood as learning from a case or several cases deductively, whereas quantitative investigation of a large number of cases is resembling to inductive learning.

This work uses the case-study method because the inquiry is focused on the representation and inference of precedent knowledge; it requires an in-depth, *qualitative* investigation. In addition, a rough, general assumption of precedent analysis can be derived directly from some previous architectural theories; but to implement the assumption in a computational approach, we must be more specific with the assumption. Obviously, the best way to be specific is to refer to an example—that is, a case study.

Why the case of Beijing's old city

The case chosen in this work is the design of the "new courtyard house" in Beijing's old city. Of course this choice does not imply that the way the precedents have been used and analyzed by the designer in this case was the best. The choice is made primarily because of the typicality of the case. As addressed earlier, urban renewal design is one category of design which typically uses precedent. The design of the "new courtyard house" is a typical (not a unique) urban renewal design. Moreover, Beijing's old city is a typical historic cityscape; it is unique in terms of its beauty, but it is not different from any other old cities of the world in terms of conflict between development and conservation (see Appendix A). Therefore, we have good reason to believe that the conclusions drawn from this case study have great potential for generalization. In addition, the environment in this case has clear spatial organization in all levels of scale; this regularity in the environment can simplify the research but without reducing its realism.

The method used in this case study is basically to analyze and interpret design descriptions (made by the designer) according to a preselected framework of architectural knowledge. This method corresponds to what is called *document study* in social science (Bailey, 1978). Section 2.1 gives more explanation on this method.

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The weakness inherent in the case-study approach is the potential to deliberately choose a unique case and even manipulate the case to cater for a theory. This problem is recognized in this work, hence emphasis is put on the independence between choice of case and choice of theory. In other words, the selection of another case, be it studied using the same method, will not change the conclusions of the study. This point will become clear as we move into the presentation of the case study in the next chapter.

1.3.3 Specifying the task of precedent analysis

After circumscribing a domain problem, the next step in the design of ARPRAN is to specify the specific computation task. What is the input? What is the output? What knowledge is required to perform the task? These questions are answered from two perspectives in this work.

First, the work discusses the task from an architectural point of view, identifying the general characteristics of precedent knowledge and the relation between precedent analysis and architectural design. Through this discussion, the general assumption used in the case study is specified. The work indicates that morphology, operation and performance of built environment constitute a model of precedent knowledge. This model not only explains what we observed in our case study, but also provides a framework with which we can specify several tasks of precedent analysis with respect to architectural design.

Second, the work defines the task from a computational point of view, comparing precedent analysis to example-based machine learning. This study aims at establishing a framework for the input, the output, the knowledge base and the major procedures of precedent analysis. Since the system to be developed is new in the architectural domain, we shall adopt a model already developed in Artificial Intelligence (AI). In this work the model for ARPRAN is the *machine learning* system.

Why machine learning

Machine learning is a research field in AI, where computer modelling of the learning process is focused. More specifically, the field of machine learning is organized around three primary research foci, i.e., (1) the development of learning systems to improve performance in a predetermined set of tasks (also known as the "engineering approach"); (2) the investigation and computer simulation of the human learning process; and (3) theoretical exploration of possible learning methods and algorithms independent of application domain (Carbonell, 1983).

Presently, machine learning research is carried out with a number of major paradigms and multiple sub-paradigms; among these, example-based inductive learning and analytic learning are two major paradigms most widely studied. *Inductive learning* is one of inducing a general concept description from sets of positive and negative examples. *Analytic learning* (or deductive learning) is based on learning from few exemplars (often a single one) plus a rich underlying domain theory. In many practical situations, however, some sub-paradigms based on *combining both inductive and analytic learning* are more applied. Machine learning systems developed with such "combined" paradigms are also the model for the system of architectural precedent analysis.

I use a machine learning system as a model for a precedent analysis system first of all because of the nature of the precedent analysis. The process of precedent analysis has many features similar to the process of example-based learning combining both inductive and analytic learning. For example, the precedent analysis requires a system to be able to acquire new facts or rules according to some given example(s) and instructions. This is very similar to the general problem defined in machine learning. The similarities between precedent analysis and machine learning allow us to specify the major components in a precedent analysis system—such as the input, the output, the knowledge base and the major procedures—by analogy with those presented by the machine learning researchers.

Machine learning is a widely studied field in AI research, where solid theoretical foundations are being established (Carbonell, 1990). It is

sufficiently developed as a general method to be applicable in the specific area of architectural precedent analysis. Of course, the application of a general method developed in AI to the architectural domain is a problem in itself within which the representation of the particular domain knowledge is central. And the investigation of the later problem is exactly the aim of this work.

1.3.4 Studying the representation of domain knowledge

In this work, domain knowledge means both the knowledge to be gained through precedent analysis and the knowledge needed for the analysis. The concept of *representation* here, however, should be distinguished from that of *computer representation*. This differentiation is clearly indicated by Charniak & McDermott (1985, p. 320), who distinguish between *abstract representation* and *concrete representation*; the former refers to the *content* of representation and the later is about how it is *indexed*. This work is focused primarily on the abstract representation.

The representation system developed in this work has two main theoretical sources: (1) studies towards the formalization of architectural knowledge, and (2) theories developed in the field of cognitive science. These theoretical sources are used in combination with the design case study. The architectural sources, including a model of precedent knowledge and some available representation systems, are partially dealt with through the first two parts of the work, i.e., the definition of the domain problem and the specification of the domain task. In this part, the work integrates those architectural sources with cognitive theories, in order to reconstruct the architectural recognition process in our case study.

The cognitive theories referred to in this work are mainly those concerning spatial conception and representation; they originate from studies in cognitive psychology and linguistics. The cognitive theories taken into consideration in this work include theories on the nature of drawing and verbal description, on how people perceive and categorize spatial objects

and on how spatial relations can be described with language. These theories reflect some deep cognitive structure with demonstrably efficient and effective characteristics, hence are very relevant to the computation task of architectural precedent analysis.

Why cognitive theories

The need to apply cognitive theories in this work emerges out of the requirement to reconstruction: the theories can help us understand and reconstruct the spatial recognition process in our design case study, which serves as a criterion in the development of the precedent analysis approach.

The available representation systems for architectural space are unsatisfactory with respect to representing the spatial concepts emerging in the case study, because these methods cannot convey information that makes *semantic distinctions* among the locations in an abstract spatial pattern. Some basic semantic distinctions, such as indoor/outdoor, privacy/public locations, are essential to the description of architectural space, especially when the description is aimed at specifying the performance of a space (producing such descriptions is the ultimate goal of this precedent analysis). To fully understand the necessity and the application of the semantic distinctions in spatial representation, however, we must resort to the theories developed in cognitive science.

Cognitive science is a broad interdisciplinary field that draws primarily on cognitive psychology, artificial intelligence, linguistics, philosophy, and neuroscience. These disciplines are to some extent distinct in their methods, theories, and results, yet they are strikingly unified by the convergence of their core questions and by the emergence in each of them of a computational, or information processing, view (Stilling *et al.*, 1987). It is also the computational view that methodologically justifies and supports our application of cognitive theories in the architectural domain.

Applying theories of cognitive science to the design of a working system, one must understand the relation between the development of a machine and the study of human intelligence. This relation is analogous to that between a *normative theory* of reasoning, which says how people *ought*

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to reason, and a *descriptive theory*, which says how they actually *do* reason (Harman, 1986). As Harman has argued, normative and descriptive theories of reasoning are intimately related. At a certain point, it is not easy to distinguish a descriptive theory of reasoned revision from a normative theory. Any normative investigation must begin by considering how people actually do reason and how people criticize reasoning. On the other hand, any descriptive theory has to make use of idealization.

It is also true to the study of knowledge representation. It has been argued neither that human mind should be a model for machine representation, nor that artificial intelligence studies should be the model on which psychological descriptions should be based; but it is also assumed that an exchange of ideas would be fruitful between two fields where an understanding of knowledge representation is desired, both to examine possible representations and to identify phenomena against which to evaluate them (Conway & Wilson, 1988). This is because the only model we have for a working intelligent system which uses and represents large amounts of knowledge is the human mind.

To summarize the research framework, we can say that it is a study of the computational theory of architectural precedent analysis, including three important issues: (1) the definition of the domain problem, (2) the specification of the computation task, and (3) the representation of the domain knowledge. The framework has also three distinct characters: (1) using a real design case as a basis for defining the domain problem, (2) introducing machine learning methods as means to specify the computation task of architectural precedent analysis, and (3) applying cognitive theories in architectural knowledge representation.

1.4 Outline of the thesis

This chapter has introduced the concept of architectural precedent analysis and the problem of its computerization. A research framework towards the

computerization of precedent analysis has been described and some method-
ological considerations behind this research framework have been discussed.

Corresponding to the three issues addressed by the research frame-
work, i.e., (1) the definition of domain problem, (2) the specification of
computation task, and (3) the representation of the domain knowledge used
in performing the task, the proceeding chapters are divided into three parts.

The first part, *the use of architectural precedent*, consists of two
chapters.

Chapter 2 presents the design case study, the design of the "new
courtyard house" in Beijing's old city. At first, the design problem and its
background, the design solutions and the designer's major ideas are describ-
ed on the basis of several professional reports made by the designer. The
description is focused on the conceptual design of the new house type.
Then, the chapter gives an interpretation on the use of the precedents by
analyzing and inferring some properties of the precedents which have been
used by the designer either explicitly or implicitly. The interpretation is
made according to the designer's verbal description as well as sketches.
Finally, the chapter draws a number of remarks on the use of precedent
knowledge in the conceptual design.

Chapter 3 reviews a number of available systems for architectural
spatial representation with respect to some observations made of the case
study. The systems reviewed include the topological representations of plan,
the rectangular dissections of plan, shape grammars, zoning diagrams and
the grid schemata of classical architecture. The study indicates that none of
these systems can be independently used for the representation of the spatial
concepts which appeared crucial in the design case, and moreover they are
difficult to be integrated in a reasoning approach to the use of precedent, as
implied by the case. As a conclusion, the chapter indicates that a new
representation system is needed.

The second part, *the task of precedent analysis*, contains three
chapters.

Chapter 4 and Chapter 5 define the precedent knowledge and the
precedent analysis from an architectural perspective. Chapter 4 starts with

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a detailed discussion on the concept of performance, operation and morphology of built environment and their interrelationships. The discussion aims to derive a broader definition of the concepts, which are considered as the elemental aspects of the precedent knowledge, constituting the basic structure of architectural precedent analysis.

Chapter 5 illustrates some general characteristics of architectural design, focusing on the role of precedent knowledge and precedent analysis. It indicates that the analysis of architectural precedent is an indispensable procedure for most architectural design actions. Particularly, such precedent analysis is useful for the specification of non-quantifiable objectives, for precedent-constrained design and for design by analogy. Finally, the chapter gives a definition of architectural precedent analysis and summarizes the main tasks of analysis.

Chapter 6 defines the process of precedent analysis from a computational perspective, and compares precedent analysis to example-based learning. It first addresses a general requirement on the input and the output of a system for precedent analysis, and draws some general features of such a system. Then, based on a review of some paradigms of example-based learning and a comparison between precedent analysis and the learning methods, the chapter points out that (1) a system for precedent analysis can be treated as a machine learning system that uses both similarity-based and explanation-based methods, and (2) a system for precedent analysis requires representational tools different from most commonly studied learning systems. Finally, the chapter illustrates a sketchy structure of ARPRAN by presenting two exemplar problems of precedent analysis. The two exemplar problems are extracted from the design case study presented in Chapter 2.

The third part, *the representation of domain knowledge*, includes also two chapters, which treat ARPRAN as a new representation system integrated with principles of spatial cognition.

Chapter 7 focuses on the input, output and knowledge base of the new system. It starts with a cognitive discussion of two distinct forms of spatial representation, imagery and proposition, and indicates that the distinction between them has been reflected in ARPRAN's representation

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proposal as a distinction between the input of the precedent example (i.e., the labelled line drawing of plan, or the LLD) and the output of the analysis (i.e., the labelled location net, or the LLN). Then, the chapter points out that the value of an imagery-based input, such as the LLD, is to make use of the equivocality of architectural plans. By introducing the concept of structural description, the chapter further indicates that the essence of the architectural precedent analysis is to *re-present* the imagery-based, equivocal representations of architectural plan(s) as proposition-based, meaningful description(s). In addition, the chapter argues that the assignment of meaning to a plan as well as any object is always schematized, because of the perceptual bias towards seeing and interpreting objects in space. These notions lead to the construction of some semantic distinctions in ARPRAN's knowledge base.

Chapter 8 discusses the process of ARPRAN's representation of precedents. Precedent analysis is a spatial categorization process directed by a frame which is constructed according to pre-existing knowledge. "Frame construction," as the first major procedure of ARPRAN, is to establish a set of principles which connect the target performance to their precedent examples. The frame is responsible for selecting rules for "plan abstraction" and "generalization," two other major procedures of ARPRAN. This is an application of the top-down principle of visual perception. In contrast, "plan abstraction" and "generalization" can be seen as two operations in a bottom-up process. Plan abstraction is to turn a LLD plan into a LLN local description by dividing a plan into locations, categorizing the labels in the LLD, and merging the locations. Generalization is to form a global description on the basis of the local descriptions.

Finally, Chapter 9, the concluding chapter, summarizes the major ideas, contributions and limitations of the present work, and discusses the potential extension and generalization of the work.

In the appendixes, a brief introduction to Beijing's old city and more description of the "new courtyard house" project are provided for the readers who are not familiar with the city and the problems it has.

We now move into Chapter 2, presenting the design case study.

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Part I

The Use of Architectural Precedent
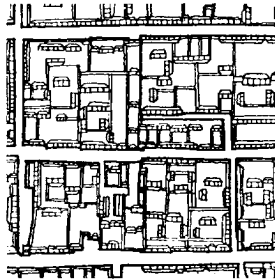
Chapter 2
The Design of the
"New Courtyard House,"
A Case Study
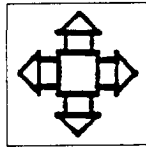
Architectural design is knowledge-based activity. Architects use precedent knowledge in their design. These are common sense. But what is the knowledge on which architectural design is based? What is precedent knowledge? Why precedent knowledge is needed? What kind of precedent knowledge is needed in design? There have been many inquiries into these problems; but there is hardly a set of coordinated answers. However, to develop an approach to precedent analysis, we must first draw a framework in which those questions can be answered coordinately, and on which we can further specify the computerization of precedent analysis.

As one important step towards the framework of precedent analysis, this chapter describes and discusses a successful architectural design—the design of the "new courtyard house" in Beijing's old city. The discussion will be focused on how precedent and precedent knowledge have been used in design problem definition and design idea generation. As mentioned in Chapter 1 (p. 12~13), the introduction of this design case has two purposes: one is to understand the role precedents might play in the early

stage of a conceptual design, another is to specify the computation task of ARPRAN. Choosing this case does not mean that the way the precedents have been used and analyzed in the case was the best possible. The choice is made because it is a typical design case in which architectural precedents have been used.

2.1 Introduction

The design of the "new courtyard house" was carried out by a research/ design group of Tsinghua University in Beijing. Among several recent experimental housing projects for urban renewal of Beijing's old city, this has been widely regarded as the most successful one. Three factors contribute to the professional success of this project. (1) It suggested a feasible strategy to the conservation and the urban renewal of the old city. (2) It provided an effective method for the reform of housing investment system in China. (3) It has presented a good conceptual design.

The success of the conceptual design of the "new courtyard house" has been attributed to its "abstractly inheriting" the features of the old city (Wu, 1989). This suggests that, the design captured adequately properties of precedents that are very crucial. A careful study of how this was achieved will thus be very instructive.

Before moving into the description of the design, this section first briefly introduces the general assumption of precedent knowledge which has been used in the case study and explains the data sources of the case study.

2.1.1 A general assumption

Precedent usually means a former action that may be used as an example for present or future action. In this thesis, I use the term to mean a pre-existing building or other built environment that may be used as an example or constraint for the current design work. A precedent is an artifact, an

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object of entity. So we can talk of *a property of a precedent*, which means a characteristic aspect of the precedent. *Precedent knowledge*, or *knowledge of precedent* is used to mean the facts or rules about a precedent or its properties.

An artifact may be described in terms of how it is *made out*, how it *works*, and what it *does* in respect to what *should be done*. Seen from these different perspectives, the characteristic aspects of a building can be respectively called the *morphology*[1], the *operation* and the *performance* of the building (Tzonis, 1990; Zandi-nia, 1992). Morphology refers to the formal aspects of a building; it may be a description of the appearance, the composition or the spatial organization of the building. Operation is the dynamic aspects of a building; it describes the activities that may happen, such as how people may move, how light may go through, how air may flow in or around the building. Performance is about the qualitative aspects of a building; it is the ability a building conducts the activities with respect to a norm. These concepts will be discussed in detail in Chapter 4.

Parallel to morphology, operation and performance, *form* and *function* are more frequently used in the architectural domain. However, difficulties often arise out of "function," because of its ambiguity (Zandi-nia, 1992). In fact, when the function of a building is mentioned, it sometimes means how an activity may happen in the building and sometimes means how the building performs with respect to the purpose of the building. "Function" is thus rarely used in this work.

2.1.2 Data sources of the case study

The study is focused on the identification and interpretation of the concepts and their underlying connections which are relevant to the use of the precedent knowledge in the conceptual design of the "new courtyard house."

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[1] In Tzonis (1990), it is called *form* or *morphology*; in Zandi-nia (1992), *structure*. I prefer morphology because it covers both form and structure. Chapter 4 gives more discussion.

Some of these concepts are used explicitly by the designer in his descriptions of the design. To identify them, consequently, is not a difficult task. Other concepts, usually regarded as common sense knowledge, however, are used implicitly. To capture those implicit concepts of precedents, we need to analyze verbal descriptions as well as drawings in some detail.

Designer's verbal descriptions and drawings in this case study are extracted from several reports about the development of the "new courtyard house." The reports contain typical professional knowledge about the old house types and the street systems and the knowledge often used in the housing design by contemporary Chinese architects. They were produced by the leader of the project, Professor Wu Liangyong, of Tsinghua University, and his colleagues (Wu, 1989, 1991a, 1991b; Wu & Liu, 1989). Since the study is not intended to reconstruct the process of the design, the data provided by these papers are sufficient.

To identify the concepts, we presuppose a framework of architectural knowledge. By this I mean an initial assumption that provides a departure point for studying the material. This study applies the framework of morphology, operation and performance, which we have briefly discussed. The framework discussed so far is certainly too rough, but it provides a satisfactory departure point for the current case study.

The reports we referred to cover many issues ranging from Professor Wu's ideas on the integral conservation of Beijing's old city to detailed implementation of the new dwelling (see Appendix B for more description). To simplify the investigation I am obliged to limit the area of study as much as possible.

First, I distinguish problems and solutions that belong to the domain of architectural design from those of the urban renewal strategy proposed by Professor Wu. Problems related to the integral conservation of the old city, the treatment of the old houses, the reform of housing investment system, etc. and correspondingly the speculation of their solutions are regarded as belonging to the domain of urban renewal strategy.

Second, I distinguish the design of the prototype from the application

of that prototype in a real site of the city. With the exploration of urban renewal strategy, the design of the new dwelling has experienced several stages in one decade. However, it was remained as prototype development until a pilot project was realized in 1991. In several stages, the exploration has been carried out in different sites in the residential quarters in Beijing's old city. These sites are highly uniform, so the design of the prototypes can be seen as if in an abstract site. For this reason, Wu's papers treat the final version of the prototype, which is realized, as a result of the evolution of the previous proposals. For the same reason, I shall isolate the design of the prototypes from their implementation and ignore problems related with the particular sites. In this study, therefore, "new courtyard house" means a new prototype rather than a particular building.

Finally, by "designer" I mean a group of designers, who participated in the different stages of the research and the design under the coordination of Professor Wu.

2.2 Description of the design

2.2.1 Design problem and solutions

The design problem is to generate a new dwelling prototype to replace the decaying traditional courtyard houses in Beijing's old city. It is derived from an urban renewal strategy that aims at preserving the distinctive features of Beijing's old city while improving the housing situation (Wu & Liu, 1989; see also Appendix B). Following is the description of a typical site occupied presently by the old houses and on which the new prototype of house is destined to be built.

(1) The site is in an old residential sector, composed of traditional courtyard houses and east-west lanes (called *Hu Tong* in Chinese) (Figure 2-1). The pattern of the streets and the style of the houses were formed as early as in the thirteenth century when Beijing's old city was built. Most of the houses have been existing for more than five decades. Presently, the

Single-storied building   Two-storied building   Three-storied building   A school   0   50   100 M
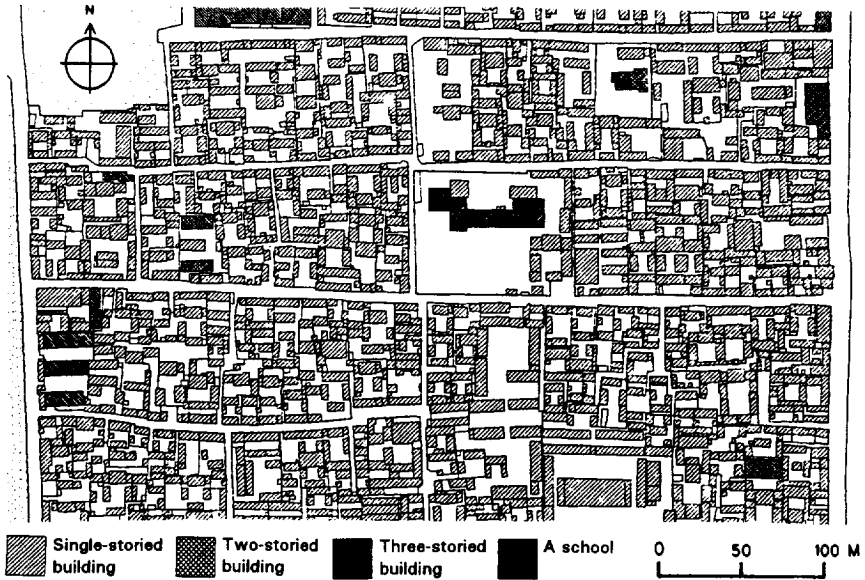
Figure 2-1 A typical area in Beijing's old city, composed of lanes and courtyard houses (Redrawn after a map of Beijing made in 1978)
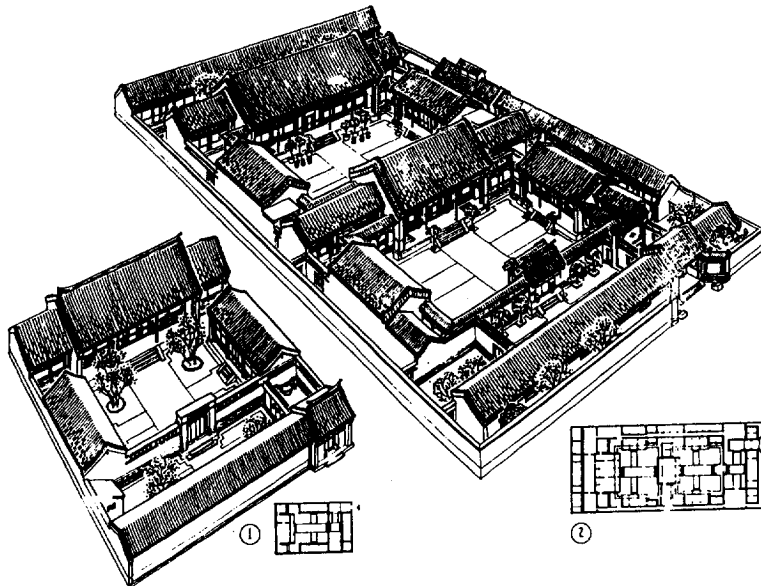
Figure 2-2 Two typical courtyard houses in Beijing (Source: Liu, 1990)

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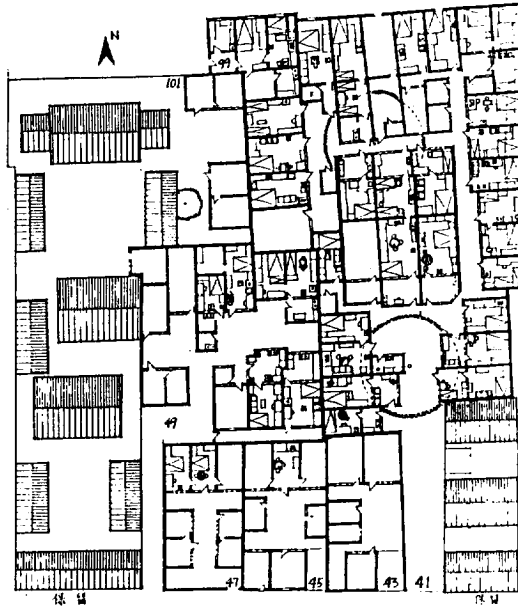
Figure 2-3 The plan of the Ju'er Lane site before renewal
(Source: Wu & Liu, 1989)

Table 2-1 The situation of the Ju'er Lane site before renewal
(Source: Wu & Liu, 1989)

Land area	2090 m² 7 courtyards
Number of households	44
Total floor area	1085 m²
Average floor area	5.2 m²/person
Number of rooms	64
Plot ratio	1:0.8 (including self-constructed buildings)
Number of storey	1
Living standard	26.66 m²/family 1.45 room/family
Service	No private toilet, no private water supply, no central warming system

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quality of the buildings is different from house to house. So, not all of the old houses in the site have to be removed. In addition, in some courtyards there are old trees worthwhile to be preserved.

(2) The courtyard houses were originally built for the extended families (Figure 2-2). Most of them are currently occupied by the nuclear families. Usually, some ten, twenty even thirty families are living in one or several connected courtyards that might belong to a single owner before. The residents are used to say that they live in this or that courtyard; it may mean a single courtyard or a group of courtyards that are connected and use a single house number. The residents living in such courtyard(s) usually have strong sense of territory and most of them have a good relationship with their neighbours.

(3) High density of population versus low density of floor-area is a distinctive problem of the site. Although many courtyards are already full of self-constructed sheds, the plot ratio is still very low. This is obviously because the courtyard houses are all single-storied. The average density of population is about 600 persons/hector. The average floor-area is about 5 m^2/person. Such a situation is typically shown by the plan in Figure 2-3 and the data in Table 2-1 (see Appendix B for more description).

The large amount of courtyard houses is a distinctive feature of Beijing's old city. However, how to treat them has been a knotty problem. There have been two extreme attitudes: to preserve entirely the old houses or to replace them thoroughly by the contemporary apartment blocks. Neither appeared practical. A third alternative, preserving the shell of the old houses and renovating the inside—that is often used in the European cities—is not applicable for Beijing, because it could hardly increase the plot ratio resulted by the single-storied old houses.

It became therefore clear that the only alternative was the introduction of a new type of dwelling that combines the advantages of both the traditional courtyard houses and the contemporary apartment blocks. It was necessary for this new prototype to be able to be inserted in the old residential sectors in order to replace those courtyard houses with the worst

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conditions, leaving those of better quality for future replacement. This idea was developed into an urban renewal strategy for Beijing's old city, which is described by Wu (1989) as the "organic replacement" of the old houses (see Appendix B). This is how the task to design a new dwelling prototype emerged.

According to Wu (1991), the design of the new dwelling prototype evolved through three main stages. Each stage resulted in a proposal (Figure 2-4, 2-5, 2-6). Following are some descriptions of the proposals quoted from Wu's reports:

> "The first stage resulted in the 'courtyard compound' proposal. It combines large, middle and small courtyards as well as one-, two- and three-storied buildings, and it is organized by two corridors.
> "The second stage resulted in the 'small courtyard compound' proposal. Since the first proposal did not result in a high plot ratio and is too large, it is difficult to be realized. In the second proposal, therefore, the overall size was reduced. It is provided several possibilities of courtyard combination, in order to have good adaptability.
> "The third stage resulted in the 'basic courtyard' proposal. It uses two- and three-storied buildings to form a basic courtyard. It has satisfied many requirements simultaneously, such as the requirements on the traffic, the sunshine, the privacy of the living units, the size of the courtyard and so on. . . ." (Translated from Wu, 1991)

> "The 'basic courtyard' (of the third stage proposal) occupies an area of 30m x 30m, . . . including a courtyard of 15m x 13m, . . . Because the corridors are aside the courtyard, an area in the courtyard, about 10m x 10m, will not be disturbed by the traffic in the building compound. It is thus like an 'outdoor living room' for the residents." (Translated from Wu, 1989)

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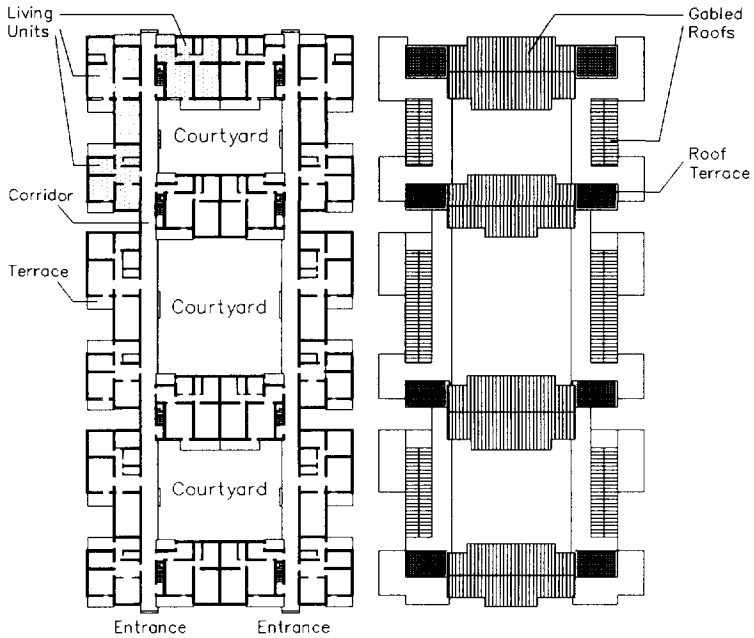
Figure 2-4 The first proposal of the "new courtyard house"
(The plans of the ground floor and the roof, redrawn after Wu, 1989)
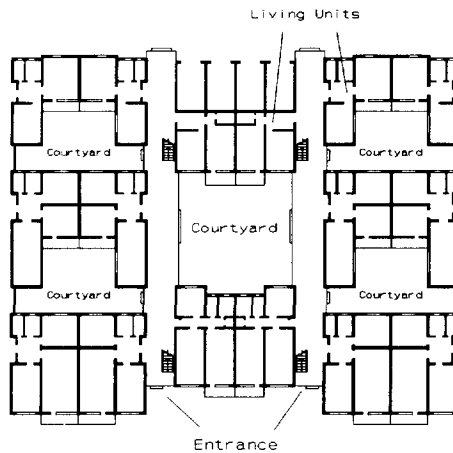
Figure 2-5 The second proposal of the "new courtyard house"
(The plan of the ground floor, redrawn after Wu, 1989)

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Plan of the second floor

Plan of the first floor

Plan of the ground floor
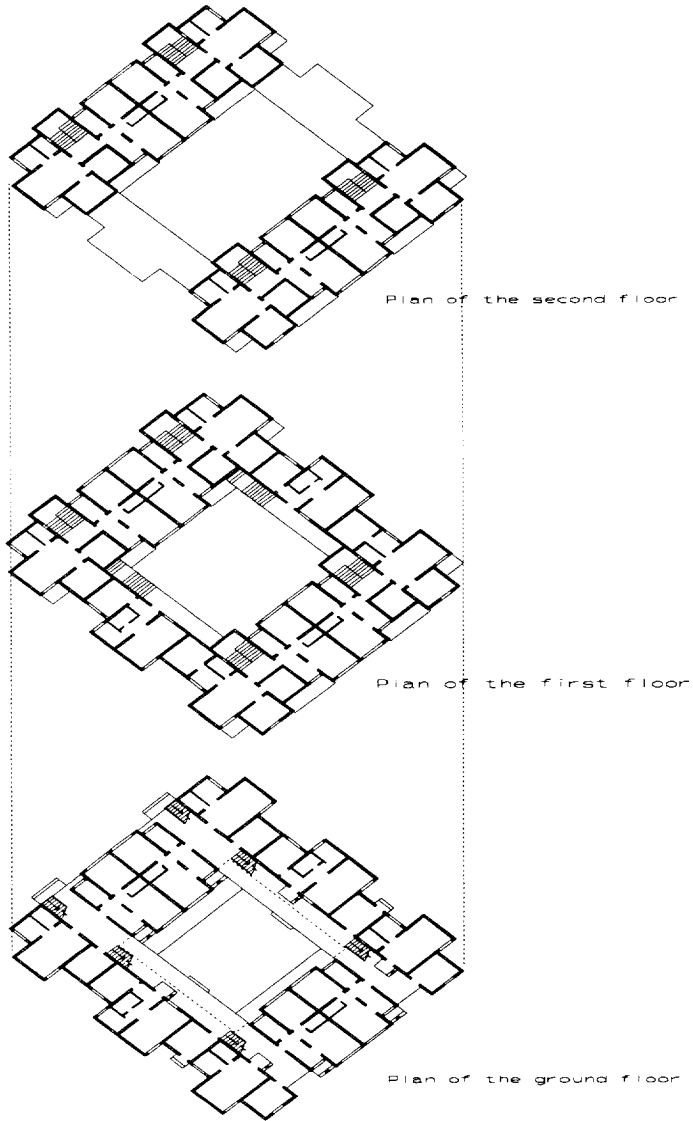
Figure 2-6 The third proposal of the "new courtyard house"
(The plans of the basic courtyard, redrawn after Wu & Liu, 1989)

2.2.2 Description of the major ideas of design

In this sub-section some descriptions relevant to the conceptual design of the "new courtyard house" are presented.

A general vision of the new design is described by Wu (1989) immediately after the design problem—"to design a new dwelling prototype"—is stated.

> " . . . Is it possible to develop a 'new courtyard house' system supported by the contemporary structure system while fitting the traditional urban fabric? Such a system should have the good sense of privacy in the walk-up apartments as well as the good sense of community in the courtyard houses. It should meet the requirements of modern living, yet avoid the unsatisfactory appearance of the walk-up apartments that are drawn up in orderly ranks. In addition, the 'new courtyard house' must have a high plot ratio that is similar to that of the walk-up apartments. Otherwise, it could not compete (with the walk-up apartments)." (Translated from Wu, 1989)

The above quotation was an initial specification of the design problem, or a problem definition. It implies a direction the design follows, and uses a number of concepts that give important clues to study which precedents and how they have been used.

Other useful clues can be found in the major ideas of design solutions. As described in Wu (1989), a key step in generating the design solutions is the decision of applying a circulation pattern that enables effective organization of the living units.

> "From the outset . . .it was decided to go beyond the composition pattern of the ordinary courtyard houses in Beijing, because it does not fit the requirement of multiple households. Instead, the design absorbed the composition method of the large mansions in Suzhou, Fujian and Guangdong (note: cities in Southern China), in which the service corri-

dors are off the central axis. This circulation pattern allows the courtyards to be extended, upon condition of the site, in north and south direction, forming multiple rows of courtyards, or in east and west direction, forming multiple columns of courtyards. The corridors are penetrating the buildings, thus the stairs can be arranged. This solution to the problem of vertical circulation can lead to a high plot-ratio." (Translated from Wu, 1989)

Wu uses "fishbone" to name this crucial circulation pattern and asserts that it is also characteristic to the street system in Beijing's old city (Figure 2-7). In addition, a statement is made about the characteristic of the

(b) Beijing's old city

(a) A typical Southern large mansion

(c) Street and lanes in Beijing's old city
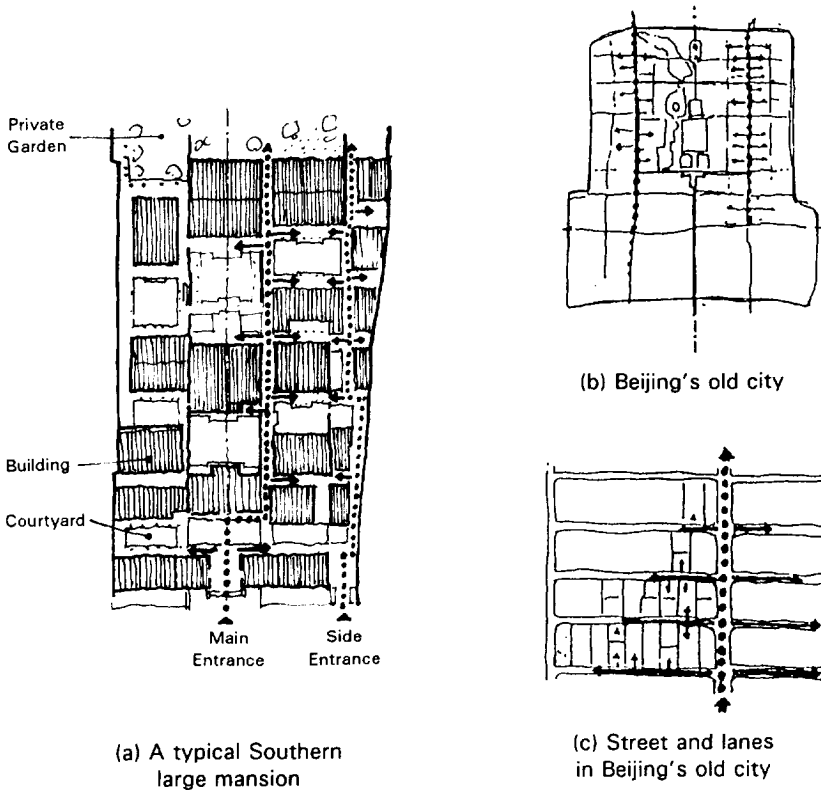
Figure 2-7 Sketchy plans showing the "fishbone" circulation pattern in a typical Southern large mansion and in the street system of Beijing's old city (Source: Wu, 1989)

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new design, "The 'new courtyard house' is a synthetic composition of the closed courtyard system and the 'fishbone' circulation system." (Wu, 1989)

Obviously, the above descriptions I supply are not a protocol of the design process. Out of the designer's justification texts, they provide a number of concepts from that we can identify which precedents are used by the designer, and how they are used.

2.3 Interpretation

2.3.1 Precedent entities used in the new design

The strategy adopted in the design of the "new courtyard house" can be summarized as: "Transferring a number of properties of the precedent types to a new design type." The first step in the study is to identify the specific precedents employed by the designer in the development of the new building type. This is not difficult; one needs just to look at the documentation supplied and ask the question: "Which preexisting built environments are mentioned as the sources of the new design?"

We can identify a number of types, or instances of types, of built environments which have been used as the precedents. These precedents are entities of built environment. They are:
- *the contemporary structure system,*
- *the traditional urban fabric,*
- *the walk-up apartment,*
- *the courtyard house,*
- *the ordinary courtyard house in Beijing,* and
- *the Southern large mansion.*

The contemporary structure system
In the present problem context this means a construction system that is used currently for Chinese urban housing. In Beijing, the most economic and appropriate construction system for the kind of public housing considered

in this design task, is a mixed system of brick and reinforced concrete that uses bricks for load-bearing walls and pre-fabricated concrete components for floors, lintels, etc.

The traditional urban fabric

In the present problem context, "traditional urban fabric" means the spatial pattern of the old residential sectors that is composed of the courtyard houses and the street-lane system (Figure 2-1, p. 32).

The walk-up apartment

This is the most popular urban housing type currently used in China. It is often called "multiunit housing," has usually $5 \sim 6$ stories, without elevators, and it is composed out of $3 \sim 5$ "units." Each "unit" has a number of living units organized around a single stair case. In each "unit," each floor has $2 \sim 3$ living units (Figure 2-8). "Walk-up apartment" is used here as an important precedent housing type from which some design properties are transferred to the new design.

(a)   (b)
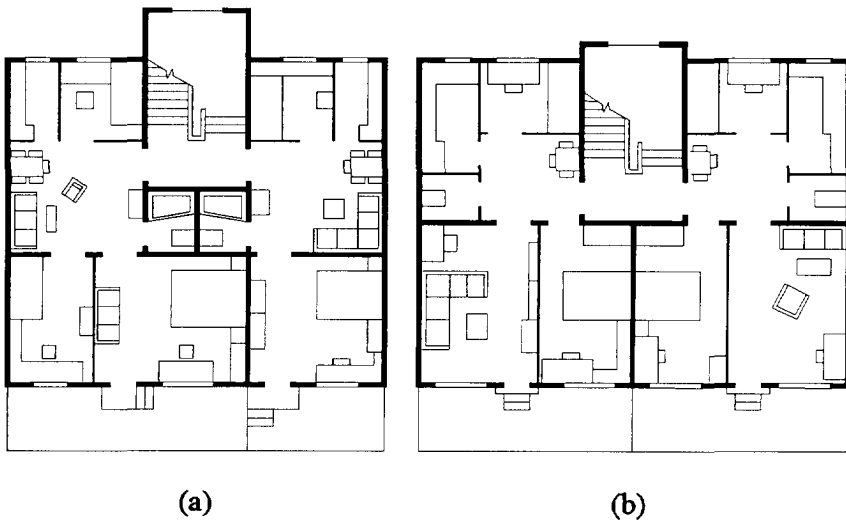
Figure 2-8 Typical walk-up apartments.

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The courtyard house and *the ordinary courtyard house in Beijing*

The "courtyard house" is a vernacular housing type generally adopted in Northern China in Ming (1368 ~ 1644 A.D.) and Qing (1644 ~ 1911 A.D.) dynasties, most commonly found in Beijing (Figure 2-2, p. 32). As a distinctive feature, its main courtyards are all surrounded by four buildings. Therefore, it is called in Chinese *Si He Yuan Zhuzhai*, or *Four Closed Courtyard House*. The plan of the house is laid out according to the social structure of feudal patriarchal clan system and the structure of its ethical code. The rooms and the courtyards are arranged symmetrically along the south-north axis. The main rooms facing south are for senior members of the family, whereas the rooms in the wings facing east and west are for younger generations. The side-rooms with small yards, usually attached to both sides of the main rooms, are used as kitchen, toilet, and storerooms. The courtyard is usually enclosed by the rooms on all four sides. There are no windows or only small windows in the outer walls; instead, all doors and major windows face the courtyard, which is planted with flowers and trees. In the large houses, the rooms are often connected with a winding corridor or a veranda. The "ordinary courtyard house in Beijing" is also character-ized by the location of its main gate: the main gate is always located at the southeast corner (when the building is on the north side of the lane) or the northwest corner (when the building is on the south side of the lane). The "ordinary courtyard house in Beijing" is a kind of "courtyard house."

The Southern large mansion

This means a vernacular house type which is often used in the cities of Southern China. It is usually composed of many courtyards. The courtyards are usually smaller than that in Northern China. As a distinctive feature of such house, there are usually several long corridors connecting the court-yards. These corridors, used for service or fire prevention, are separated from the main circulation line of the central axis (Figure 2-7, p. 39).

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2.3.2 Properties of precedents used in the new design

We have identified *which* precedent entities were used in the development of the "new courtyard house," we now proceed to find out *how* these precedents were used, more specifically, which properties present in the precedents were taken into consideration or were transferred into the new building type. In this search, as mentioned, we shall be guided by the general assumption of precedent knowledge, i.e., morphology-operation-performance of built environment. Following questions will be asked: "Which morphology, operation, performance properties of the precedents can be found in the case documents? How can the case descriptions by the designer be analyzed in terms of these concepts?"

Some of the precedent properties have been explicitly stated by the case documents, such as:
- the good sense of privacy in the walk-up apartment,
- the good sense of community in the courtyard house,
- the unsatisfactory appearance of the walk-up apartment,
- the high plot ratio of the walk-up apartment,
- the "closed courtyard" of courtyard houses, and
- the multiple "fishbone" circulation corridors of the Southern large mansion.

Certainly these are not all the properties that are used in the design. They are only part of the explicitly stated properties. To investigate now those that are not explicitly stated, we now analyze some concepts about the new design in combination with the proposals, such as:
- *being supported by the contemporary structure system,*
- *fitting the traditional urban fabric,*
- *having a good sense of privacy,*
- *having a good sense of community,*
- *meeting the requirements of modern living,*
- *avoiding an unfitting appearance,* and
- *having a high plot ratio.*

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Being supported by the contemporary structure system

This means that the physical organization of the building employs a specific construction system which, as mentioned, is a mixed system of brick and concrete.

Fitting the traditional urban fabric

This describes a quality of the new design. It implies that some properties that contribute to the formation of characteristics of the old urban fabric should be shared by the new design so that the new design could be perceived harmonious to the old spatial structure. In other words, it is a quality caused by the fact that when people *stay* in or around the new building, or *move* from outside into it, they can *perceive* that there is similarity between the new building and the old one, and continuity between the new building and the old street system. In turn, this quality depends on the physical aspects of the new design. If the physical organization and the elements of the new design have certain form, then, people can perceive that there is similarity between the new building and the old one. Meanwhile, if the space of the new building is organized in certain way, then, people can perceive that there is a continuity when they move from the out side into the building.

Therefore, we say that "fitting the traditional urban fabric" is a concept about the formal quality of the new building as it relates to the old, which makes people perceive it with satisfaction. It describes a performance.

Some of the morphological aspects in the new building type are matching some of those of the precedent and as a result they cause the "fitting" perception. Some of these morphological aspects have been explicitly stated by the designer, others can be elicited from the proposals.

The statement that "the 'new courtyard house' is a synthetic composition of the closed courtyard system and the 'fishbone' circulation system" (Wu, 1989) suggests that two categories of formal properties have been used in combination in the new design: one category is related to the closed courtyard system; another, to the 'fishbone' circulation system. The 'fish-

bone' circulation system is evidently characterized by the 'fishbone' circulation that is drawn from the Southern large mansions and the street system of Beijing's old city. The closed courtyard system is characterized by several formal properties that are drawn from Beijing's courtyard houses.

Comparing the plan of the three design proposals and that of the old courtyard houses, we find that three most distinctive features of the closed courtyard system are incorporated in the new design. The first is evidently the formal pattern of four buildings around a courtyard. We may call it "building-courtyard pattern." The second is that the overall arrangement of the new proposals is bi-lateral symmetrical, though the lack of central bay makes it diverse from the symmetry in the sense of the traditional buildings. We may call this formal property "symmetrical layout." The third is that in the new proposals, the buildings on the north and south side are always higher than those on the east and west side. This formal aspect has some correspondence with that in the old courtyard houses, where the north buildings are always the highest and the north/south buildings are often perceived dominant in the layout. We may call this property "height difference." Although these properties are not explicitly stated as that of the 'fishbone' circulation pattern, they are actually used in the thinking by the designer.

In addition, "the buildings and courtyards can be flexibly extended, combined and inserted among the old buildings" is also a formal property that can cause people to perceive that the new design is organically integrated with the old environment. Finally, an important physical feature that contributes to the "fitting" quality is evidently the use of the sloping tiled roofs, which are characteristic to the traditional courtyard houses.

Having a good sense of privacy and *having a good sense of community*
These are both vague concepts and there are hardly absolute definitions of them. The "Good sense of privacy" can be roughly understood, with respect to the contemporary standards in housing design in China, as a quality of the living unit in terms of how it provides a clearly defined territory for a family and reduces physical, visual, and auditory disturbances from the

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outside. In the present design problem, this concept must be understood with respect to the intention to improve the corresponding quality in the traditional courtyard houses. Similarly, the "good sense of community" is posed by the intention to improve the quality of the apartment blocks where the neighbours often have less contact with each other.

Like "fitting the old urban fabric," the achievement of the "good sense of privacy" or the "good sense of community" also requires the occurrence of some activity that can be described as, say, "when people move in the building, there is less disturbance to the living units" or "when people move in the building, they have chances to meet each other." This, in turn, depends on some formal properties.

In Wu's reports, we can find some descriptions related to the "good sense of privacy" and the "good sense of community," which show what formal properties have been used by the designer to achieve these qualities. For instance, "minimizing the public circulation distance" and "keeping a distance between the living units which have opposite windows" are usually the formal properties of the walk-up apartments, which can reduce disturbance. "Living units around courtyard," "Direct connection between the living units and courtyard," "Outdoor 'living room'" and "Shared gate of the courtyard" are considered as the formal properties which may cause the "good sense of community" in the courtyard house, hence are transferred to the new design.

Meeting the requirements of modern living
This also denotes a quality of housing. Apparently, by mentioning this desired quality for the new design, the designer means that some formal properties of the precedent contemporary houses should be used, next to the traditional ones, in the new design. These formal properties can prescribe some activities of living, and it is the occurrence of these activities that gives rise to the quality of "modern living." These formal properties can be found in the walk-up apartments.

First, each living unit should have a complete set of facilities: one to three bed rooms, a living room or a multi-functional hall, a kitchen, a

bathroom and a private outdoor space such as a garden, a balcony or a roof terrace. Second, the total floor-area of each unit (exclude private outdoor space) is about $30 \sim 40$ m² (for one-bed-room-units), $50 \sim 60$ m² (for two-bed-room-units) or $60 \sim 80$ m² (for three-bed-room-units). Third, each living unit has at least one bed room with a window facing south, not only because south is traditionally the most favourable orientation, but also due to the climate of Beijing.

Avoiding an unfitting appearance
This should be analyzed in conjunction with "meeting the requirements of modern living." While the living standard of the walk-up apartment is kept, the aggregation of the living units should comply with another pattern to avoid the unfavourable appearance of the common walk-up apartment, what has been referred to as "drawn up in orderly ranks." This, again, requires the occurrence of some formal properties that can make people perceive a "fitting appearance," fitting into the traditional urban fabric.

Having a high plot ratio
The "plot ratio" indicates the density of building layout. That the new design should have a "high plot ratio" is derived from the urban renewal idea that the new buildings taking the place of the old should accommodate approximately all the original residents and at the same time increase the average floor-area. According to the professional experience, the conventional walk-up apartments, if carefully arranged, can satisfy that need easily. Thus, if the new design is intended to compete with the conventional walk-up apartments in economic performance, it must have a plot ratio no less than that of the conventional apartment.

Therefore, the "high plot ratio" is the parameter of a formal property that can cause a property of building operation "accommodating a large number of people" and, further, the quality of "good economic perform-ance." Usually, to minimize the distance between the north and the south buildings and to maximize the depth of the buildings can bring about a "good economic performance." In effect, the proposals have offered all

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these required formal properties.

From the above discussion, we may conclude that some of the identified qualities are those of the precedents and the same time the desired qualities to be achieved by the new design, they are the *performances* of the built environments. To achieve these performances, however, the new design has to be able to conduct some activities and interactions, or the *operations* of the built environments. In turn, the operations require some formal properties occur in the new design. These formal properties, or the *morphology* of the built environments, can be transferred from the precedents. Table 2-2 summarizes the properties discussed in this section in terms of the performance, operation and morphology of the built environment.

2.4 Some remarks

We can observe from the design case a number of situations in which precedent or precedent knowledge is usually used in design.

First, it is noticeable the use of precedent in the problem definition, such as that the new design should "have the good sense of privacy in the walk-up apartments as well as the good sense of community in the courtyard house," and that the new design should "have a high plot ratio that is similar to that of the walk-up apartment." The connection of the problem definition to a precedent like these is because of the difficulty in specifying the criteria for the performances. As we have mentioned, such difficulty is obvious with the "good sense of privacy" and the "good sense of community". As for the "good economic performance," although it can be specified quantitatively, in the conceptual design stage and in the problem like the one we studied here, it still seems lack of an absolute standard for what is the "high plot ratio." However, when connecting these to a precedent they become describable, because we know that in the precedents these performances are satisfactory, if not optimum. This is very important to the conceptual design of architecture, where an effective and efficient way is

Table 2-2 Summary of some identified properties of the precedents and their use in the new design

Desired quality of the new building (performance)	Required activity causing the performance (operation)	Formal property transferred from the precedents (morphology)
"Fitting the traditional urban fabric"	"When staying in/around the building or moving from outside into the new building, people perceiving similarity and continuity between the new and the old"	"Building-courtyard pattern", "Symmetrical layout", "Building height difference", "Flexible combination of the parts", "Sloping tiled roofs" of "the courtyard house"; "'fishbone' circulation pattern" of "the street-lane system"
"Good sense of privacy"	"When people moving or acting in the building, there is less physical, visual and auditory disturbance to the living units"	"Clearly defined territory for nuclear family", "Minimized public circulation", "Distance kept between living units that have opposite windows" of "the walk-up apartment"
"Good sense of community"	"When people moving or acting in the building, they have chance to meet each other"	"Living units around courtyard", "Direct connection between living units and courtyard", "Outdoor 'living room'", "Shared gate of the courtyard" of "the courtyard house"
"Modern living"	"Activities of living"	"Complete set of facilities", "Adequate floor-area", "One bed room facing south" of "the walk-up apartment"
"Good economic performance" (to compete with walk-up apartment)	"Accommodating a number of people"	"High plot ratio" (minimizing distance between north and south building; maximizing the depth of the building) of "the walk-up apartment"

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looking for a satisfactory solution instead of a globally optimized one.

Second, the precedent knowledge is used to solve new problems in the design. In the design case, the introduction of the "fishbone" circulation pattern of the Southern large mansion is to solve the new problem "how to organize a number of living units together to form a courtyard compound of adequate size," because that circulation pattern has successfully solved the multi-room and multi-courtyard organization problem in the Southern large mansion that is also a courtyard compound. This way of using the precedent knowledge is known as design by analogy (Winston, 1992; Tzonis, 1990).

Third, another distinct role the knowledge of precedent plays is to link the new design to the existing environment. In the design case, typical buildings or urban spaces, of the existing environment, are treated as the precedents from which some characters of composition are extracted and used in the new design. Such is the case of the design of "new courtyard house," where "the traditional urban fabric," "the courtyard house," "the street-lane system" are treated as precedents. These can be identified as "place-grounded precedents." (Hancock, 1986). The way of using place-grounded precedents is also termed by Delevoy (1978) as *archetypology*, that is to "find the minimum structural marks which are sufficient to bring a group of architectural beings closer to the neighbouring groups"(p. 16).

Fourth, there is yet one more role of precedents that can be identified in the design case. Some of the precedents are playing double roles; they are both analogical examples and place-grounded types. For example, the "courtyard house" or the "ordinary courtyard house in Beijing" is this kind. Therefore, we may identify three kinds of precedents. The first is used only for analogy; the second is used only for "arche-typology"; the third is used for both.

In the previous discussion, we have identified a number of morpho-logical aspects in the "new courtyard house" that may account for its "fitting the traditional urban fabric." Yet, how to define the quality of "fitting" *computationally*, and how to develop a representation system for describing the relevant formal aspects, are still issues to be investigated.

The investigation, I believe, will lead to an extension of some previous work of design computation. For example, Zandi-nia (1992) defines *operation* of a building as "the pattern of flow of people and objects within that building as prescribed by the interrelations and associations between them." This definition, viewed from his work, is sufficient and clear enough. To explain what we have encountered in the design of "new courtyard house," however, it seems that "operation" needs a more general definition which takes into consideration "people perceiving similarity between the new building and the old as they move through the new building." This will be further discussed in Chapter 4.

In addition, spatial concepts such as "building-courtyard pattern" and "'fishbone' circulation pattern," cannot be represented efficiently and effectively through most available representation systems for architecture (in the next chapter, we shall review some of such representation systems). This suggests that a more relevant approach to representation of architectural space is needed.

2.5 Summary

A prerequisite to the computerization of precedent analysis is to define the role precedent and precedent knowledge may play in the architectural design process. For this, it is necessary to have a framework in which precedent, precedent knowledge, their uses in architectural design and the task of precedent analysis can be defined.

This chapter describes a design case that can be used as a heuristic device to understand the role precedents play in the architectural design. The design problem is to generate a new dwelling prototype to replace the decaying traditional courtyard houses in Beijing's old city. A number of design objectives are considered by the designer in the conceptual design of the new house type. These objectives are mostly connected to the precedents, since the precedents are known to be satisfactory in respect to the performances described in the objectives. Meanwhile, it is also identified

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two ways in which precedent can be used in design generation, i.e., to constrain the design in order to keep the continuity of the traditional urban fabric, and to solve new problems by using old solutions.

In the next chapter, these observations will be applied in a review of some available representation systems for architectural space.

Chapter 3
A Review of Some
Representation Systems for
Architectural Space
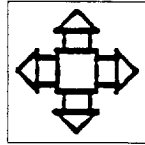
A prerequisite to the use of architectural precedents is the representation of built environment: how a built environment can be represented so that certain aspects relevant to an objective could be disclosed while the irrelevant aspects hidden. As will be displayed, the architectural precedent analysis developed in this work is virtually *an* approach to the representation of precedent built environment.

For the representation of built environment, there are already a few available systems; they have been developed for various purposes, from improving a design method to automatizing a design process, from explaining a composition style to studying a spatial order. In this chapter, we review some of these representation systems with respect to the needs of the precedent analysis task implied by the case study. The systems we review include the topological representations of plan, the rectangular dissections of plan, shape grammars, zoning diagrams and the grid schemata of classical architecture. These systems are selected for review because they have

been formed into several paradigms during their widespread applications in architecture, and they have been used (entirely or partially) in the representation of spatial organization or composition, which is also the central concern of this work.

These representation systems, I should suggest, are all contributive to some extent to the precedent analysis approach developed in this work; yet, none of them could independently take over the precedent analysis task addressed in this work, that is, the representation of the spatial concepts emerging out of the case study. Moreover, as I shall suggest, most of these available systems are associated with a "retrieving" approach to the use of precedents, that is, simply decomposing a precedent into elements or rules, storing them in a database and retrieving directly for use; whereas the approach developed in this work is a "reasoning" one, a basic feature of which is the capacity of learning new knowledge according to particular objectives.

The systems reviewed have been developed each with a specific problem domain. In its own problem domain, each of the systems might be regarded as efficient and effective. It thus makes no sense to judge any of them as a good or a bad method on a general ground. However, in order to evaluate those systems with respect to the problem we are addressing, we must have a frame of reference with which we can correlate the systems with our problem and make the systems comparable with each other.

The frame of reference used in this study is a classification system for architectural representations suggested by Tzonis & Oorschot (1987), who have classified different representations of architectural spatial organization according to their "abstractness." In the following section, I shall first introduce this classification system, and then use it as a frame of reference to explain what information need to be conveyed by the representation of the spatial concepts, such as the "building-courtyard pattern," and the "fishbone circulation pattern." As was emphasized, the representation of these concepts is a criterion with which we review those available representation systems.

3.1 A classification system for architectural spatial representation

3.1.1 Three abstraction levels

Tzonis & Oorschot (1987) suggest that we may describe the spatial organization of a building on three abstraction levels. Central to this classification system is the concept of *location*, which is the spatial primitive, or the atomic parts of the descriptions on all levels. A location in a building could be defined as the atomic parcel of space where a distinct activity can take place (Koutamanis, 1990).

At the first or the most abstracted level, according to Tzonis & Oorschot, we may describe a building in terms of how activities, people, equipment or other elements are separated from each other and assembled in parcels of space, i.e., in locations. In other words, if we choose to represent architectural spatial organization on this level of abstraction, we need only to indicate which spaces or parts of space can be clustered together and regarded as a location. This level is thus called the *clustering* level.

The second is the *topological* level, which concerns the way locations have access to each other. At this level of abstraction, we need to specify not only spatial clusters as locations, but also how the locations are connected to each other. The connection could be physical access, visual access or auditorial access. The other relations, such as the distance between the locations, are not exposed at this level of abstraction.

The third is the *metric* level, which describes the way locations occupy euclidean space (i.e., three dimensional space), the shape and the size of locations. Following is a list of some formal attributes concerned by this level of abstraction and their description tools:

> "1. Euclidean *distance* between locations. The distance from location to location considered pairwise. The information can be tabulated in the form of a matrix.

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2. Relation between inside and contained outside surface giving us an overall index of *density* of a solution.

3. Coordinating metric framework: the division of a building into regular parts, through space constraining systems (such as grids, polar or rectilinear), defining their geometry and their limits.

4. Preordered ranking system of elements (such as the genera of classical architecture or industrial prefabricated) which specify elements according to design attributes, for example:

> proportion,
> contour profile, etc.
> internal subdivision of elements
> proportion
> shape and profile contour
> size

5. Relations between elements as they are placed within the metric framework constrained by:

> rhythmic patterns of association
> modular coordination of association
> shape patterns of association"

(Tzonis & Oorschot, 1987, p. 100).

3.1.2 The abstraction level of the spatial concepts in the design case

Taking the three abstraction levels as a frame of reference, we may say that the spatial concepts in our design case is something between topological level and metric level of abstraction. This is due to the nature of the design problem of the case. To understand this point, let us consider again the design of the "new courtyard house" and see what information need to be conveyed by the so-called "building-space pattern" and "fishbone circulation pattern."

The design of the "new courtyard house" is characterized by "abstractly inheriting" the features of the old city. An important account for

such "inheriting" is the transference of the two spatial organization patterns to the new design. These two patterns represent two spatial concepts derived from the old environment and they might be considered as two constraining frameworks imposed upon the new design. They convey the minimum conditions of spatial organization that must be satisfied by the new design.

The "building-space pattern" prescribes that it should be perceived in the new design at least five locations, i.e., an outdoor location and four indoor locations, and the least spatial relations perceived should contain that the four indoor locations are respectively positioned at the four cardinal directions of the outdoor location (Figure 3-1, a). Similarly, in the "fishbone circulation pattern," the necessary locations are one circulation location and two utility locations, and their spatial relations must be perceived as that the two utility locations are connected respectively to the left and right side of the circulation location (Figure 3-1, b).

Obviously, the information conveyed by the two patterns is partially

(a)

(b)
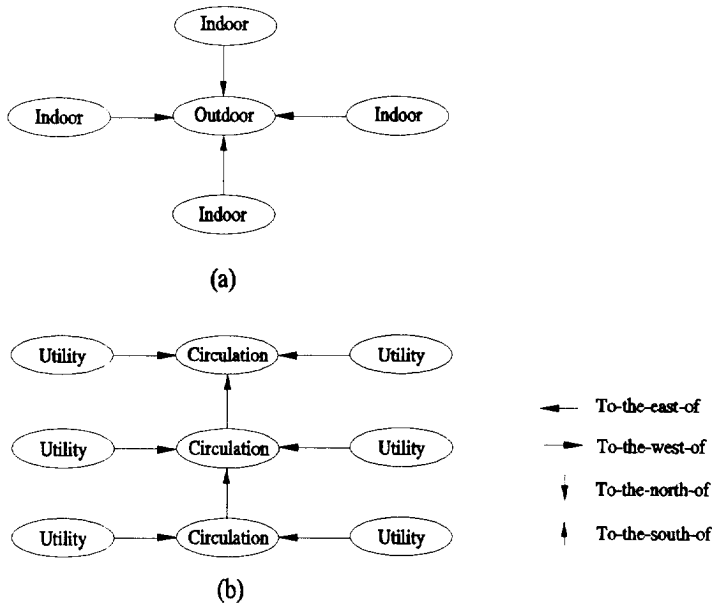
Figure 3-1 Information conveyed by the two spatial concepts:
(a) the "building-space pattern"; (b) the "fishbone circulation pattern"

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topological and partially metric. The two patterns should be regarded as belonging to a particular level of abstraction. As we shall see, the available representation systems for architectural space are difficult to adequately convey the information on this abstraction level.

3.2 Representation systems for architectural space

3.2.1 Topological representations of plan

The topological feature of space organization is often expressed with graphs. The universe of graphs is very simple; it contains only two kinds of element: nodes and links. Yet, graphs are convenient means for representing a set of objects and connections between them, hence widely used in many domains. In architecture, graphs are used primarily for representation of two kinds of information: either the adjacent relationship or the accessing relationships between spaces. Such graphs are usually called *adjacency graph* and *access graph* respectively. In adjacency graphs, usually a node represents a space (e.g., a room), and a link represents a partition between two spaces (e.g., a wall). In access graphs, a node stands for a space, and a link for an access (usually circulation access) between two spaces (Figure 3-2, a, b).

Adjacency graph was first introduced by Grason (1968) into architecture for solving the problems of architectural layout. Grason generates exhaustively all possible adjacency graphs with the proper number of nodes, subject to the topological constraints of the problem, and systematically adds information on wall directions and wall lengths so as to arrive at completely specified solutions. We shall discuss this method together with the method of rectangular dissections.

Access graphs are used mostly in studying the topological organization of a building. For instance, using access graphs, Zandi-nia (1990) has

developed a system which can automatically generate or evaluate topological organizations according to some constraints. Hillier & Hanson (1984), Brown & Johnson (1985) use access graphs (they call *justified access graph*) to study the "depth" of space sequence in buildings and urban blocks (Figure 3-2, c).

Access graph is also more relevant to precedent analysis. The power of access graphs lies at their simplification of architectural spaces and spatial relations: each space is abstracted into a point standing for a

(a)   (b)

(c)
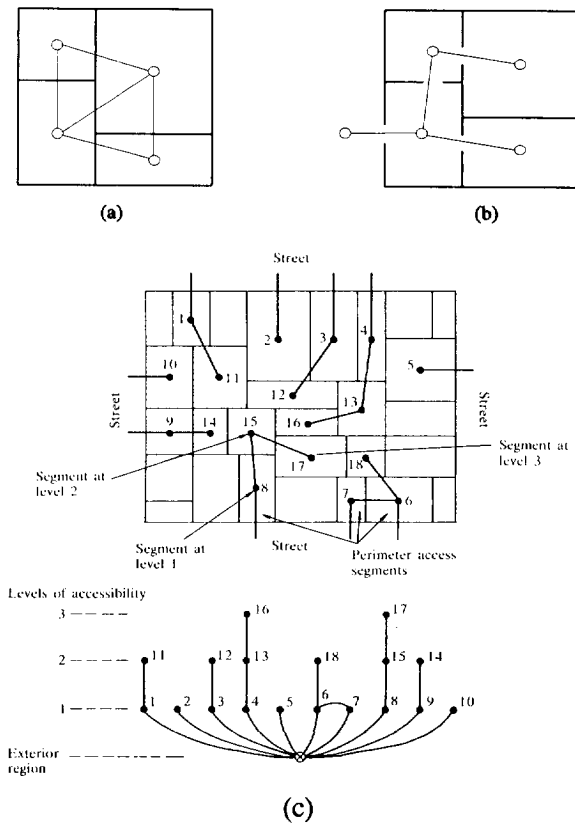
Figure 3-2 (a) Adjacency graph; (b) Access graph;
(c) An example of using "justified access graph" to study
the "depth" of urban block (Source: Brown & Johnson, 1985)

location, and the relations between the locations is either connected or not. The simplicity makes access graphs easy to understand and efficient to compute, if they are applied to a problem in which a built environment is treated only as a container of activities—in other words, a problem in which the only concern is how people and materials could or could not flow from one place to another (Tzonis & Oorschot, 1987).

However, the problem of precedent analysis emerging from our case study obviously relates to not only the flow of activities but also the features of the location themselves (e.g., whether it is a building or an open space, as in the "building-space pattern") and the relative positions between the locations (e.g., the utility locations on the left and right side of a circulation location). Therefore, the representation in our problem may not be simply reduced to a topological one. The representation, as will be further discussed in Chapter 7, requires some *semantic distinctions* among the locations as well as their spatial relations.

3.2.2 Rectangular dissections of plan

A rectangular dissection of plan is a rectangle partitioned into smaller rectangles like an ordinary floor plan, but with the rectangle dimensions left unspecified (Figure 3-3). This representation method was first used by Steadman (1973) to study the floor-plan layout of small houses in Britain.

The abstraction level of rectangular dissections lies between
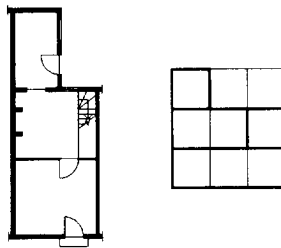
Figure 3-3 A building plan and its rectangular dissection: each location occupies at least one grid

topological and metric representations: the locations in a rectangular dissection are assigned with a shape but without dimensions; the relations between the locations are not directly specified as in graphs but in fact are also topological. This feature makes rectangular dissection considered as a better tool than adjacency graph for exhaustive enumeration of all the possible floor-plan layouts under certain constraints, because the metric constraints imposed by the rectangular representation themselves overcome many difficulties inherent in graphs. For instance, there is no problem of planarity with rectangular dissections, because they are evidently all planar. The limitation to rectangular rooms rules out certain patterns of room adjacency. The wall alignment is distinguished in the dissections while it is ignored by the adjacency graphs. These constraints reduce largely (compared with graph) the possibilities of configuration with given number of rooms, and make the exhaustive enumeration become practical if the number of rooms is no more than 7. Of course, the use of rectangular dissection on the representation of plan of small houses in Britain is justified by the fact that most of the rooms are rectangle-shaped and the actual number of spaces which can be represented by rectangle is usually no more than 7 (Steadman, 1973).

The rectangular dissection of plan was also found useful as an intermediate abstract representation in solving automated floor-plan design problem (Galle, 1986).[1] By using rectangular dissections, the search for the floor plans that satisfy given topological and dimensional constraints can be divided into two steps. The first step is searching a stored collection of rectangular dissections (with up to eight rooms) to find all those that are feasible with respect to the topological requirements of a given problem. The second step is varying the sizes of the rooms so as to satisfy the dimensional requirements (Mitchell, Steadman and Liggett, 1976; Krishnamurti & Roe, 1978; Bloch, 1979).

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[1] The problem is typically expressed as: "Given a list of rooms, dimensional constraints on their areas and extensions (possibly including restriction to certain modular dimensions), and topological constraints on interconnections of rooms or their access to open air, find: one or more floor plan(s) composed of the rooms so as to satisfy the constraints." (Galle, 1986)

The two-step-approach utilizes again the nature of rectangular dissections. Compared with adjacency graph, representation with rectangular dissection has already largely reduced scope that contains the configurations which are potentially "meaningful" to architecture, because the conditions of well-formedness which inherent in the rectangular dissection is *more near* to that of a normal architectural plan. However, as shown by Flemming (1986), there are some solutions generated by the two-step-approach, though satisfying the given constraints, obviously violating common principles of a good architectural plan. It is because "the conditions of well formedness which inherent in the rectangular dissection is still not near enough to that of the normal architectural plan."

This critique to rectangular dissection also explains partially why the method cannot be applied to the representation of the spatial concepts in our design case. In addition, I shall suggest from a cognitive point of view that the rectangular dissection is basically an imagery representation, in which the properties and relations relevant to the objective of a precedent analysis task cannot be specified. However, as will be seen, the notion of metric but dimensionless representation along with the rectangular dissections has been adopted by the representation proposal developed in this work, because the spatial concepts we concern need to be expressed at an abstraction level similar to that of the rectangular dissections.

3.2.3 Shape grammars

"Shape grammar" is a rule-based technique for generating architectural forms. It was introduced by analogy with the grammar of combining words in a natural language. In a natural language, not every string of words is a sentence: only strings that comply with the rules of grammar count as sentences. In the formal configuration domain, there is a similar situation: not every possible combination of shapes has architectural meaning; even it is meaningful, it may be irrelevant or uninteresting to a specific task. Shape grammars are thus introduced to make the combination of shapes as

meaningful and relevant configurations.

The shape grammar technique builds forms through recursive replacement of shape tokens. It requires a starting state, and a set of pre-defined shape rules. The starting state may be a point, a shape or a combination of shapes. The rules are usually written in the following form:

Shape A → Shape B

(IF "there is shape A" THEN "it may be replaced by shape B").

The rules can be formulated in different ways. Figure 3-4(a) shows a set of shape rules which allow a plan be formed in a bottom-up manner. Starting with a "room", we can replace it with a "three-room building"; with a "three-room building", we can replace it with a "five-room building"; the "three-room building" may also be replaced with "three-room building with a courtyard in front of it" or a "three-room building with a courtyard behind it"; etc., etc. Figure 3-4(b) shows another set of shape rules which let the plan to be formed in a top-down manner. Of course, both bottom-up and top-down rules can be formulated in one set of shape grammar.

This apparently simple technique can be very powerful when used with an in-depth understanding of particular types or families of designs, or when applied to formal generations based on well-defined canon. Stiny and Mitchell (1978) present a shape grammar for generating villa floor plans in the style of Palladio (see also Mitchell, 1990). In a more or less similar manner, many other grammars have been formulated for the generation of well-defined stylistic classes (e.g., Stiny, 1977; Stiny 1980; Stiny & Mitchell, 1981; Flemming, 1987).

The fundamental effect of shape grammar is that, with the formulation and application of a set of shape rules, it sets up a *clear scope* and a *structure* for exploring the possibility of form configuration. The scope is confined by the range of *primitives of shape tokens*, and the range of *operations* that transform and combine the shape tokens. The structure is defined by the usually tree-like organization of the shape rules, according

to which, the search may be carried out in either depth-first or breadth-first fashion. Mitchell (1990) emphasizes that shape grammar promises an efficient generation-and-test process by assuring (or even guaranteeing) the generated configurations falling into some acceptable range.

Undoubtedly, it is very important to possess a stylistic scope and a searching structure in design. Just as Mitchell (1990) puts it: "Possession of a style is essential. Without this, an architect attempting to design is like the scholars Gulliver encountered at the Academy of Lagado, who tried to write books by randomly combining words. That way, one would never get to the end." (p. 239).
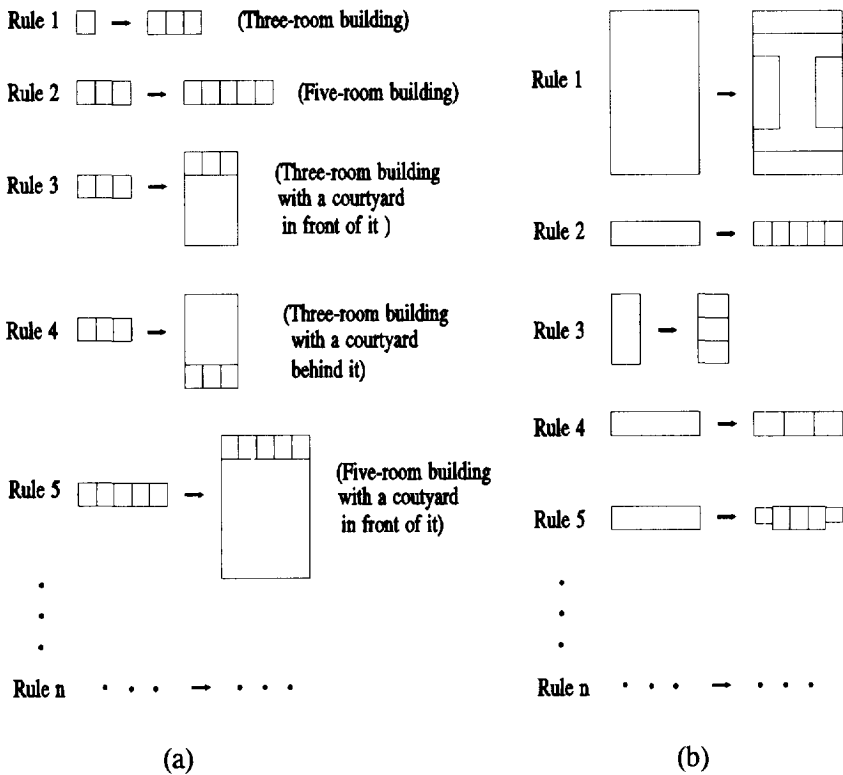
Figure 3-4 Shape rules (a) in the bottom-up manner, and (b) in the top-down manner

As will be further elaborated, establishing a scope and a structure for design is also at the central concern of precedent analysis: the precedent analysis is in fact an approach of relating formal configuration principles to a particular design objective. Therefore, it would not be unreasonable if we imagine that our system for precedent analysis results in a set of shape rules that could be afterwards used by a design system. Thinking in this way, however, two questions might be raised about a shape grammar. First: Whether the scope and the structure defined by the shape rules are enough for composing a design? Second: Can a shape grammar really guarantee the generated forms falling into certain stylistic classes (or types)?

Indeed, shape grammars seem particularly efficient for capturing certain types of syntactic knowledge, but only certain ones. In addition, even if they succeeded to capture syntactic knowledge, this knowledge is a *necessary* condition in design, but not *sufficient* one in most problems.

In a design process, the role of syntactic rules like shape grammars is basically *prescriptive*, that is, it directs the design action by saying what should be done. This is quite different from the role of *proscriptive* principles that constrain the design action by saying what should *not* be done. Evidently, the proscriptive principles provide a larger scope than the prescriptive rules do. This position will be more clear if we compare the shape grammar of Palladian villas with the canon of classic architecture described by Tzonis & Lefaivre (1986).

It seems that even shape grammars provide rigid scope to design, they may benefit the design process by enable the design quickly structured. Quickly structuring a design is indeed a problem that is encountered by using proscriptive systems in a generation process. Yet, we should not forget that it is not only stylistic aspects that can serve as the means in structuring a design problem, but also the other aspects, i.e., operation and performance of built environment, as we have seen. Those aspects other than style, however, are often difficult to be encoded within the syntactic rules as what shape grammars have promised.

That applying shape grammar can guarantee the generated forms falling into certain stylistic classes (or types) is also a conditioned promise. The

fundamental question here is whether classifying the architectural types according to the syntactic properties represented by shape tokens is the most effective way which could be used in design. Evidently, this depends on the nature of the design problem. Mitchell has also noticed this question. He wrote, "Of course there can be differences of opinion about the extension of a class of possible buildings, and hence about whether or not a grammar provides a well-formed representation." (Mitchell, 1990, p. 181). In actuality, the differences of opinion are often beyond the realm of shape grammars. In other words, there are other ways of classifying the type of architecture, which are necessary in solving some design problems but impossible to be expressed through shape rules. For example, in the design of "new courtyard house", the effective solution has been developed on the principle of the circulation organization in the precedent house types, rather than the syntactic relations between the building shapes of the precedents.

Comparing the classification manner used by shape grammar and that usually adopted in practical design, such as the "new courtyard house", we might say that shape grammar is mainly based on local composition rules. In practice, however, designers often depend on more global composition principles. Moreover, effective classifications are often not only involved in knowledge of composition, but also related to the knowledge of how the composition performs.

In conclusion, shape grammar is powerful for those design problems in which the stylistic canon can be defined clearly by the syntactic rules and the stylistic aspect is dominant in structuring the design problem. However, the tasks confronted by our precedent analysis, as it emerges out of our case study, can hardly be benefited by the formulation of shape grammars.

3.2.4 Zoning diagrams

Zoning diagrams are the representation tools used in the "SAR 73" design method for recording design agreements and standards (norms) in multi-partite planning or design, for phasing design decision-making and for

evaluating an existing urban area or a design proposal (SAR, 1973). By describing the zoning principles such as the position and dimension of buildings and open spaces, a zoning diagram shows the properties of spatial composition of a piece of urban area.

The zoning diagram may illustrate both plan and section (Figure 3-5, a). In SAR's convention, three kinds of zones are used, i.e. *O-zone, B-zone* and *ob-zone* (Figure 3-5, b). A B-zone is an area which is (or should be) always filled with buildings, i.e., it is always a built area. An O-zone is an area which contains (or should contain) exclusively open space, i.e., it is always a non-built area. An ob-zone is an area between an O-zone and a B-zone, and it is either built or non-built. Zoning according to this convention, the following relations are evident. (1) O- and B-zones indicate the position and minimum dimensions of buildings and open spaces. (2) Ob-zone is a margin between the other two. (3) The maximum dimension of a built area is a B-zone plus the ob-zones that are near to the B-zone. (4) The maximum dimension of a non-built area is an O-zone plus the ob-zones that are near to the O-zone.

The zoning diagrams are usually added with other descriptions to form a set of documents. Such descriptions may include, for instance, the position and dimension of some special buildings or open spaces (i.e., non-

(a)   (b)
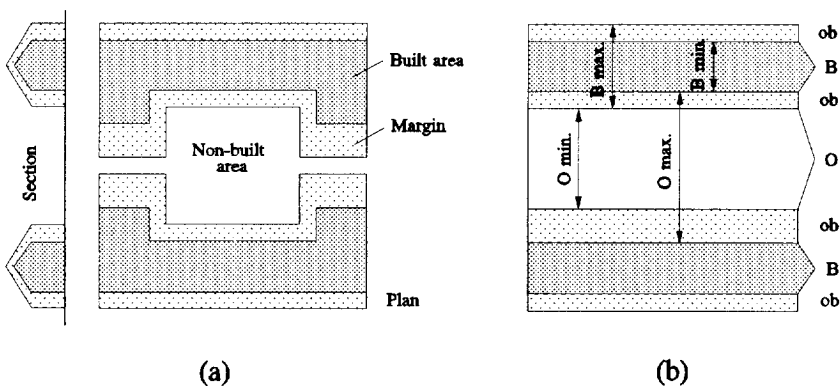
Figure 3-5 (a) A zoning diagram showing both plan and section
(b) The SAR convention of zoning

thematic elements), the notation of the purpose of the buildings and open spaces, and other explanation for the diagrams. According to *SAR 73*, all the documents together constitute a *tissue model*, which shows the order of a piece of urban area.

Now we look at the way in which the zoning diagram describes the spatial organization of built environment. The spatial primitive of representation is *element*, which is defined through four kinds of properties, i.e. its category, its position, its dimension, and its purpose (or function).

The *category* of an element is one of four types of space, i.e., the thematic built, the thematic non-built, the non-thematic built, and the non-thematic non-built. The distinction between thematic and non-thematic elements is based on the observation that, in an urban area showing strong order, some elements of similar properties may occur throughout the area and always in the same position with respect to the other elements. These elements are thus called *thematic elements*. Consequently, those that occur incidentally and those that are always placed uniquely are *non-thematic elements*. Evidently, it is the existing of the thematic elements that makes the area have a recognizable order, or *theme*.

The *position* of an element is defined by the zone of built or non-built. The *dimension* of elements is defined together by the built- or non-built-zones and marginal zones. The *purpose* (or function) of an element means the activities which can happen in the element, and it is noted by the explanation text.

In the way of zoning diagram representation, it is obvious that there is an order of priority for element definitions, that is, category precedes position, position precedes dimension, and they all precede the definition of purpose. This reflects SAR notion on the relationships between space and its use, between the position and dimension of a space.

The notion has been formed through observation of traditional architectures. One idea which is at the root of SAR notion is that the relationship between a function and an element is not constant. It is argued in *SAR 73* that "analysis of function along does not necessarily determine the form of an element." This is especially a characteristic in the description of the

traditional built environment. Habraken (1988) asserts, "in the modernist tradition we are used to name the spaces of the house after the function they hold," but in the traditional houses, there are often spaces that "there is not one specific function. The Atrium for instance, was a place where many things might occur. It is best understood as the most 'public' space of the Roman house." So is the courtyard in the "courtyard house" in China.

3.2.5 The grid schemata of classical architecture

Tzonis & Lefaivre (1986) have developed a formal canon of classical architecture which consists of three major levels: the first level, termed as *taxis*, is concerned in the overall organization, or the coordinating structure, of a building; the second level, *genera*, is about the order of elements; the third level, *symmetry*, concerns how the elements are chosen and placed in relation both to each other and to a coordinating structure. It is suggested that if a building can be recognized as a classical architecture, then its formal composition must confirm to a set of principles respectively on these three levels.

Immediately relevant to our discussion of spatial representation is the method used by Tzonis & Lefaivre in describing the principles on the "taxis" level. They suggest that taxis contains further two sublevels: *grid* and *tripartition* schemata. There are two sets of grid schemata in the classical composition, i.e., the *rectangular* grid schemata and the *polar* grid schemata. A grid schema is an overall coordinating structure underlying the organization of classical composition: it regulates the positioning of building elements and thus the physical appearance of its more general and fundamental partner, tripartition. The tripartition schema appears to be embodied in the generic 3 x 3 pattern, as,

$$
\begin{array}{ccc}
a & b & a \\
b & c & b \\
a & b & a
\end{array}
$$

which is contained by a rectangular or polar grid system. From this pattern

abstract plan layouts are derived through deletion, fusion, addition (or repetition) and embedding of parts (Tzonis & Lefaivre, 1986, p. 24). These operations allow the transformation of 3 x 3 pattern into every possible classic architectural plan. Through addition, for instance, the 3 x 3 pattern can be transformed into the 5 x 3 pattern:

a	b	a		a	d	b	d	a
b	c	b	(addition)	b	e	c	e	b
a	b	a		a	d	b	d	a

From the viewpoint of three levels of spatial abstraction, the grid schemata of classical architecture can be regarded also as a representation between the topological and the metric level: a grid schema abstracts the spaces in a building as a set of dimensionless and shapeless locations; yet the relations among the locations are governed by a metric coordinating structure. These features make the grid schema method much relevant to our concern, i.e., describing those spatial concepts derived from the case study. In effect, the relevance could be found from a more fundamental dimension.

Tzonis & Lefaivre (1986) suggest that the classical canon they proposed is *proscriptive* rather than *prescriptive* in the sense that its constituents "do not so much direct action as constrain it . . . In other words, instead of telling us what to do, they tell us what not to do. This may seem to be a subtle equivocation. But it explains why so many new classical formal arrangements have been, are, and probably will continue to be created out of the same canon. By constraining rather than directing, the classical canon allows for a certain degree of freedom and invention in responding to those forces of change that lie outside the world of forms" (p. 6).

Similarly, the proscriptive notion can be applied to the precedents which have been used in our case design: the spatial concepts derived from the precedents are also operating as some sort of proscriptive constraints on the new design. This may explain why the new design is "abstractly inheriting" the feature of the old city.

Compared to the grid schemata of classical architecture, however, our precedent spatial concepts (e.g., the "building-space pattern" and the

"fishbone circulation pattern") have also some distinguishable features. First, in so far as the present investigation, they can not be regarded as constituents of a well-established formal canon like that of classical architecture. Second, the spatial concepts not only impose generic coordinating structures on the new design but also constrains the type of locations which can be placed in the coordinating structures. This is why representation of these spatial concepts must be embedded with some "semantic distinctions" (which will be discussed in Chapter 7), dislike the grid schemata in which locations are only syntactically differentiated.

3.3 Using architectural precedent: a retrieving versus a reasoning approach

The last section evaluated some representation systems with respect to the representation of the spatial concepts derived from our case study. We now look at those systems from another point of view, in respect to the way precedent knowledge is connected to design generation systems.

Towards the computerization of using precedent knowledge, we might choose between two general approaches. A commonly applied approach is to treat precedent knowledge as a collection of elements, rules (or principles) or prototypes which are predefined and stored in a database. In solving a particular design problem, the database is searched and then the elements, rules or prototypes satisfying some given conditions are retrieved and further manipulated by some design generation system. This is exactly the way in which the rectangular dissections of architectural plan have been used in solving the automated floor-plan design problem: a collection of rectangular dissections are stored as prototypes of plan, which are to be selected according to the topological requirements of a given problem. The same strategy has been also followed by some systems based on shape grammars: the method is selecting—from a set of predefined shape rules—those applicable rules for form transformation. A common feature of these

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systems is their *direct* application of elements/rules/prototypes to design synthesis, without any modification when they are retrieved (of course, the prototypes may be transformed and the rules are used for transformation after they are retrieved).

In contrast to the above approach, another alternative is to treat the precedent knowledge as something contained implicitly in a collection of precedent examples that are stored as entities in a database. In solving a particular design problem, the relevant examples are retrieved and analyzed so as to provide information for design synthesis. In this case, some pre-defined rules or principles are also involved, but they are *indirectly* used for design generation: they are used as knowledge for analyzing the precedent examples, and it is the new rules/prototypes derived from the precedent examples that are eventually applied to design. This approach, as will be seen, is the one followed by the work in developing the new system of architectural representation.

Obviously, the first approach treats precedent knowledge as a *collection* of components from which one just *selects* or *retrieves* what are available, whereas the second approach treats precedent knowledge as a *system* from which one *infers* new information. We might therefore call these two general approaches respectively as a "retrieving approach" and a "reasoning approach" to the use of precedent knowledge (Figure 3-6). In Chapter 6, I shall further characterize the reasoning approach with the notion of *learning*: new knowledge for design is learned according to some given precedent examples and predefined knowledge. The notion of learn-ing, however, has not been associated with any available systems for architectural representation.

Then, why do we have to develop the reasoning approach? What is the advantage of such an approach? First of all, the reasoning approach is developed in order to account for the usage of precedents that we have identified from our case study. As remarked in the last chapter, three ways of using precedents are identifiable from the design of the "new courtyard house": first, precedents are used for specifying design objectives; second, precedents are used to keep historic continuity of the site; and third,
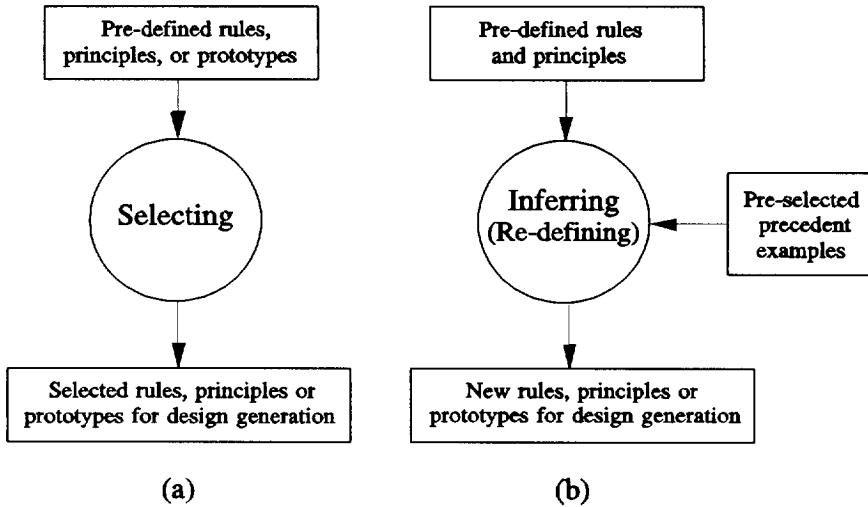
Figure 3-6 Two general approaches to the use of precedent knowledge: (a) a retrieving approach, (b) a reasoning approach

precedents are used for solving new problems analogically (Chapter 2). These correlations between precedent and design will be further elaborated in Chapter 5.

What is to be argued here, is that such correlations between precedent and design is hardly describable with a retrieving approach. Consider the specification of the design objective "good sense of privacy." If we attempt to describe this process by using a retrieving approach, we have to solve a problem of criterion: we need to set a criterion for "good sense of privacy" in order to define a collection of prototypes labelled as "having good sense of privacy," or rules saying how to get "good sense of privacy." But is there an absolute criterion for "good sense of privacy"?

In effect, there is hardly an absolute criterion with which we can designate a pattern as "having good sense of privacy." However, by using a reasoning approach we could avoid the dilemma of designating an absolute criterion. With a reasoning approach, we specify the "good sense of privacy" via the representation of the precedent examples rather than just through predefined rules or prototypes. We could assume that a number of

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precedent examples are satisfactory with respect to "good sense of privacy," and we just need to pick out from the examples those aspects that are plausibly relevant to the "good sense of privacy." This way is obviously not aimed at defining the "good sense of privacy" with an absolute value, but aimed at finding a manner through which a satisfactory "good sense of privacy" can be reached.

Moreover, specification via representation of examples permits one infer each time a description that is tailor-made for a particular design synthesis task, that is, for a synthesis at certain abstraction level and for trading-off among conflict design objectives. This will be explained in the next chapters.

3.4 Summary

As an investigation towards the definition of using precedent (the other was the case study in the last chapter), this chapter has reviewed a number of available representation systems for architectural space. The systems have been review with basically two criteria, both of them are based on the observations made out of the design case study.

The systems we have reviewed include topological representations of plan, rectangular dissections of plan, shape grammars, zoning diagrams and schemata of classical architecture. They are all contributive to some extent to the precedent analysis approach developed in this work; yet, none of them could independently take over the precedent analysis task, that is, the representation of the spatial concepts referred by the design case in the last chapter. Moreover, most of the available systems are associated with a "retrieving" approach to the use of precedents, i.e. simply decomposing a precedent into elements or rules, storing them in a database and retrieving them directly for use; whereas, the approach developed in this work is a "reasoning" one, a basic feature of which is the capacity of learning new knowledge according to particular objectives. From the next chapter on, we present the reasoning approach to the use of architectural precedents.

Part II

The Task of Precedent Analysis
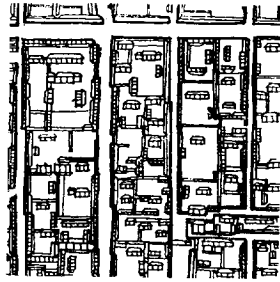
Chapter 4
Morphology, Operation
and Performance: A Model of
Precedent Knowledge
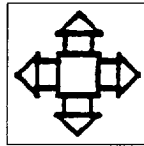
In Chapter 2, we observed in a case study several roles precedent knowledge could play in a conceptual architectural design. In Chapter 3, we reviewed a number of available methods of architectural representation in terms of their ability of carrying out the precedent analysis tasks implied by the design case; and we conclude that these methods are hardly satisfactory, although they each contain some useful notions which can be absorbed in the design of ARPRAN.

Based on the studies presented in Chapter 2 and 3, this chapter and the next chapter attempt to draw a framework in which the task of precedent analysis can be defined from an architectural perspective and on which precedent analysis can be further defined computationally. In this chapter we focus on the concept of performance, operation and morphology and their interrelationships, which are considered in this work as the elemental precedent knowledge and constituting the basic structure of architectural precedent analysis.

4.1 The concepts

Morphology, operation and performance of built environment were already briefly introduced in Section 2.1 (p. 28 ~ 29) as a general assumption of precedent knowledge. As we have seen in the design case study, these concepts and their interrelations constitute the basic elements and structure of the domain knowledge needed in precedent analysis as well as conceptual design. We have also observed that, although the concepts of performance, operation and morphology have been used in some previous work (e.g., Tzonis, 1990; Zandi-nia, 1992), they need more general and formalized definitions in order to be useful for the precedent analysis task addressed in this work. Now we discuss these concepts in some detail.

4.1.1 Morphology of built environment

Morphology is often used to refer to the formal aspects of a building or an urban area (Steadman, 1983; Tzonis, 1990). It can be defined as the form and structure of a built environment or any of its parts. *Form* is mostly used to mean the shape, appearance or image of an entity, while *structure* refers more to the aggregate of elements of an entity in their relationships to each other. Although *form*, *structure* and *morphology* are often used interchangeably, in this work I use morphology instead of the two others to emphasize that both apparent shape and internal relations are important formal aspects in precedent analysis. Zandi-nia (1992) uses *structure* to term the formal aspects of building, because his work is focused on the pattern of connectivities embedded in the physical organization of a building.

Morphology of a built environment can be considered from different perspectives, i.e., as different hierarchies of organization. For example, a building can be seen as a hierarchy of construction elements; it can also be seen as a hierarchy of spaces. Furthermore, in each hierarchy of organization, morphology can be described on different levels of organization and

different levels of abstraction.

By *level of organization*, I mean a level on which a built environment is considered as an entity. For instance, a house can be seen as a level of organization in a residential sector, whereas a room can be seen as a level of organization in a house. Of course, there can be different ways to divide a built environment into levels of organization, and there are hardly definite rules for such division. Habraken, for example, divides the built environment into several levels of organization according to territorial control (Habraken, 1982, 1986).

When morphology of a built environment is considered on different levels of organization, the basic components (or primitives) are usually different. For instance, the morphology of an apartment house on the building level, may be described in terms of the shape and the organization of living units. Here the living units are primitives of the description of the apartment house. On a lower level, the living unit level, the primitives may be rooms. In this work, the precedent analysis is concentrated on several organizational levels and the description of morphology depends on the operation and performance in concern.

By *level of abstraction*, I mean a level on which the morphology of a built environment is abstracted in order to expose certain attributes for investigation or communication. There is, again, no definite rule for the division of levels of abstraction. As was introduced in the last chapter, Tzonis & Oorschot (1987) suggest three levels of morphological abstraction focusing on three strata of design attributes, i.e., the clustering, the topological and the metric levels. In this work, the abstraction level on which we describe the morphology of precedents is between topological and metric levels. This level of abstraction, as was indicated in the last chapter (p. 56~57), is derived from our case study.

In short, morphology of built environment refers to the physical organization and appearance of a building or an urban area or any of its parts. To describe the morphology of a built environment, is to describe the appearance and organization of its components.

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4.1.2 Operation of built environment

Operation is the dynamic aspects of a built environment. It is about how a building would work, or what events may happen in a building (Tzonis, 1990). Zandi-nia (1992) defines operation of a building as "the pattern of flow of people and objects within that building as prescribed by the inter-relations and associations between them." This definition, viewed from his work, is sufficient and clear enough. But to explain what we have encountered in the design of the "new courtyard house", it seems that a more general definition is needed.

If operation is defined as only about the "flow of people and objects," then, what about that people can perceive the similarity between the new building and the old building when they stay in the new building, as we discussed in the case study? Evidently, "people perceive similarity" is a status of interactive activity between the building and the people, it may happen as a result that there are some similarities between the new and the old. In addition, people can only perceive the similarity when they stay or move in or around the building.

Operation of built environment can thus be defined more generally as: *the status of interaction and association among actors or between actors and environment when certain activity (or activities) happens in/around a built environment*. The actors may be people, material, equipment or force. This definition not only covers "flow of people and objects," but also embodies "perceiving."

According to this definition, when the operation of a built environment is described, there are always two parts, the first is an activity, the second is a status. For example, the encounter situation, as a result of the flow of people in a building (Figure 4-1), can be described as:

When PERSON-X walks from ROOM-A to ROOM-B, and   (a)

PERSON-Y walks from ROOM-C to ROOM-D,   (b)

PERSON-X meets PERSON-Y.   (c)

Here, (a) and (b) express the activities and (c) is the status of interaction
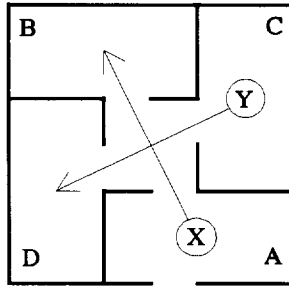
Figure 4-1 The encounter situation in a building

between the actors. Similarly, the "perceiving" operation can be described as:

- When PEOPLE stay in BUILDING-A,
- PEOPLE perceive BUILDING-A similar to BUILDING-B

or

- When PEOPLE move in BUILDING-A,
- PEOPLE perceive BUILDING-A similar to BUILDING-B

With the same approach, the operations mentioned by Tzonis (1990) can also be formally described:

(1) "Air can circulate without obstruction under the building":
- When AIR flow from ONE-SIDE-OF-BUILDING to ANOTHER-SIDE,
- AIR is not obstructed by BUILDING.

(2) "The overall bearing structure is channelling forces independently from those of the structure enclosing each apartment":
- When FORCE acts on BEARING-STRUCTURE,
- FORCE does not act on THE-STRUCTURE-ENCLOSING-EACH-APARTMENT.

(3) "People can look around from high up":
- When PEOPLE stay on DECK,
- PEOPLE overlook SURROUNDING.

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4.1.3 Performance of built environment

Performance is about the qualitative aspects of built environment. Tzonis (1990) explains it as a description of what artifacts do in respect to what has to be done. Performance of built environment, in the problem context of this work, can be defined as: *the quality of a built environment which is perceived as if the built environment can conduct some activity in/around the built environment with respect to a norm.* This definition is developed from—but more general as well as more specific than—the one given by Zandi-nia (1992): performance is "the actual behaviour of a design with respect to a norm." The present definition is more general in the sense that it is concerned with not only built environments in design or to be designed but also precedents. It is more specific in terms of emphasizing on the spaciality of the built environments, because "behaviour" is a term applied in general to any systems and is often related to mechanical or electronic devices (Davis, 1984). Moreover, the present definition addresses the subjectivity of the quality of conduct.

When the performance of a built environment is described, there are also two necessary parts. The first is a point of view. The second is a degree of the quality of conduct with respect to a norm implied by the point of view. The degree can be described qualitatively as well as quantitatively. For example, the "good sense of privacy" describes a performance. The "sense of privacy" is the point of view; and "good" can be seen as a qualitative description of the quality as a result of comparing the quality with some standard that says what is "good" and what is "not good" from the point of view of privacy.

"Fitting the traditional urban fabric" describes also a performance (a desired performance for the "new courtyard house"). Here, the viewpoint can be understood as "relation to the traditional urban fabric"; and "fitting" is a qualitative description derived from a norm that "regulates" what is "fitting" and what is "not fitting," or what is "more fitting" and what is "less fitting."

As far as the performances like the "good sense of privacy" and "fit-

ting the traditional urban fabric" are concerned, a question would be raised naturally: Is there a norm or standard that classifies the qualities from these viewpoints? The answer is: There is certainly no absolutely defined norm or standard for such classifications. This situation is similar to the one we mentioned earlier in discussing the description of morphology of built environment. Nevertheless, we still can identify a relative norm or standard. At least, we may assume that such a relative norm or standard is existing somewhere in the designer's mind and in the public opinion of culturally-defined group. Otherwise, how can it be agreed that the "new courtyard house" is a successful design?

However, it is a fact that such norms or standards are often difficult to describe if they are not related to concrete examples. We saw this fact in the design of the "new courtyard house" where the performances desired to be achieved by the new house prototype are mostly described in connection with a precedent. This is one of the fundamental reasons why precedent analysis is needed. We shall return to this topic later.

4.2 Facts and rules of precedent knowledge

Morphology, operation and performance constitute an important part of precedent knowledge. They are *facts* of a precedent built environment. Here, "facts" should be understood as the concepts in the *projected world*, rather than in the *real world* (Jackendoff, 1983). In other words, they bear more subjectivity than objectivity, because—as mentioned earlier—there is hardly definite way in which morphology can be described and the norm related to some performances can be specified.

Morphology, operation and performance are interrelated. This inter-relationship, as Tzonis (1990) indicates, "can be expressed in constraints that state which performance of a building may result from which operation and, in turn, which operation may result from which form, a rule chain whose links are neither deterministic nor closed." The constraining relation-ships between morphology, operation and performance constitute another

part of precedent knowledge. These are *rules*. They can be expressed in the IF-THEN form.

In the design case study, we interpreted a number of performances by relating them with their causal operation and morphology. These causal relations can be expressed with IF-THEN in two basic forms:

IF morphology M, THEN operation O.

and

IF operation O, THEN performance P.

For example:

(1)   IF   there is "building-courtyard pattern",
       THEN "when people stay in the building,
              people perceive similarity between the new and the old."

(2)   IF   "when people stay in the building,
              people perceive similarity between the new and the old,"
       THEN the building "fitting the traditional urban fabric."

(3)   IF   there is "clearly defined territory for nuclear family,"
       THEN "when people move or act in the building,
              there is less physical disturbance to the living units."

(4)   IF   "when people move or act in the building,
              there is less physical disturbance to the living units."
       THEN the building has "good sense of privacy."

Sometimes, performance and morphology are directly connected by IF-THEN, as:

IF morphology M, THEN performance P.

Such connection often occurred in the archaic thinking. For example, in an ancient manual of house construction, there are full of statements arguing that "if you use such and such dimensions in your house, you will get such

and such luck" (Yu, 1992).

Again, rules expressing the constraining relationships between morphology, operation and performance bear subjectivity. Such subjectivity is due to the subjectivity of morphology and performance. An extreme example of subjectively connected rule chain is evidently the archaic arguments that connect the luck of people directly to the form of their house.

In practical situations, the rules are often not simply stated as a chain, but as a network. As we have seen in the design of the "new courtyard house," it is not only one morphological aspect that causes an operation, and also it is not only one operation that causes a performance. Viewing from the other side, one aspect of morphology can cause not only one operation and it is also true that an operation can cause not only one performance. Thus, the interrelations between performance, operation and morphology may build up a complex network like the one in Figure 4-2. Such network is the basis of the explanation structure of performance used in architectural precedent analysis, as will be presented in Chapter 6.

Facts and rules based on morphology, operation and performance of built environment, in effect, not only constitute knowledge about precedents, but also compose the base, if not all, of architectural domain knowledge. They are considered as the "bare minimum of architectural domain
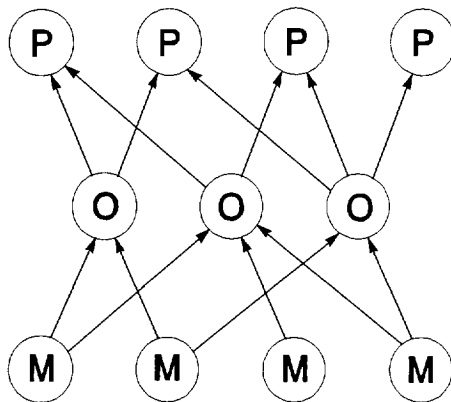

Figure 4-2 The network structure of the interrelationships of performance, operation and morphology.

knowledge." (Tzonis, 1990). Reasoning constrained by the rule chains of morphology, operation and performance in one kind or another, is pervasive in architectural thinking. For example, design generation can be seen as a reasoning process that starts with desired performances of a building and terminates with a morphological description. Design evaluation, on the other hand, is to predict the performance of a design according to its morphological description and to compare the performance with a desired performance. The "pattern languages" written by Alexander (1977) are actually a set of rules which prescribe the relations either between performance and operation or between operation and morphology, though in loosely described forms. Viewed from this point, precedent analysis can be seen in general as a reasoning process that infers, from a performance description of a precedent built environment, plausible morphological description(s).

4.3 The hierarchies and levels of organization

As mentioned earlier, the morphology of built environment can be described as different hierarchies of organization and on different levels of organization. Which hierarchy or level is used in a morphological description, depends on the operation and ultimately the performance of built environment that we are concerned with. These are important notions in this work. To make them more clear, we now introduce some concepts related to a way of morphological description and use these concepts to analyze the morphology of Beijing's old city. Finally, we shall discuss how the levels of morphological descriptions in our design case study could be defined.

4.3.1 Dependency hierarchy and territorial control

The concepts of dependency hierarchy and territorial control come from Habraken's design theory and have been applied in SAR's design method (Habraken, 1982, 1983, 1986; SAR, 1973). As a way of looking at the built

environment, we shall find these concepts useful in understanding the relation between morphology, operation and performance of built environment and the hierarchical nature of Beijing's old city.

Habraken (1983) notes, "complex forms are inevitably hierarchical in nature." From an attitude of design, he distinguishes two kinds of hierarchies: an assembly hierarchy and a dependency hierarchy. An *assembly hierarchy* is a hierarchy of part-whole relations. In building one may say that the bricks make the wall and the walls make the house. Here the wall is a part out of which a house may be built, and the bricks are the parts of which the walls are made.

In contrast, a *dependency hierarchy* means a hierarchy in which entities *contain* one another rather than *make up* each other's constituent parts. For example, we can say that furniture makes a room or houses make a neighbourhood. Obviously, it does not mean that the room is assembled out of furniture and the neighbourhood from houses. It means that we can place and arrange furniture in a room, and we can build and demolish houses in a neighbourhood.

Both assembly and dependency hierarchies are ways in which we may describe the morphology of built environment. And obviously, we can define different assembly hierarchies as well as different dependency hierarchies. However, which hierarchy we apply to the description of a built environment, depends on the intention with which we describe the built environment. In fact, when we describe a built environment, our intention is always to reflect some properties of that built environment in order to make the built environment *meaningful* for us. This notion will be further elucidated in Chapter 7 from the cognitive point of view. For now, let us consider how Habraken uses dependency hierarchies as means of morphological description for his purpose of disclosing the property of built environment.

Habraken points out that design decision-making should be organized according to two kinds of dependency hierarchies: first is a hierarchy of elements which reflects the nature of physical organization of a built environment, and second is a hierarchy of territories which reflects the

pattern of social control in the built environment. The dependency hierarchy of elements can be understood as being composed of a number of levels of elements, such as furniture, walls, streets, infrastructures, etc. Whereas the dependency hierarchy of territories is the organization of spaces on different levels, such as rooms, neighbourhoods, cities, etc.

Habraken argues that, if these two dependency hierarchies are so defined in a built environment that they correspond to each other, the design decision on each level of elements can be made by the people who have direct power to control the corresponding level of territory. In this way, the design may achieve the best result with respect to balancing between mass production and variation. This idea has been presented in his housing design theory, as the division of a house into support and infill (Habraken, 1964). He suggests that the support elements of a house, such as the dividing walls between the living units should be decided collectively by architects and all residents, whereas the infill elements, such as the internal walls, should be left to the particular residents of the house.

Whether the houses designed according to Habraken's theory have been successful or not, is indeed a topic beyond this work. What I would like to point out is that Habraken describes morphology by using the dependency hierarchies because he intends to enable a kind of operation of built environment (i.e., the territorial control of environment), hence a kind of performance of it (achieving better living condition and variation in design). In addition, we may find the concept of dependency hierarchies applicable to Beijing's old city and useful for further understanding our case study.

4.3.2 The levels in Beijing's old city

Beijing's old city (see Appendix A) is famous for its regularity in planning and construction, hence a good example to explain morphology of built environment. In addition, an analysis of Beijing's old city is helpful for further understanding the nature of the design problem and the task of precedent analysis confronted by ARPRAN.

The scope of our analysis will be confined to the most typical part of the city, i.e., the Inner City part (Figure A-1, p.210), and its thematic patterns, i.e. the ordinary streets and residential buildings.[1]

We start from physical organization, to identify the dependency levels of physical elements. According to Habraken, the criterion for identifying dependency levels is the possibility of change, i.e., if modification in level A does not disturb the pattern of level B whereas modification in B must cause change in A, then A can be seen as a higher level and B as a lower dependency level. According to this criterion, we may identify at least seven levels in Beijing's old city (Figure 4-3).

The city wall can be seen as an independent level, because any change within the city can be independent of the wall. Once the city wall is defined, the city is defined. This is especially the case in the construction of Chinese cities. The main street network can be seen as another level below the city wall. Then, there are the lane system, the property division walls, the building structure system, the infill walls, and finally, the furniture in rooms.

Correspondingly, we can identify six levels of territory, i.e., the city, the blocks, the sub-blocks, the units, the buildings and the rooms (Figure 4-3). Presently, this territorial pattern does not fully corresponding to the pattern of social control. However, it reflects more or less how the present morphology was originally formed. For instance, in the cities before the Northern Song dynasty (960 ~ 1127 A.D.), the blocks were usually built as closed territories (called *Li Fang*) with their own gates. They were a relatively independent level in the control hierarchy. Although in the times of Beijing's old city, the system of *Li Fang* was not used any more, the morphology formed by it has been remained and it still shows the possibility

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[1] Habraken (1983, 1986) points out that in a built environment, one can always find the thematic versus the nonthematic elements. Thematic elements are those occurring throughout the area and they are always placed in the same position with respect to the other elements. In Beijing's old city, the thematic elements are those streets and buildings in or around the residential sectors.

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of being regarded as an independent level of control. More important, the territorial pattern shows the potential to add social control.

In the next section, we take a closed look at the levels with which the design of the "new courtyard house" has been concerned and explain some considerations in ARPRAN's representation scheme.
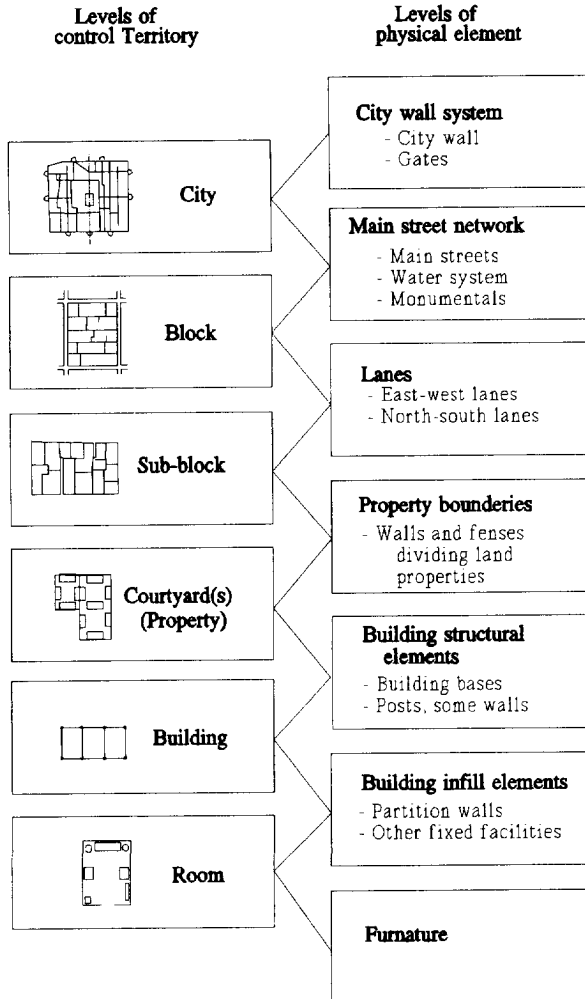

Figure 4-3 The dependency levels in Beijing's old city

4.3.3 The levels in the case study

An important issue in precedent analysis is the selection of primitives. In this work, we consider the issue as determined by two factors. One is the organizational levels concerned, which is determined by the design problem for which a precedent analysis is carried out. Another is the levels of abstraction, which is determined by the design itself, and this was already discussed before. Now we discuss the level of organization which is concerned by the design of the "new courtyard house."

The design of the "new courtyard house" was involved in the modi- fication on the level of building structure, and this was caused by a change in the pattern of territorial control on both courtyard and building levels. In the old courtyard house, the courtyard level was controlled by large com- pound families and the building level by family members (e.g., the son or his family); whereas in the "new courtyard house," the control power of the courtyard level become a group of small families and the building level is replaced by a unit level which is controlled by small families (Figure 4-4).

Correspondingly, the levels directly concerned by ARPRAN would be the courtyard(s), the building, the living unit and the building structure.
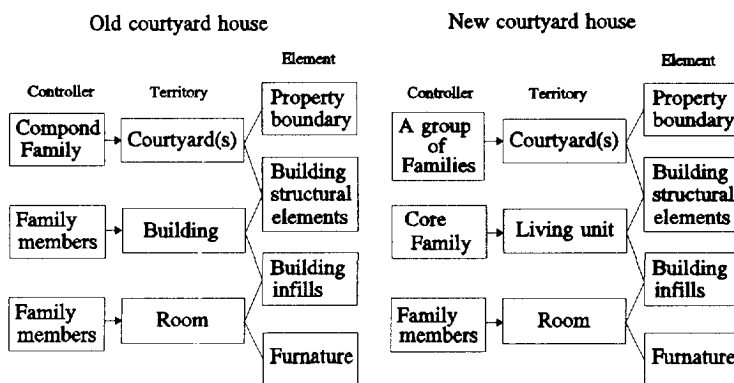

Figure 4-4 Comparison of the organizational levels between the new and the old courtyard houses

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In other words, we can say that, on the one hand, ARPRAN is concerned with the analysis of the old courtyard houses with respect to how they are composed of buildings; and on the other hand, ARPRAN is concerned with the analysis of the walk-up apartments with respect to how their living units are put together.

4.4 Summary

This chapter has attempted to draw a framework of precedent knowledge, with which we can further develop the reasoning approach to precedent analysis. We discussed in detail the concepts of performance, operation and morphology and their interrelationships. The model of precedent knowledge constituted by these concepts are considered as the basis of precedent analysis.

The description of morphology of built environment is the ultimate result of precedent analysis. Yet, for any built environment, its morphology can be described as different hierarchies of organization, on different levels of organization and on different levels of abstraction. Which particular hierarchy or level should be applied in a morphological description, depends on the operation of built environment in concern and the operation, in turn, is connected to a performance of built environment. In other words, we should always find an appropriate hierarchy or level with which the morphology that constrains the operation can be described. This is an important notion developed in this work. As we have seen, this notion differentiates the approach in this work from many others, which are often regardless of the interrelationships between morphology and operation.

In the next chapter we shall discuss further the role the precedent knowledge plays in architectural design and define the tasks that the precedent analysis should fulfil.

Chapter 5
Precedent Analysis for Architectural Design
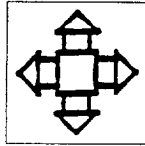
Architectural design is a complex human activity. Yet, it is still possible to describe the rationality of designing. This has been attempted by many researchers since the early 1960's, and it has resulted in many descriptions, definitions, models and classifications of design and design behaviour. The aim of this work is certainly not to give an overall evaluation of those design theories, not even to develop a new one. Our discussion of architectural design in this chapter is to indicate the role of precedent knowledge in the design process and, more important, to prepare for the formalization of precedent analysis.

5.1 Some aspects of architectural design

Architectural design is primarily characterized as a problem solving process; it is, to some extent, accountable by the information processing theory of problem solving (Newell, Shaw and Simon, 1957, 1967; Rowe, 1987). The

nature of architectural problems, on the other hand, characterizes the problem solving in architectural design as one quite different from that in, say, mathematics. Both of these general characteristics of architectural design have to be considered when architectural design is described computationally. To draw its problem solving aspect is to provide a rational, computational basis for architectural design. To address the specific natures of architectural problem is to avoid a rigid position in architectural problem solving, such as the one ever taken by the "analytical paradigm" (see Chapter 1, p. 7).

5.1.1 The nature of architectural design problem

Speaking of design problems, a distinction can be made between those that are *well defined* and those that are *ill defined*. Well-defined problems are those for which the ends, or goals are already prescribed and apparent; their solution requires the provision of appropriate means. For ill-defined problems, on the other hand, both the ends and the means of solution are unknown at the outset of the problem solving, at least in their entity (Newell *et al.*, 1967, p. 71; Bazjanac, 1974, p. 8).

Most architectural problems are ill-defined. For example, an architect is asked to design a house, or to improve the quality of a neighbourhood. Although the general problem may be clear, the architect has to spend much time to clarify what is required exactly. A large part of the problem-solving activity, then, consists of problem definition and redefinition.

Very often, the architectural problem is so ill-defined that it can only be called *wicked problem* (Churchman, 1967; Bazjanac, 1974). Wicked problem has, among others, a number of characteristics relevant to our discussion. First, it lacks a definitive formulation, or indeed the very possibility of becoming fully defined. Second, it lacks an explicit basis for the termination of problem-solving activity. Third, different definition, or formulation of the problem implies differing solutions, and vice versa. In other words, the problem's definition depends on a preconception that, in

turn, implies a definite direction towards the problem's solution. Finally, solutions that are proposed are not necessarily correct or incorrect. This follows logically from the first characteristic: the impossibility of definitive formulation (Rowe, 1987; Lawson, 1980).

The nature of the architectural design problem determines that the description of the problem often has to be connected to some previous problems and solutions, or existing buildings. In the design of the "new courtyard house," the general design problem "to generate a new dwelling prototype to replace the decaying traditional courtyard house" is a typical wicked problem. Although it is clear that the new house should be better than the old one in terms of living conditions, it is not clear what it means exactly by "better." Thus in the initial problem definition one has to interpret "better" by relating it to some precedents.

5.1.2 The problem-solving behaviour in design

The behaviour of architectural design has been modeled with a cyclic and expanding structure (Figure 5-1): horizontally, it contains phases known as *analysis*, *synthesis* and *evaluation*; vertically, the three-phases move cyclically from abstract to concrete (Asimow, 1962; Mesarovic, 1964). This model does illuminate certain commonly observable features of design
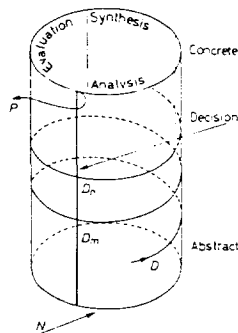

Figure 5-1 A model of architectural design

activity, but at a comparatively low level. A major limitation of the model is that it says nothing of where designs come from—how do we advance from analysis to synthesis? (Rowe, 1987; Coyne *et al.*, 1990).

From the information processing perspective, the design phases are often described as *problem representation*, *solution generation* and *solution evaluation* (Rowe, 1987). Problem representation is in fact a process of defining and/or redefining the problem. In order to distinguish this *representation* with the one we use for knowledge representation (see Chapter 1), we use the term *problem definition*.

Problem definition, solution generation and solution evaluation in design, clearly, are interdependent sub-classes of activity. The choice of solution generation strategy may markedly affect the manner in which a problem is defined, and vice versa. This is also true between solution generation and solution evaluation. Usually, it is in terms of solution generation strategy that problem-solving procedures are described (Rowe, 1987).

Relevant to architectural design, a number of solution generation strategies, or techniques, are often studied, such as generate-and-test, means-ends analysis, hill-climbing, analogy, etc.. Usually, these techniques are used mixedly in one design process, but maybe one or two of them are more salient. According to different use of these techniques, architectural design are often classified into different types (Broadbent, 1988; Coyne *et al.*, 1990; Zandi-nia, 1992). An argument in this work is that most of the techniques in architectural problem solving are necessarily connected to precedent knowledge. In Section 5.2, we shall discuss the use of precedent knowledge in design.

5.1.3 Starting from a pre-parametric description

An important behaviour of design, which is often addressed in design theories, is that at the outset of design a designer usually creates a sketchy plan of building, which is a rough global spatial organization. In such a

sketch, the geometry of building is inexact, but "it is precisely this rough-edged character that assists the designer in externalizing preconceptions of spatial organization." (McIntosh, 1987). A scheme of global spatial organization, as Tzonis (1990) indicates, enables designer to "capture essential characteristics without loosing themselves in details of local problem."

Design at a sketch level is termed by Ulrich (1988) as *pre-parametric design*. This type of design is called pre-parametric because it is concerned with specifying gross design configurations rather than particular numerical values for pre-determined parameters.

In architecture, pre-parametric design appears at the early stage of conceptual design (sometimes called schematic or preliminary design). The product of this stage of design can be called a pre-parametric description. We might define the pre-parametric description in this way: it is a specification of gross spatial organization, maybe including some crucial dimensions of the elements but only to such an extent that the design can be evaluated with respect to some desired performances.

An important task of pre-parametric design is to describe the morphology of a building in order to make some desired performances distinguishable. Usually, these desired performances are qualitative and often difficult and also unnecessary to be specified with particular numerical values at the outset of design. These desired performances are "usually strongly valued and self-imposed," or "big ideas"; and they are often known as "primary generators." (Darke, 1979; Rowe, 1987). In this sense, pre-parametric description of architecture sometimes need not absolutely exclude dimensional assignment, because some sort of performances has to do with dimensions and some not. Also, it is difficult and unnecessary to draw a clear line dividing pre-parametric and parametric descriptions. Nevertheless, we still use the term pre-parametric because most of the performances discussed in this work are less relevant with dimensions.

Precedent knowledge and, consequently, precedent analysis are much relevant to pre-parametric design, because the "big ideas" often come from precedents. This has been discussed by many researchers. An important principle for the derivation of precedent knowledge is that the description

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of the precedent knowledge should be compatible with that of pre-parametric design. This is also a reason why precedent analysis is necessary for the use of precedent: if the descriptions of some aspects of a precedent is stored in a database, they might not fit for current use; in order to make the descriptions compatible with the need of a design, the precedents have to be analyzed, or re-presented.

5.2 Precedent knowledge in architectural design

Architectural design is often classified into different types according to the manner with which solution is generated. For example, Broadbent (1988) describes *pragmatic design, iconic design, analogical design* and *canonic design*. Gero (1990) distinguishes between *routine design* and *non-routine design*, and non-routine design is further divided into *innovative design* and *creative design*. Coyne *et al.* (1990) use *prototype refinement, prototype adaptation* and *prototype creation* to name different kinds of design. Most of these design types, in fact, are involved in two general ways of using precedent knowledge. One way can be called precedent-constrained design; another is design by analogy. In this section, we first discuss these two ways of using precedent knowledge in design generation and then discuss the role precedent knowledge plays in problem definition and solution evaluation.

5.2.1 Precedent-constrained design

Architects often connect their designs to precedents, consciously or unconsciously. Hancock (1986) points out that the epistemological idea behind the use of precedents is to make the design solution convincing, because "a critically maintained continuity of precedents is regarded (in the absence of absolute "truth") as the only convincing ground we have for valid action and belief, in design as in other fields." (p. 68) He summarizes that, to be

broadly convincing, precedents used in design must be grounded in one or more of three realms, i.e., place, type, and principle.

Place-grounded precedents are those accumulated at a particular place where the site of new design is located. To design new buildings under the constraint of place-grounded precedents is to keep the historic continuity of the place. This is often regarded as one of the most important tasks that the new work might fulfil—as in the urban renewal design. *Type-grounded precedents* are those from which "culturally rooted form-function analogues" can be extracted. In other words, to use type-grounded precedent is to keep certain cultural values imbedded in the building forms. Also, this is often considered as an important task by designers. *Principle-rooted precedents* are those which have established "accumulated insights and effective techniques" for the discipline; use of them "can most easily be broadened to a consensus when and to the degree that the principle cited has both a historically evident durability and an important connection to the task at hand." (Hancock, 1986, p. 71)

Design by using precedents grounded in place, type or principle can be referred to as *precedent-constrained design*, in which solution is usually generated through refining a prototype or adapting a prototype (Coyne *et al.*, 1990), or repeating a typical existing design (Broadbent, 1988).

Usually, the prototype or the principles can be well defined and stored somewhere, ready for use. Yet, this is not always the situation—very often, there is no ready or tailor-made prototypes for use—such as the one in the design of the "new courtyard house," where there is lack of a prototype "fitting the traditional urban fabric." Of course, we might say that the old courtyard house is obviously the best prototype that fits the traditional environment. But it is also obvious that designing by completely copying the old courtyard house is out of the question here. The eventual solution is based on an analysis of the old courtyard house type. The success of the design can thus be attributed to an adequate description of the old type, or in other words, an adequate explanation of why the old type is recognized as "the old type" that fits the traditional urban fabric.

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5.2.2 Design by analogy

If precedent-constrained design is regarded as something mostly related to the "routine design," then *design by analogy* is more related to the so-called "creative design," or "prototype creation."

Analogy is a particularly useful approach for solving an unfamiliar new problem without adequate or directly applicable knowledge. By analogy, relations between the new problem and some past experience or knowledge about a particular design can be found. This experience or knowledge can be placed in the new situation so that solution to the new problem can be generated (Winston, 1992). A good example of using analogy in architectural design is given by Tzonis (1990). The example shows how Le Corbusier, when designing the famous *Unité d'Habitation*, derived his major ideas from several different artifacts through analogical reasoning.

In the design of the "new courtyard house," as we observed, the designer also used analogical reasoning to solve the problem of organizing living units: he related this problem to the solutions founded in the southern large mansions. Here, two important procedures are involved: first to find the right precedent which can serve as an example of analogy, second to find the relevant aspects in the example. Clearly, here it is necessary to resort to the analysis of precedent.

Of course, creative designers are not confined to the use and analysis of architectural precedents; they may use and analyze any precedent artifact, as Le Corbusier used huts, ships and bottleracks in the design of *Unité d'Habitation* (Tzonis, 1990). This work, however, is concerned only with the use and analysis of architectural artifacts.

5.2.3 Problem definition and solution evaluation

The nature of architectural design problem determines that the problem's definition is often difficult to be clearly stated in the sense that neither goals nor criteria for solution evaluation can be explicitly described at the outset.

This leads to defining design problem by referring to precedent.

In the design case study, we saw this kind of problem definition, such as that the new design should "have the sense of privacy in the walk-up apartments as well as the sense of community in the courtyard house." This type of description is often encountered in architectural problem definition, because the problem such as how "to achieve a good sense of privacy" is usually a typical ill-defined or wicked problem. At the outset of a design it is very difficult or even impossible to specify explicitly such problem to an extent that we can have definite means to solve it. Problem definition has another task, that is, to set criteria for evaluation of solutions. Still, for the "privacy" problem, it is hard to describe a set of such absolute criteria.

These difficulties, however, can be partially overcome by relating the problem to a precedent. In other words, we do not know what are the general means to achieve *the* "good sense of privacy" in the "new courtyard house," but we know that in the common walk-up apartments there is means with which we can reach *a* satisfactory result. It is the same for solution evaluation: we do not have *the* absolute value to judge whether a solution has achieved the "good sense of privacy" or not, but we do know that the "sense of privacy" in the walk-up apartment is *a* satisfactorily good one. We may compare our solution to the walk-up apartments.

Relating a problem to a precedent can reduce the difficulty to define the means and criteria, but at the same time it raises another problem, that is, to identify the means and criteria in the precedent. One of the aims of precedent analysis is to solve this second problem.

5.3 Summary

Through out the design case study and the discussion of precedent knowledge, a framework of architectural precedent analysis has been illustrated. Now we summarize it as following.

Architectural precedent analysis can be defined as a process of deriving, from the general documents of a built environment, a description

of the morphology which may possibly cause a known performance of that built environment. The general purpose of architectural precedent analysis is to make design problem-solving more effective and efficient. More specifically, architectural precedent analysis enables an appropriate use of precedent knowledge in design problem definition, in precedent-constrained design generation and in design by analogy.

In design problem definition, a desired performance aspect of the new design is often expressed in connection with a precedent so as to be describable. Consequently, the task of precedent analysis is to produce a satisfactory definition of the performance in concern.

In precedent-constrained design, one purpose of using precedent is to keep the historical continuity of a place. For this, the task of precedent analysis is to generate an adequate morphological description of a precedent in order to transfer some of the morphological characteristics of the precedent into a new design.

In design by analogy, precedent knowledge is used to solve similar problem in a new situation. In this case, the task of precedent analysis is to find the relevant aspects for analogical reasoning.

Although we identified three tasks of precedent analysis, we may also describe some features which are common to all three tasks. First, the process of precedent analysis is to search for the plausible causes of a performance of a precedent. Second, the causes of the performance can be described in terms of an operation of the built environment and ultimately be described in terms of a morphology of the built environment. Third, the description of the morphology must be operational in the sense of being useful to architectural design generation or evaluation. Fourth, the search is usually focused on one or a few precedent examples which are known as having the performance under study. Finally, the process of search is guided as well as constrained by domain knowledge.

These features will be further discussed in the next chapter in which we shall treat the process of precedent analysis as a machine learning process and we shall describe the structure of ARPRAN through two examples of precedent analysis.

Chapter 6
Architectural Precedent Analysis
as Example-based Learning
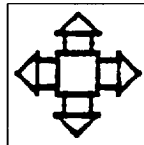
In the last chapter, precedent analysis was studied from an attitude of architectural design. In this chapter, we examine the process of precedent analysis from a computational point of view.

After the study of the design case, an assumption adopted in this work is that architectural precedent analysis is primarily a learning process. This assumption leads to the perspective with which the computation of precedent analysis is treated as a kind of machine learning. Methodologically, such a treatment is of significance to the investigation of ARPRAN; it allows the computerization of architectural precedent analysis to be defined and developed on the basis of a set of relatively well-studied theories and methods, such as those paradigms of example-based learning. Of course, a general assumption like the one adopted in this work must be followed by a more detailed comparison between the particular characteristics of architectural precedent analysis and the problems addressed in studies of machine learning, so as to clarify at which point precedent analysis can be

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adapted to the established theories and consequently applying the methods, and at which point it is beyond the limits of those theories hence must use particular approaches. Such a comparative study is in the right focus of this chapter.

This chapter will first describe, from an information processing viewpoint and in a general manner, the task of precedent analysis, i.e., to illustrate a general framework of the input and the output of a system for precedent analysis and to draw some general features of such a system. Then, the chapter reviews some theories of example-based learning, discussing the possibility of treating precedent analysis as a machine learning process. After that, the chapter will specify several distinctive features of precedent analysis by comparing it with some commonly addressed tasks of example-based learning. Finally, the chapter will illustrate a sketchy structure of ARPRAN by presenting two exemplar problems extracted from the design case study.

6.1   The computation task of architectural precedent analysis

An architectural precedent analysis task can be generally described as following:

> Given: A performance and the precedent(s) known as having
> the performance.
> Find: A working morphological description that accounts
> for the performance.

A "working morphological description" means that the description should be useful for a variety of design problem-solving tasks including (1) to describe and evaluate some non-quantifiable design objectives, (2) to trans-

fer some of the characteristics of a place into a new design, and (3) to find some relevant aspects for analogical reasoning in design.

What kind of description is "useful," indeed, is difficult to be exactly defined. In this work, we assume that a useful description in design is a global organization showing spatial relations between locations and such descriptions can be used as a framework in the generation of pre-parametric designs. More specifically, we assume that the spatial concepts we derived from the case study, such as the "building-courtyard pattern" and the "fishbone circulation pattern," are useful descriptions.

So far, our general description of the task of precedent analysis is still not specific enough for ARPRAN. With such a general vision, however, we are ready to further discuss some general features of a computation system for precedent analysis in order to sketch a clearer framework.

6.1.1 The general purpose

The general purpose of a precedent analysis system is to make an architectural design computation system more effective and efficient. As mentioned in Chapter 1 (p. 7~8), some early design systems were reductive in their conception and led to poor production—thus ineffective. This is because not all the objectives in architectural design can be quantified hence processed and optimized by means of numerical calculation—as it was supposed in the "analytical paradigm." If the objectives in a design are to be processed through merely quantitative method, then some objectives which are non-quantifiable must be overlooked. This would lead to reductive conception and poor production in design. In the old paradigm, the architectural design computation was regarded as a search for the optimum solution to a problem and hence the systems were designed to search through out the solution space. Sometimes this is extremely inefficient because of the combinatorial nature of design solutions.

These difficulties, however, can be overcome by associating problem definition and solution generation to a precedent. Under the situation that

there is no way to specify an absolute value of an objective, at least we can specify, within the domain of the precedent, certain means by which the objective can be achieved to a satisfactory degree. More important, architectural design never proceeds with a single objective. In a good precedent solution, an objective is usually realized synthetically with other objectives. Thus, once the means towards an objective is identified from the precedent, it is usually relatively easy to be synthesized with the means for the other objectives. This could largely reduce the searching time and improve the efficiency in a design computation system. Eventually, design is not to find *the* optimum solution, but *a* satisfactory one.

The task of precedent analysis is to identify the means to achieve a performance stated in a design objective. A system taking the precedent analysis task thus aims at providing means by which a design system can improve its efficiency and effectiveness.

6.1.2 The learning feature

Precedent analysis requires a system to be able to acquire new facts or rules from a number of given precedent example(s) and a predefined knowledge base. The facts or rules acquired may be entirely new in the sense that they are acquired inductively from the examples. Or they may not be called "new knowledge" because they are the result of a deductive process, which may be just a re-organization of some facts and rules in the knowledge base. In any case, the "knowledge" of the system will be changed after carrying out a precedent analysis task and such a change, as discussed earlier, can improve a design system's effectiveness and efficiency.

From this point of view, precedent analysis can be regarded as a typical learning process, and a system for precedent analysis a system of example-based learning. Simon (1983) has defined "learning" as "any change in a system that allows it to perform better the second time on repetition of the same task or on another task drawn from the same population."(p. 28)

6.2 A brief review of some paradigms of example-based learning

Before we further explore the features of precedent analysis, in this section, we review briefly some paradigms of example-based learning. Since detailed studies of these paradigms can be found in a lot of literature in Artificial Intelligence and machine learning, following description will focus only on those aspects relevant to this work.

The ability to learn is a fundamental characteristic of intelligent behaviour.[1] Consequently, machine learning has been a focus of Artificial Intelligence since the beginning of AI in the 1950's.

Today, machine learning research is carried out with a number of major paradigms and multiple sub-paradigms; among these, inductive learning and analytic learning are two major paradigms most widely studied (Carbonell, 1990). *Inductive learning* is one of inducing a general concept description from sets of positive and negative examples. Because this form of learning is mostly based on searching for features that are common to the training examples, it is also referred to as *similarity-based learning* or *similarity-based generalization* (Mitchell, Keller & Kedar-Cabelli, 1986; Lebowitz, 1985).[2] Similarity-based methods are not the only form of inductive learning (Shavlik & Dietterich, 1990), but it is most relevant to this work.

Analytic learning is a more recently studied method, which is based on learning from few exemplars (often a single one) plus a rich underlying

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[1] A simplest form of learning is directly implanting new knowledge into a system. It requires no inference or other transformation of the knowledge on the part of learner. It is thus called *rote learning* (Carbonell, Michalski & Mitchell, 1983). This type of learning is usually not within the consideration of machine learning.

[2] The term similarity-based generalization was suggested by Lebowitz (1985). Mitchell *et al*. (1986) use this term to cover both the methods that search for similarities among positive examples, and the methods that search for differences between positive and negative examples.

domain theory. The methods involved are *deductive* rather than *inductive*. One of the sub-paradigms of analytic learning is called *explanation-based learning*. In many practical situations, both similarity-based and explanation-based methods are actually used in performing a learning task. Therefore, some studies are focused on the development of combined methods of learning. As will be discussed, this combined method is in fact more adequate to performing the task of architectural precedent analysis.

6.2.1 Similarity-based learning

Similarity-based learning is one of the most widely studied method in AI. Until recently, "learning from examples" implied mainly this kind of learning. Similarity-based learning can be defined as following: given a set of examples and counter examples of a concept, the learner induces a general concept description that describes all of the positive description and none of the counter examples (Carbonell, 1983).

 According to the type of examples available to the learner, similarity-based learning can be classified as learning from only positive examples and learning from both positive and negative examples. When only positive examples are available, they provide instances of the concept to be acquired but do not provide information for preventing overgeneralization of the inferred concept. In this kind of learning situation, overgeneralization might be avoided by considering only the minimal generalizations necessary, or by relying upon a priori domain knowledge to constrain the concept to be inferred. When both positive and negative examples are available, positive examples force generalization whereas negative examples prevent overgeneralization. An early famous work taking similarity-based method was the structural description of toy blocks presented by Winston (1975).

 Later development of similarity-based learning has concentrated on analogical learning, or learning by analogy (e.g., Burstein, 1983; Carbonell,

1983; Gentner, 1983; Winston, 1982).[1] It involves mapping some underlying causal network of relations between analogous situations. Kedar-Cabelli (1985b) gives a four-stage unifying framework for concept learning by analogy, which is described below in Figure 6-1.

Given: ● a new, target concept, (e.g., the atom)
Find: ● a familiar, base concept, (e.g., the solar system)
         ● causal networks of relations of the base concept, and
         ● causal networks of relations of the target concept derived from
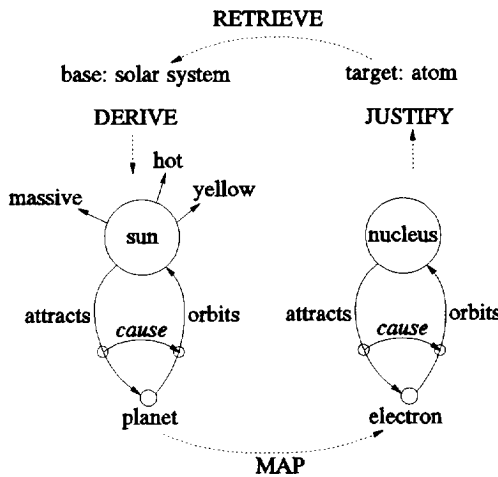   the base concept
Process:

Figure 6-1 A framework for concept learning by analogy. The example shows the analogy of "The hydrogen is like our solar system." (After Kedar-Cabelli, 1985b)

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[1] Analogical learning uses priori knowledge or theory that is primarily a library of precedents, but this knowledge or theory is "qualitatively different than the domain theory" used in the explanation-based learning (Mitchell *et al.*, 1990). Therefore, analogical learning is still regarded as a kind of similarity-based learning.

6.2.2 Explanation-based learning

In the recent years, some work developed the learning methods generally called explanation-based learning, which contrast sharply with similarity-based methods (e.g., Mitchell *et al.*, 1986; DeJong, 1986; Minton, 1984; Keller, 1983). Explanation-based learning (EBL) is to generalize from a single example by analyzing *why* that example is an instance of the concept.

Mitchell *et al.* (1986) describe a unified approach to EBL, dubbed explanation-based generalization (EBG), which clarifies many of the common aspects of EBL methods. The EBG method has in general two steps. The first step is to *explain*: to construct according to a set of domain theory an explanation structure that can prove why a given training example satisfies a given concept that is the target of learning. The second step is to *generalize*: to determine a set of conditions within the explanation structure that are sufficient for making the training example to be an instance of the target concept so that these conditions can be applied to other individual objects for an efficient judgement of their membership of the target concept.

They suggest a clearly specified pattern of input and output of EBL, as shown in Table 6-1. The input contains a goal concept (it is preferred to use the term target concept here), a theory for constructing explanations, an example, and an operationality criterion that defines what it means for a

Table 6-1 The explanation-based generalization problem (According to Mitchell *et al.*, 1986)

Given:
- *Goal Concept*: A concept definition describing the concept to be learned. (It is assumed that this concept definition fails to satisfy the Operationality Criterion.)
- *Training Example*: An example of the goal concept.
- *Domain Theory*: A set of rules and facts to be used in explaining how the training example is an example of the goal concept.
- *Operationality criterion*: A predicate over concept definitions, specifying the form in which the learned concept definition must be expressed.

Determine:
- A generalization of the training example that is a sufficient concept definition for the goal concept and that satisfies the operationality criterion.

Table 6-2 An example of EBG given by Mitchell *et al.* (1986)

Given:
- Goal Concept: Pairs of objects $<x, y>$ such that SAFE-TO-STACK (x, y), where
  SAFE-TO-STACK(x, y) means NOT (FRAGILE(y)) & LIGHTER (x, y).
- Training Example (expressed with a semantic net, see Figure 4-2a):
  ON (OBJ1, OBJ2), ISA (OBJ1, BOX), ISA (OBJ2, ENDTABLE),
  COLOR (OBJ2, RED), . . .
- Domain Theory:
  IF VOLUME (p_1, v_1) and DENSITY (p_1, d_1) THEN WEIGHT (p_1, v_1*d_1),
  IF WEIGHT (p_1, w_1) and WEIGHT (p_1, w_2) and LESS (w_1, w_2) THEN
  LIGHTER (p_1, p_2),
  IF ISA $(p_1,$ ENDTABLE) THEN WEIGHT $(p_1, 5)$ (default),
  LESS $(0.1, 5)$, . . .
- Operationality Criterion: The concept definition must be expressed in terms of the
  predicates used to describe examples(e.g., VOLUME, COLOR, DENSITY) or
  other selected, easily evaluated, predicates from the domain theory (e.g.,LESS).

Determine:
- A generalization of training example that is a sufficient definition for the goal
  concept and that satisfies the operationality criterion.

description to be useful. The target concept is the one to be explained; it denotes the sets of instances. An explanation is a proof that the instance is a valid example of the concept. After generalizing the explanation, EBG produces an operational description that constitutes sufficient conditions for recognizing the target concept.

As an example, Mitchell *et al.* consider the target concept *SAFE-TO-STACK(x,y)*, that is, the set of object pairs $<x,y>$ such that x can be safely stacked on y. The target concept definition, training instances, theory, and operationality criterion are given in Table 6-2 and Figure 6-2 (a).

The definition of *SAFE-TO-STACK* specifies that an object can be safely stacked on a second object if the second object is not fragile or the first object is lighter than the second. The domain theory encapsulates the system's knowledge about objects, weight, etc. The training example illustrates an instance of two objects, *OBJ1* and *OBJ2*, that can be safely stacked on top of each other. Finally, the operationality criterion specifies that the explanation must be in the form of easily evaluated predicates.

When EBG learns from this example, it proves that *OBJ1* is *SAFE-*

TO-STACK on *OBJ2* (Figure 6-2, b). The proof is then generalized by regressing the goal concept through the proof structure. The regression process replaces constants with variables while preserving the structure of the proof. The purpose of regression is to find the weakest conditions under which the proof structure will hold. In this manner EBG produces the following sufficient conditions for describing the concept *SAFE-TO-STACK*:

VOLUME(x, v_1) and

DENSITY(x, d_1) and

LESS(v_1*d_1, 5) and

ISA(y, ENDTABLE)

These conditions specify that *x* can be safely stacked on *y* if *y* is an endtable and the volume times the density of *x* is less than 5. This description satisfies the operationality criterion and is justified by the proof.
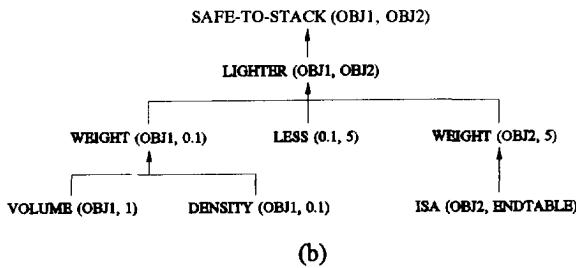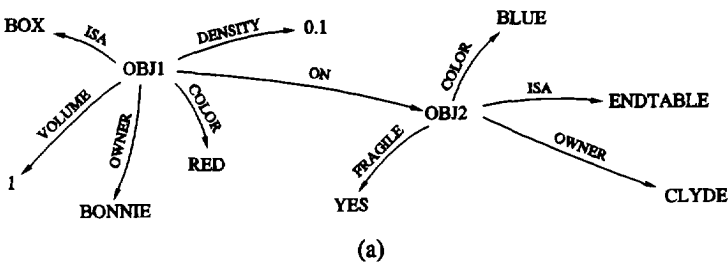

(a)

(b)

Figure 6-2 (a) The training example described with a semantic net. (b) The explanation structure (after Mitchell *et al.*, 1986)

6.2.3 Comparison between the two methods

The power of explanation-based learning arises from the use of a domain theory to derive the analysis process. Thus, while inductive learning is data-intensive, explanation-based learning is knowledge-intensive (Minton *et al.*, 1990).

Mitchell *et al.* (1986) emphasize that similarity-based methods have a fundamental difficulty, that is, their inability to justify the generalizations that they produce; whereas explanation-based methods can overcome this difficulty. In order to compare the two methods, they apply their EBG method to the same example that has been used by Winston *et al.* (1983) presenting an analogical program. Mitchell *et al.* indicate that although the analogical program does construct an explanation, and also uses this explanation to generalize from a single example, the system has no domain theory of the kind used in the EBG method. Instead, Winston's program constructs its explanation by drawing analogies between the training example and a library of precedent cases. This library of precedent can be seen as a kind of theory, but it is qualitatively different from the domain theory used in EBG: it is described by examples rather than by general rules and hence it is a weaker domain theory (if it can be called domain theory).

However, because it does not rely on a strong domain theory, the similarity-based, analogical method is more suitable in the situation where there is lack of a well-defined domain theory. Mitchell *et al.* recognize this advantage of analogical method and indicate the possibility of use it as a weak domain theory to guide generalization.

Kedar-Cabelli (1985b) compares similarity-based methods and explanation-based methods from another point. He indicates that the concept generalization requires picking out the relevant causal relations for the purpose of using the concept. The conventional analogical methods are not successful in doing this; while an explanation-based method can be useful here, because it can automatically generate the appropriate causal network based on the purpose of the analogy being performed.

In fact, the comparisons made by Mitchell *et al.* and Kedar-Cabelli

are leading to two new perspectives in machine learning research, each incorporates aspects of both similarity-based and explanation-based methods. Shavlik & Dietterich (1990) summarize these two views as: one is knowledge-guided inductive learning systems, another is knowledge-based systems whose knowledge is incomplete.

6.2.4 Researches combining the two methods

Combining similarity-based and explanation-based methods is becoming a new paradigm in machine learning (Lebowitz, 1985; Mitchell, 1986; Kedar-Cabelli, 1985a, 1985b). Mitchell *et al.* (1986) suggest that this kind of combined approach to generalization will probably be essential in domains where only imperfect theories are available.

Lebowitz (1985) develops a system called UNIMEM, which examines a database of the voting records of congresspersons, searching for empirical, similarity-based generalizations. The system then attempts to verify these empirical generalizations by explaining them in terms of a domain theory. This approach has the advantage that the similarity-based techniques can be used to generate a candidate set of possible generalization from a large number of potentially noisy training examples. Once such empirical generalizations are formulated, explanation-based methods can help prune and refine them by using other knowledge in the system.

While Lebowitz's method uses first similarity-based then explanation-based approach, an alternative method is to first apply explanation-based methods to each training example, then to combine the resulting generalized examples using a similarity-based generalization technique (Mitchell, 1984).

Kedar-Cabelli (1985a, 1985b) proposes yet another alternative method for combining similarity-based and explanation-based methods. This method, called *Purpose-Directed Analogy*, is primarily based on the four-stage unifying framework of the conventional analogical method (see Figure 6-1), but replacing the *derive* stage with an *explain* stage.

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The motivation for this modification stems from an observation that in the conventional analogical methods, such as those presented by Gentner (1983), Burstein (1983) and Winston (1982), are all limited in their ability to automatically generate the causal network relevant for the purpose of a particular analogy, since explicit knowledge of purpose is not supplied as an input in these methods. Purpose-Directed Analogy attempts to overcome this limitation by making a specialized notion of "purpose" an explicit input to the analogy. The *explain* stage thus uses this "purpose" to automatically generate the relevant causal network for learning concepts by analogy. Figure 6-3 below illustrates an example showing the stages of Kedar-Cabelli's method.

Given: • goal concept (e.g., HOT-CUP)
        • purpose of goal concept (e.g., enable an agent to drink hot liquids)
        • domain theory (e.g., "IF HAS-PART (x, handle) THEN GRASPABLE(x)")
        • a new, target example (e.g. styrofoam-cup1)

Find: • a familiar, base example (e.g., ceramic-mug1)
        • an exaplanation of how the base example is a member of the goal concept (e.g., how ceramic-mug1 is a HOT-CUP), and
        • an explanation of the target example is a member of the goal concept derived from the explanation of the base example (e.g., how styrofoam-cup1 is a HOT-CUP)
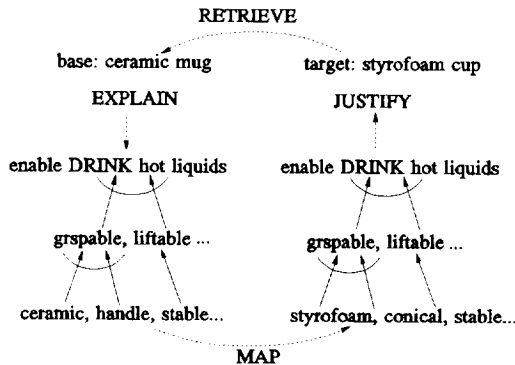
Process:

Figure 6-3 Purpose-Directed Analogy (After Kedar-Cabelli, 1985b)

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6.3 Further discussion on architectural precedent analysis

Having introduced the major ideas of example-based learning, we now return to architectural precedent analysis. Following is a comparison between the task of architectural precedent analysis and the tasks usually addressed by researchers of example-based learning.

6.3.1 Similarity to example-based learning

In Section 6.1, we discussed two important characters of precedent analysis, i.e., the general purpose of improving the efficiency and effectiveness of design system and the feature of learning from example(s). These characters justified us for comparing between precedent analysis and example-based learning. In addition to these, we can say that the task of precedent analysis described in Section 6.1 is also *structurally similar* to the task of example-based learning which requires the use of both similarity-based and explanation-based methods.

First, the input of precedent analysis contains a generally described performance, in the sense that it has a definition but the definition is difficult to be used directly by a design system. For example, if the "good sense of privacy" is an input performance, it can be accompanied by a general definition, such as "less-disturbance received by the people in a living unit," that indicates which aspects are relevant. But this general definition is not ready to be applied directly by a design system, because it still needs to be further specified. Such an input performance is equivalent to a target concept in example-based learning, such as the one SAFE-TO-STACK, which is defined in terms of the predicates FRAGILE and LIGHTER (see Table 6-2).

Second, the focus of precedent analysis is usually one or a few

precedents which are known for having the performance in concern. These examples are equivalent to the training example(s) in example-based learning. In explanation-based learning, the single example serves two functions: first, it guides the search for an operational definition thereby making the search more tractable; second, to the extent that the example is representative of the instances of the target concept, the example leads to recognize (Minton *et al.*, 1986, p. 71). In similarity-based learning, the multiple examples are used for comparison and to find empirical conclusions. We may find all these roles played by the precedent(s) in a precedent analysis process.

Third, the input of precedent analysis requires also an operationality criterion. "The operationality criterion imposes a requirement that learned concept definitions must be not only correct, but also in *a usable form* before learning is complete" (Mitchell *et al.*, 1986). Although it has been debated in the field of machine learning whether the operationality criterion should be addressed (DeJong & Mooney, 1986), it is clearly meaningful to assign an operationality criterion in architectural precedent analysis. The operationality criterion for a precedent analysis task depends on the design task and it points out what should be a "working morphological description."

Fourth, the searching or analyzing process in an architectural precedent analysis is also guided and constrained by a domain theory, as in the explanation-based and the combined learning methods, although the domain theory for precedent analysis is a kind of *incomplete theory* or can only be called *weak domain theory* (Mitchell *et al.*, 1986). The domain theory used in architectural precedent analysis consists mainly of the rules expressing the constraining relationships between morphology, operation and performance, which guides the search and explanation. In addition, there are also rules for the manipulation of spatial relations. These will be further specified later.

Finally, precedent analysis is inevitably involved in both deductive and inductive learning, corresponding respectively to explanation-based and similarity-based learning. This is due to the nature that architectural thinking

is fundamentally constrained and guided by the constraining relationships between performance, operation and morphology, but rules based on such relationships allow only "constructing plausible explanations summarizing likely links between features of the precedent example and the target performance" (Mitchell *et al.*, 1986). In other words, they may imply the relevant aspects for the construction of morphological description, but more reliable analysis often requires a supplementation from the comparison of several examples.

6.3.2 Some distinctive features

Being structurally similar to most tasks of example-based learning, precedent analysis has also a number of distinctive features that requires a system for precedent analysis be different at some aspects from those systems developed in the domain of machine learning. The differences are fundamentally due to the structure of architectural domain knowledge that involves in spatial representation.

Spatial representation bears the nature of equivocality and subjectivity. Thus, description of the morphology of a built environment can not be treated as straightforwardly as, say, the conceptualization of SAFE-TO-STACK, which can be defined unambiguously with the conditions such as VOLUME and DENSITY. This characteristic of domain knowledge requires a system for architectural precedent analysis to use some tools of representation different from that in the SAFE-TO-STACK problem. It determines some special features of the input, the output, the domain theory, the explanation and the generalization of a system for architectural precedent analysis.

First, description of precedent example(s) should accommodate symbolic reasoning because performance and operation rely on proposition-based representation; but meanwhile the input of precedent example(s) should avoid to be arbitrary and reductive. In other words, a symbolic description of example is necessary; but a direct input of an example

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described by semantic nets, as in the SAFE-TO-STACK problem (see Figure 6-2, a), is not appropriate in architectural precedent, because a building described by a semantic net is already too abstract and arbitrary to leave some leeway for further spatial conception.

To solve this problem, in this work, I use a kind of labelled imagery representation of building as the input of ARPRAN. This input can be analyzed and interpreted by a perceptual module[1] during the explanation guided by a domain theory. I shall call such input *labelled line drawing* (LLD) of architectural plan. LLD will be shown in the example studies presented in the next section and further explained in Chapter 7.

Second, the output, "a working morphological description that accounts for the performance," should also take a form that is not only describable by symbolic representation but also able to manifest the spatial relations. As mentioned in Section 6.1, ARPRAN's output should be a global organization showing the spatial relations between the locations and such descriptions can be used as a frame in the generation of a pre-parametric design. For this purpose, I use a kind of abstract architectural plan representation, called *labelled location net* (LLN). It will also be shown in the next section. A detailed theoretical account for the use of such a representation will be given in Chapter 7.

Third, because of the ill-definedness of design problems and the equivocality of spatial representation, the rules based on the constraining relationships between performance, operation and morphology can not be regarded as a strong theory which can be used to construct a *proof* for the generalization of a concept as in the explanation-based generalization (Mitchell *et al.*, 1986). Instead, these rules can provide only a plausible explanation or some heuristics for exploration (Rowe, 1987). We shall call them *heuristic rules*. Because of this, the knowledge-guided generalization could not be conducted solely through deductive learning, i.e., learning from one example; it needs also inductive learning, i.e., learning from

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[1] The term *perceptual module* follows Hiraki *et al.* (1991), but the perceptual module proposed by this thesis operates differently from the one proposed by Hiraki *et al.*

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several similar examples. In this sense, architectural precedent analysis is a kind of learning combining both the explanation-based and similarity-based methods.

Also because of the weakness of domain theory, architectural precedent analysis is mostly an open loop learning. Carbonell (1990) distinguishes *open loop learning* from *closed loop learning*: the former implies one-pass acquisition of new knowledge, regardless of afterward evidence questioning its correctness or utility; whereas the latter permits future evaluation of the new knowledge for modification or even elimination should it not improve system's effectiveness and efficiency as desired. Most of the tasks of architectural precedent analysis can be categorized as a kind of open loop learning.

Finally, in addition to the heuristic rules that guide explanation, there are also two kinds of rules used for the manipulation of the input precedent example(s). One kind of rules will be called *translation rules*, which are in charge of the categorization of locations in a built environment. Another kind of rules guide as well as constrain the transformation and abstraction of the input example, and will be called *transformation rules*. The introduction of these rules in architectural precedent analysis, as will be discussed, is virtually because of the particular nature of precedent analysis.

6.3.3 Conclusion

To summarize the discussion in this section, we can say that a system for architectural precedent analysis can be treated in principle as a machine learning system using both explanation-based and similarity-based methods. However, on the input, the output and the domain theory, architectural precedent analysis has its own distinctive features which are different from most of the problems usually studied in the domain of machine learning. These features will be exemplified in the next section with a general description of two problems of precedent analysis and will be studied in detail in the proceeding chapters that compose the third part of the work.

6.4 A sketchy structure of ARPRAN

This section illustrates a sketchy structure of ARPRAN through a brief description of two exemplar problems of precedent analysis that ARPRAN is expected to solve. The exemplar problems are extracted from the design of the "new courtyard house", and all the data used are based on the case study analysis and interpretation in Chapter 2.

The first problem is to learn the "good sense of privacy" from two examples of walk-up apartment. The second problem is to analyze "fitting the traditional urban fabric" according to examples of old houses and street pattern. After these example-studies, we shall discuss the general framework of ARPRAN.

The purpose of these example-studies is to specify the notion developed in this chapter: architectural precedent analysis can be regarded as a process of example-based learning, but it has some distinctive features. Thus, we focus in this section on the major elements needed for solving each exemplar problem, including the input, the output, the knowledge base and the general procedures. The theoretical considerations behind the representations and the detailed procedures are to be described in the third part of this work (i.e., Chapter 7 and 8).

6.4.1 Example 1: learning the "good sense of privacy"

In this example, the system takes as input the target performance "good sense of privacy," a general definition of it, two examples of the walk-up apartment, an operationality criterion (Table 6-3, Figure 6-4) and gives as output a specified definition of the "good sense of privacy". The domain theory includes a set of heuristic rules expressed as the constraining relations between morphology, operation and performance (Table 6-4), a set of translation rules and a set of transformation rules (see Figure 6-10 for some examples of the transformation rules).

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Table 6-3 The input, output and knowledge base of example 1: learning the "good sense of privacy."

Input:

- *Target performance* (and a general definition):
  GOOD-SENSE-OF-PRIVACY (of living unit U1):
  Less chances of disturbance received by P1 from Po [LESS-DISTURBANCE (Po, P1)].
  (P1 is the people staying or moving in the living unit U1. Po is the people *not* in U1. Po includes P2, P3, ... Pn and Pp. P2, P3, ... Pn are the people staying or moving in U2, U3, ... Un. Pp is the people staying or moving in the public area.)

- *Precedent examples*: Labelled line drawings of plan of two walk-up apartments (Figure 6-4, a, b)

- *Operationality criterion*: The output description must show the global spatial organization of the public and private spaces (a morphological description).

Output:

- *Specification of the target performance*: A description of a plausible morphology accounts for GOOD-SENSE-OF-PRIVACY, in the form of a labelled location net (LLN) (Figure 6-13).

Knowledge base:

- *Heuristic rules*: Constraining relations between performance, operation and morphology (Table 6-4).

- *Translation rules*: Rules for categorizing locations in a LLD (Figure 6-7).

- *Transformation rules*: Rules for transforming the labelled metric location nets (see examples in Figure 6-10).
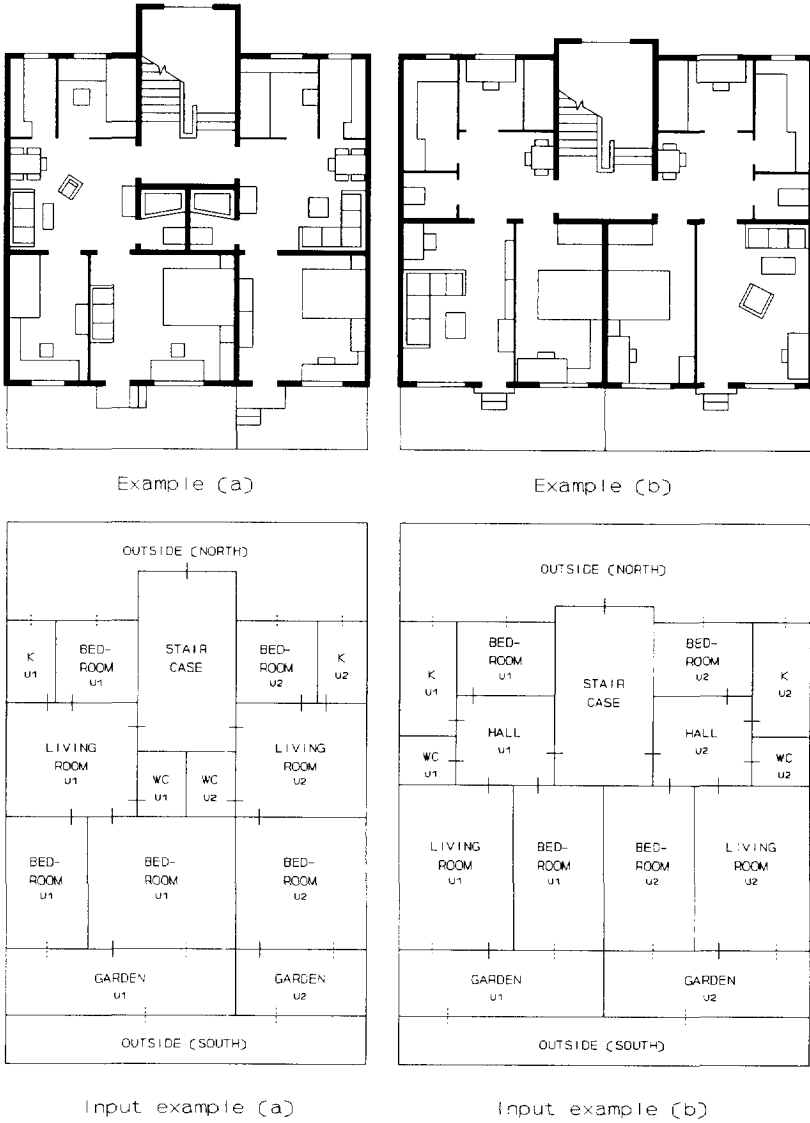
Figure 6-4 The two examples of walk-up apartment and their
descriptions in the form of the labelled line drawing of plan (LLD).

A number of issues need to be explained. First, the general definition of the target performance is already a sort of specification, but this specification fails the operationality criteria because it is still not a specification in the form of morphological description. The general definition "less-disturbance" is a performance at a lower level than the "good sense of privacy".

An important assumption adopted here is that the system does not "understand" at all the term "good sense of privacy" unless it is given some clues for starting a search. The general definition of the target performance is such a clue. It is assumed that, with this clue, the system can start the search towards the specification of the target performance. Here rises a question: How specific should this general definition be? This is obviously related to the content of the domain theory: if the rules about the performance in the domain theory are more general, then the input definition of the target performance can be less specific; and if the domain theory is less general, then the input is more specific. In the present example, we choose "less-disturbance" as a general definition because we assume that the system possesses the rules for specifying it.

Second, in both this example study and the next one, the input precedent examples are given in the form of a labelled line drawing of plan (LLD). This is based on an assumption that the input at the abstraction level of such labelled line drawing of plan is appropriate for the current learning task and its theoretical investigation. In Mitchell *et al.*'s (1986) SAFE-TO-STACK problem, the input example is described with a semantic network. Such an input is considered as too abstract to leave some leeway for further manipulation.

In Winston's (1975) structural description of toy blocks, the input is a visual scene; it is recognized by the machine and then represented with the semantic networks. Such an input form is more adequate to the current problem, but a building is much more complex than a group of toy blocks. For the simplicity of the current research, we have to make some reduction in the input description. We thus choose the labelled line drawing of plan. More important, in a precedent analysis task like the one presented here, the

architectural information is useful only if it shows how the spaces are used. Chapter 7 discusses more about the use of labelled line drawing of plan as input of ARPRAN.

Third, the operationality criterion in both example studies, is related to a pre-parametric level of description. In the current problems, the pre-parametric level of description is about the relationships between the major locations in a house such as living units, staircases, corridors and court-yards. The principles of selecting these locations have been discussed in Chapter 4, and some further discussion will be given in Chapter 7.

Fourth, in the classic machine learning methods introduced previous-ly, the domain knowledge is categorized as an item of input, but here it is listed independently. Indeed, there is no fundamental difference between calling the domain knowledge as input and categorizing it as an independent item. We distinguish the domain theory from the other items of input, because we emphasize that the present method is a knowledge-based method and the result of the learning is largely constrained by the content of the knowledge base.

The learning process contains three major steps, which can be described as following (Figure 6-5).
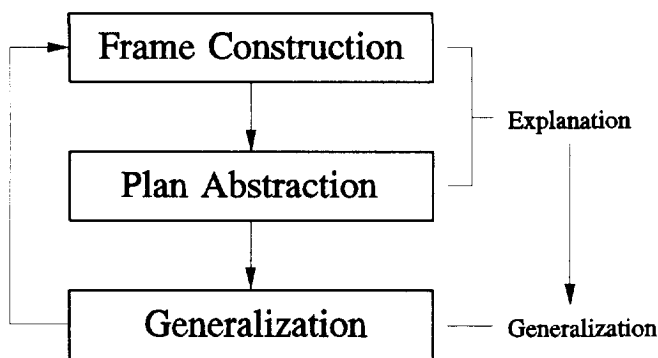

Figure 6-5 The major steps of learning GOOD-SENSE-OF-PRIVACY

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Table 6-4 Some examples of the heuristic rules for learning the "good sense of privacy."

Performance-specification:

- IF   PHYSICAL-DISTURBANCE (Po, P1) and/or
  VISUAL-DISTURBANCE (Po, P1)   and/or
  AUDITORY-DISTURBANCE (Po, P1)
  THEN   DISTURBANCE (Po, P1)

Operation-performance relation:

- IF   When P1 move-in U1 and P2 move-in U2,
  P1 not-meet P2
  THEN   NO-PHYSICAL-DISTURBANCE (P2, P1)

- IF   When P1 stay-at ENTRANCE-OF-U1 and Po move-in CORRIDOR,
  P1 meet Po
  THEN   PHYSICAL-DISTURBANCE (Po, P1)

- IF   When P1 stay-in U1 and Po move-in CORRIDOR,
  Po see P1
  THEN   VISUAL-DISTURBANCE (Po, P1)

- IF   When P1 stay-in U1 and P2 stay-in U2,
  P2 see P1
  THEN   VISUAL-DISTURBANCE (P2, P1)

Morphology-operation relation:

- IF   Separated living units
  THEN   When P1 move-in U1 and P2 move-in U2,
  P1 not-meet P2

- IF   Short public corridor
  THEN   When P1 stay-at ENTRANCE-OF-U1 and Po move-in CORRIDOR,
  P1 has-less-chance-to-meet Po

- IF   No visually accessible windows from two adjacent living units
  THEN   When P1 stay-in U1 and P2 stay-in U2,
  P2 see P1

Frame Construction

The first step is to construct an explanation structure pointing out which morphological aspects are relevant to the performance GOOD-SENSE-OF-PRIVACY (Figure 6-6). The construction is based on the given general definition of the performance and the heuristic rules connecting perform-ance, operation and morphology (Table 6-4). In Chapter 8, we shall discuss that, together with the operationality criterion, this explanation structure forms a frame (Minsky, 1975) for further manipulation of the plan.

GOOD-SENSE-OF-PRIVACY (U1)

Less disturbance (Po, P1)   Probably caused by

Less physical   Less visual   Less auditory
disturbance   disturbance   disturbance
(Po, P1)   (Po, P1)   (Po, P1)

When   When   When   When
P1 move-in U1   P1 move-in U1   P1 move-in U1   P1 move-in U1
P2 move-in U2   P2 move-in U2   P2 move-in U2   P2 move-in U2
P1 not-meet P2   P1 not-meet P2   P1 not-meet P2   P1 not-meet P2

Seperated   Short   No visually accessible   Sound insulating
living units   corridor   windows from two adjacent   walls and windows
                                         living units

Figure 6-6 The explanation structure for GOOD-SENSE-OF-PRIVACY

Plan Abstraction

The second step is to abstract each of the labelled line drawing of plan of the input example. The abstraction is directed by the frame, as well as the translation rules and the transformation rules. The procedure of the abstrac-tion of the walk-up apartment example (a) is briefly described as following.

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(1) The labels of the rooms are translated into a set of more abstracted labels (Figure 6-7). The translation is guided by the frame that tells which aspects are relevant.

(2) The plan is divided into a griding pattern by extending the lines of the walls (Figure 6-8). Each grid keeps the labels of the place where it belongs to.

(3) The labelled griding pattern is rewritten as a labelled location net (Figure 6-9).

(4) The labelled location net is transformed by merging the adjacent columns and rows. The merger is constrained by the transformation rules that regulate which two columns or rows can be merged and what is the result of the merger (Figure 6-10). (More detailed description of using the rules and the underlying theories will be given in Chapter 8.)

Through similar procedures, the walk-up apartment example (b) (see Figure 6-4) can also be abstracted into a LLN (Figure 6-11b).

LET :

OUTSIDE (NORTH) = B
OUTSIDE (SOUTH) = B
STAIRCASE = SB
K (U1) = V1
BEDROOM (U1) = V1

LIVING ROOM (U1) = V1
GARDEN (U1) = SV1
K (U2) = V2
BEDROOM (U2) = V2
LIVING ROOM (U2) = V2
GARDEN (U2) = SV2

WHERE :

B = PUBLIC LOCATION
SB = SEMI-PUBLIC LOCATION
SV = SEMI-PRIVAT LOCATION
V = PRIVAT LOCATION
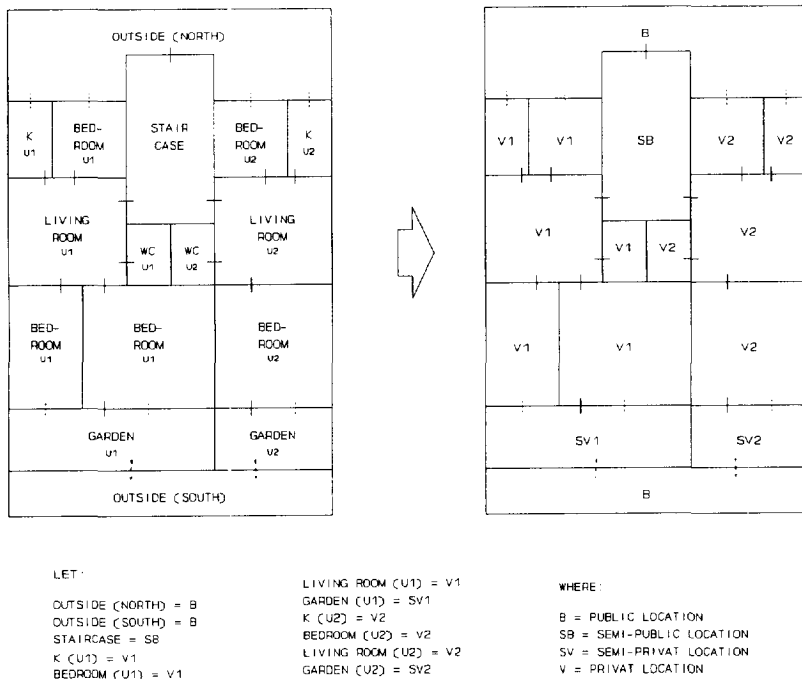
Figure 6-7 Translating the labels of the labelled line drawing of plan of example (a) in Figure 6-4 into a set of more abstracted labels

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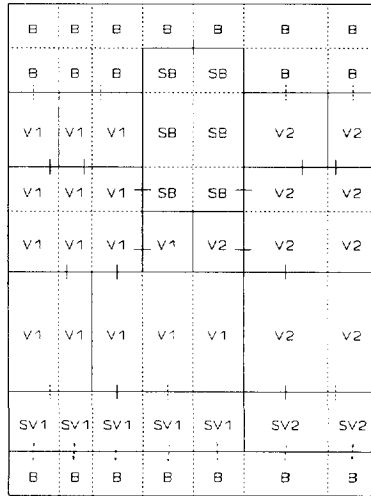
Figure 6-8 Dividing the plan into a grid pattern according to the position of the walls. Each grid keeps the labels of the location.
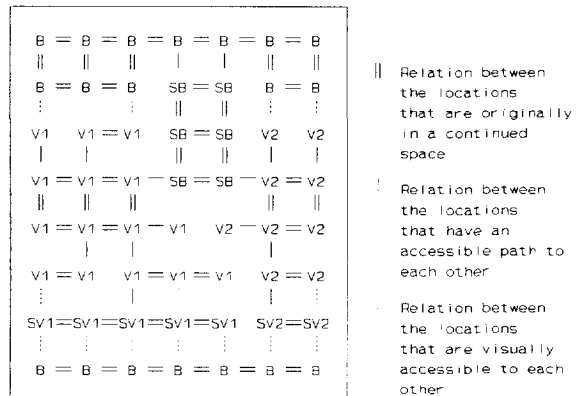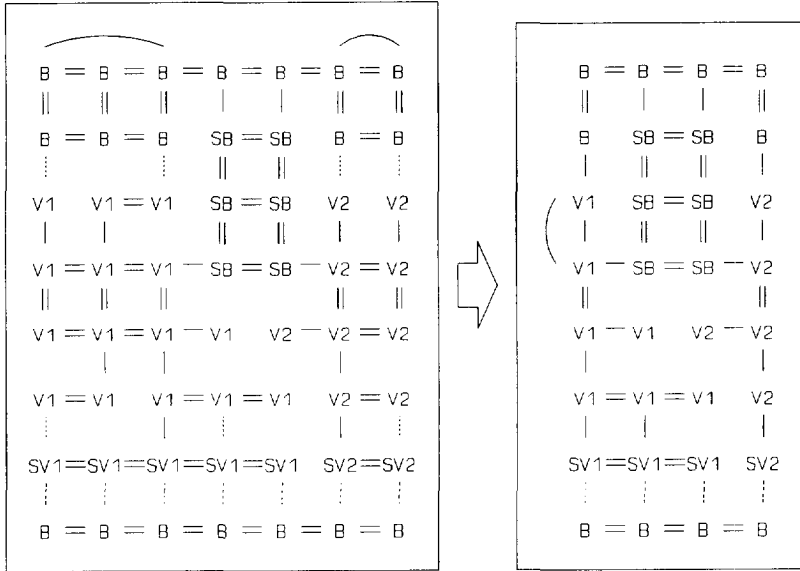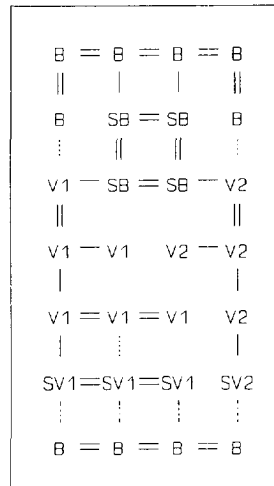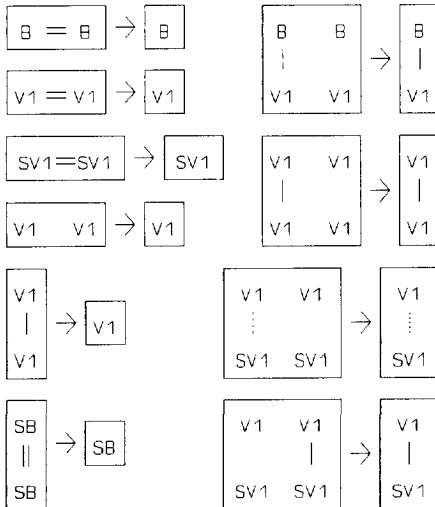

Figure 6-9 The grid pattern is rewritten as a labelled location net

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Figure 6-10 Merging the columns and the rows according to the transformation rules.

```
      B  =  B  =  B  =  B
      ||    |    |    ||
      B    SB  = SB    B
       :    ||   ||    :
      V1 — SB  = SB —  V2
      ||               ||
      V1 — V1    V2 —  V2
       |                |
      V1 = V1 = V1     V2
       |                |
      SV1=SV1=SV1      SV2
       :    :    :      :
      B  =  B  =  B  =  B
```
Example (a)

```
      B  =  B  =  B  =  B
      ||    |    |    ||
      B    SB  = SB    B
      |     ||   ||    |
      V1 — SB  = SB —  V2
      ||               ||
      V1 = V1    V2 =  V2
      |     :     |    :
      SV1=SV1   SV2=SV2
      :     :     :    :
      B  =  B  =  B  =  B
```
Example (b)
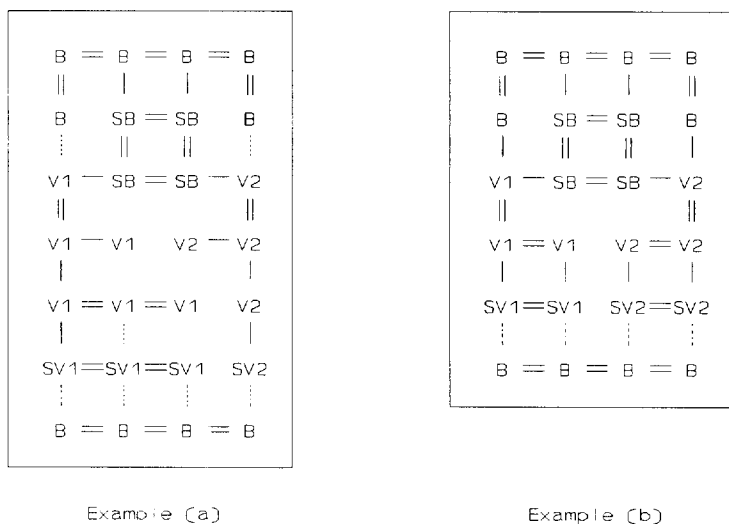
Figure 6-11 The labelled metric location nets of the two examples resulted from plan abstraction

Generalization

The third major step is to find similarities among examples and then to produce a generalized labelled location net as the output. In this stage, the labelled location nets are further simplified so as to produce a description that covers both of the examples. This stage involves trying a number of alternative transformations. Figure 6-12 shows two of the alternatives. After simplification, the system produces a description connecting the performance to the morphology as a result of the learning process (Figure 6-13).

In case that the system can not find any similarities between the examples, it will return to the first major step, to construct another frame and to choose another set of transformation rules. These will be discussed further in the following chapters.
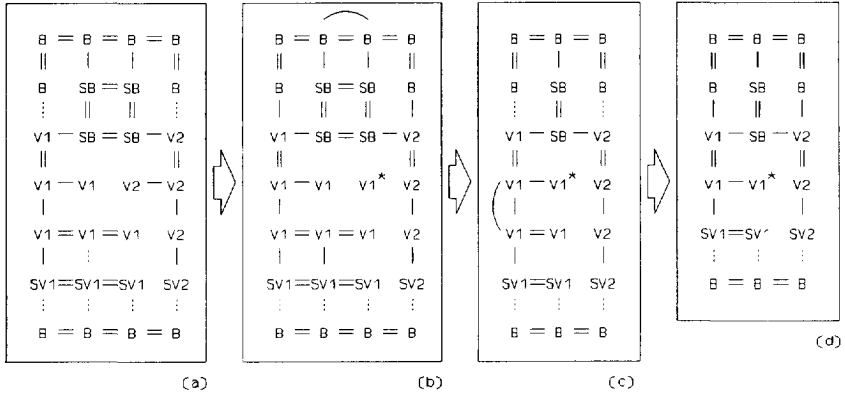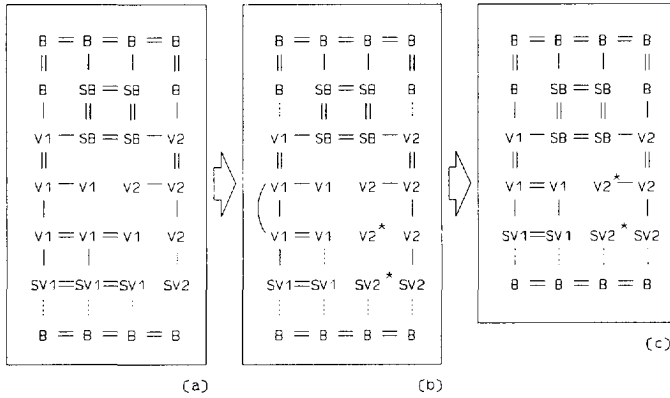
Figure 6-12 Examples of the further transformations at the generation stage.
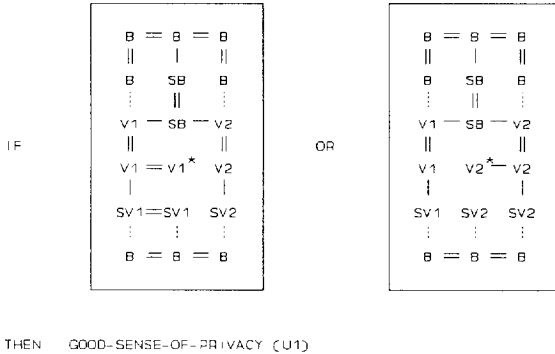
Figure 6-13 The result of learning GOOD-SENSE-OF-PRIVACY

6.4.2 Example 2: learning "fitting the traditional urban fabric"

In this example, the system takes as input the target performance of "fitting the traditional urban fabric," its general definition, an operationality criterion and a set of precedent examples, including: three ordinary courtyard houses in Beijing, a piece of street-lane area in Beijing, and two southern large mansions (Table 6-6, Figure 6-14 ~ 19).

As in the last example, the learning process in this example includes also three major procedures, i.e., "frame construction," "plan abstraction" and "generalization." Yet, there are also some variations in this example. The major variation is: instead of producing only two "equivalent" morphological descriptions as in the last example, the system outputs two groups of "graded" descriptions, each of them contain the descriptions about two aspects of the precedents (Table 6-5). This is explained as following.

First, the input precedents in this example are classified according to their degree of satisfying the target performance. This is different from that in the last example, in which the two precedent walk-up apartments are regarded as "equivalent" with respect to the target performance "good sense of privacy." (Of course, the walk-up apartments may also be classified. As

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a research example, we simplified the problem.)

In this example, the ordinary courtyard houses in Beijing are categorized as a type of precedent that is "more fitting" the traditional urban fabric than the type of southern large mansions, although both types are considered acceptable in terms of "fitting." In other words, the system is supplied with two groups of precedents, hence would correspondingly output two groups of morphological descriptions. Because the input examples are classified in terms of "fitting," the two groups of output descriptions are also graded with respect to "fitting."

Consequently, the design system which uses these outputs would be, in turn, supplied with two groups of descriptions; and it would be recommended to use at first the group of descriptions drawn from the three ordinary courtyard houses in Beijing; and if the descriptions can not satisfy the other requirements of design, then the design system could turn to another group of descriptions, i.e., the ones drawn from those of the southern large mansions. Such a mechanism of precedent analysis is coherent with our observation on the design case, in which the designer

Table 6-5 Four sets of descriptions result from two groups of precedent and two ways of transformation

	Three ordinary courtyard houses in Beijing	Two Southern large mansions
Transformation using "indoor-outdoor" categories	Description corresponding to the "building-courtyard pattern" (finally used by the designer of the "new courtyard house")	Description showing another pattern of building and courtyard pattern (not used by the designer)
Transformation using "circulation-utility" categories	Description showing one pattern of circulation (not used by the designer)	Description corresponding to the "fishbone circulation pattern" (finally used by the designer)

analyzed both types of the houses but obviously the ordinary courtyard houses were considered firstly and the southern large mansions were considered secondly.

Second, different from the last example in which all the plans are manipulated in the same manner, the frame constructed in this example suggests two directions in which the plans are manipulated. In the last example, according to the explanation structure, the labels of the spaces are translated into a set of more abstracted labels that categorizes the spaces as "Private" (V), "Semi-private"(SV), "Semi-public"(SB) and "Public"(B) locations.

In this example, however, the explanation structure suggests two ways to categorize the labels. One way is to categorize the spaces into "Indoor"(I), "Outdoor"(O) and "Semi-outdoor"(S) locations; another way is to use the categories of "Circulation"(C), "Utility"(U), and "Mixed"(M) locations. Both ways are applied to the two groups of precedents. This has lead to the formation and consequently the abstraction and generalization of four sets of morphological descriptions in this example.

Again, such an ability of the system is derived from the analysis of the method used in our case study: it is obvious that the "building-courtyard pattern" and the "fishbone circulation pattern" are the results of using two different sets of categories in spatial conception. This will be further explained in Chapter 8.

For the sake of simplicity, we present here only the final results and some instances of one set of transformation, that is, using "Indoor-Outdoor" categories to manipulate the ordinary courtyard houses in Beijing.

In addition to multi-descriptions in the result, a variation in this example is that the "generalization" step consists of two distinguished sub-steps. The first sub-step is to further simplify each LLN by merging S (or M) locations with I or O (or C or U) locations. The second sub-step is to find the common compositions of all the simplified LLNs that consist of only I and O (or C and U) locations. The aim of generalization in this example is same to that in the last example, i.e., to produce a description that covers all of the precedents in concern. The mechanism of generalization will also be explained in Chapter 8.

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Table 6-6 The input, output and domain theory of example 2: learning "fitting the traditional urban fabric."

Input:

- *Target performance* (and general definition):
    FITTING-THE-TRADITIONAL-URBAN-FABRIC:
        CONTINUITY (NEW, OLD);
    (The traditional urban fabric: old courtyard houses and street system)

- *Precedent examples*: The LLDs of three ordinary courtyard houses in Beijing, an area of old residential sector in Beijing, and two Southern large mansions (Figure 6-16 ~ 19).

- *Operationality criterion*: The output specification must be end at the morphological descriptions concerning the organisations of the living units.

Output:

- *A specified definition of the target performance*: The LLN descriptions of morphology that enable a new design "fitting the traditional urban fabric."

Knowledge base:

- *Heuristic rules*: Constraining relations between performance, operation and morphology that concerns how the spaces can be perceived having continuity either physically or visually.

- *Translation rules*: Rules for categorizing locations in a LLD.

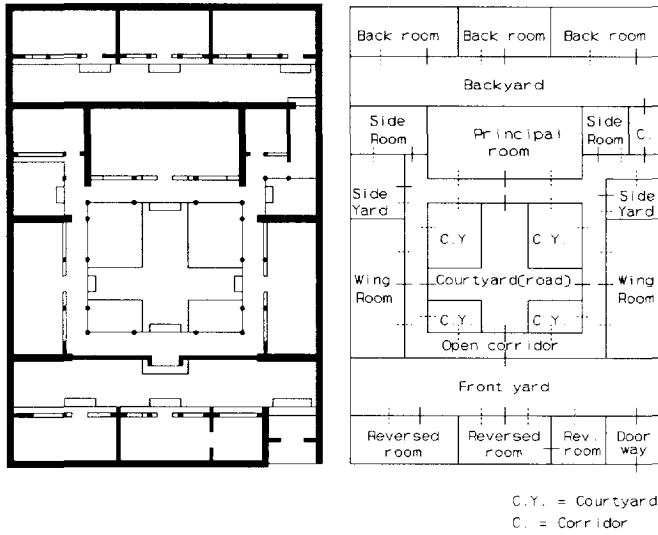- *Transformation rules*: Rules for transforming the labelled location nets.

C.Y. = Courtyard
C. = Corridor

Figure 6-14 Example (a) of the old courtyard house and its labelled line drawing of plan
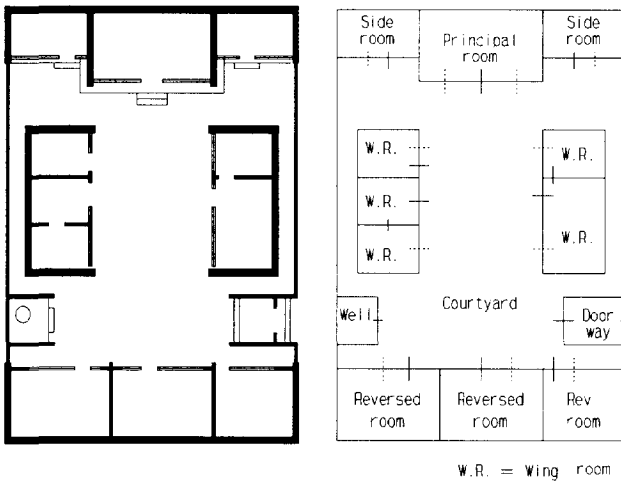

W.R. = Wing room

Figure 6-15 Example (b) of the old courtyard house and its labelled line drawing of plan

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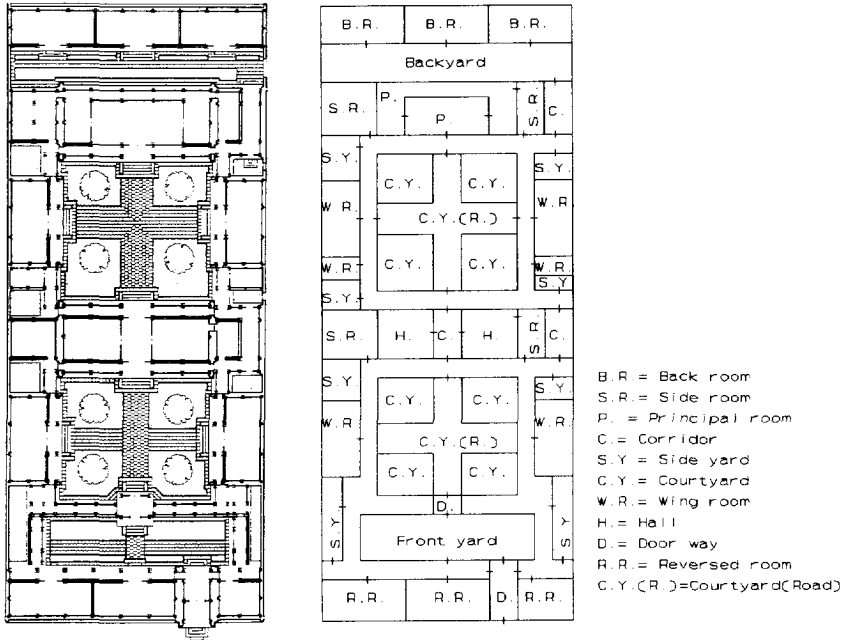**Figure 6-16** Example (c) of the old courtyard house and its labelled line drawing of plan (labels for visual access are omitted)
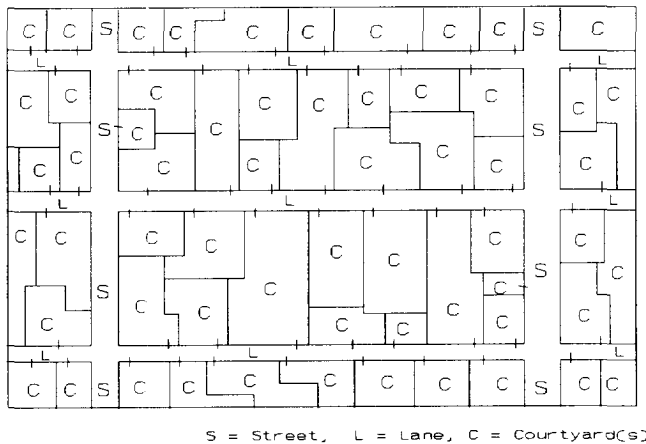

S = Street, L = Lane, C = Courtyard(s)

Figure 6-17 A typical street-lane area in Beijing's old city
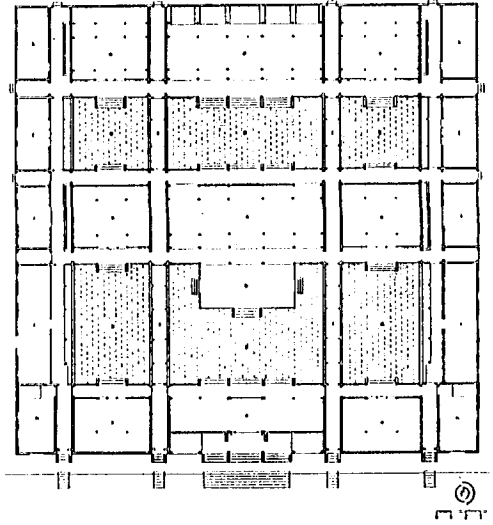
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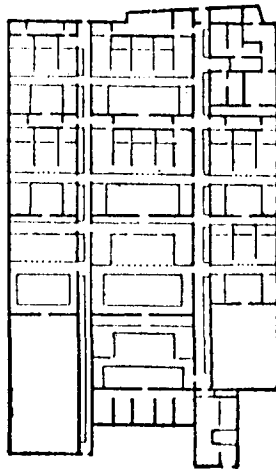**Figure 6-18** The first example of Southern large mansion

Figure 6-19 The second example of Southern large mansion

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Table 6-7 The heuristic rules used for learning "fitting the traditional urban fabric"

Operation-performance relation:

- IF   When people staying in/around the new building, people perceive similarity between the new building and the old courtyard houses
  THEN   Continuity (New, Old)

- IF   When people move from old street into the new building, people perceive continuity between the new building and the old street
  THEN   Continuity (New, Old)

Morphology-operation relation:

- IF   There is the building-space pattern of the old courtyard house
  THEN   When people staying in/around the new building, people perceive similarity between the new building and the old courtyard houses

- IF   There is the circulation pattern of the old house and the old street system
  THEN   When people move from old street into the new building, people perceive continuity between the new building and the old street
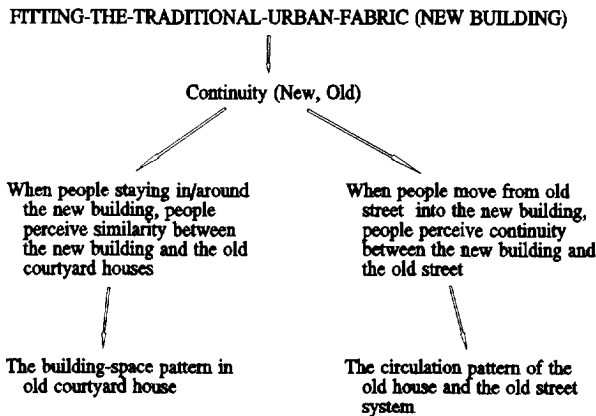
FITTING-THE-TRADITIONAL-URBAN-FABRIC (NEW BUILDING)

Continuity (New, Old)

When people staying in/around the new building, people perceive similarity between the new building and the old courtyard houses

When people move from old street into the new building, people perceive continuity between the new building and the old street

The building-space pattern in old courtyard house

The circulation pattern of the old house and the old street system

Figure 6-20 The explanation structure for "fitting the traditional urban fabric"

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| Back room | Back room | Back room |
| Backyard |
Side Room	Principal room	Side Room	C.
Side Yard	C.Y.	C.Y	Side Yard
Wing Room	Courtyard(road)	Wing Room
C.Y.	C.Y.
Open corridor
Front yard
Reversed room	Reversed room	Rev room	Door way	(a)

C.Y. = Courtyard
C. = Corridor

LET:

Backroom = I
Principal room = I
Wing room = I
Side room = I
Reversed room = I

Backyard = O
Courtyard = O
Side yard = O
Front yard = O

Open corridor = S
Corridor = S
Door way = S

WHERE:

I = Indoor space
O = Outdoor space
S = Simi-outdoor space
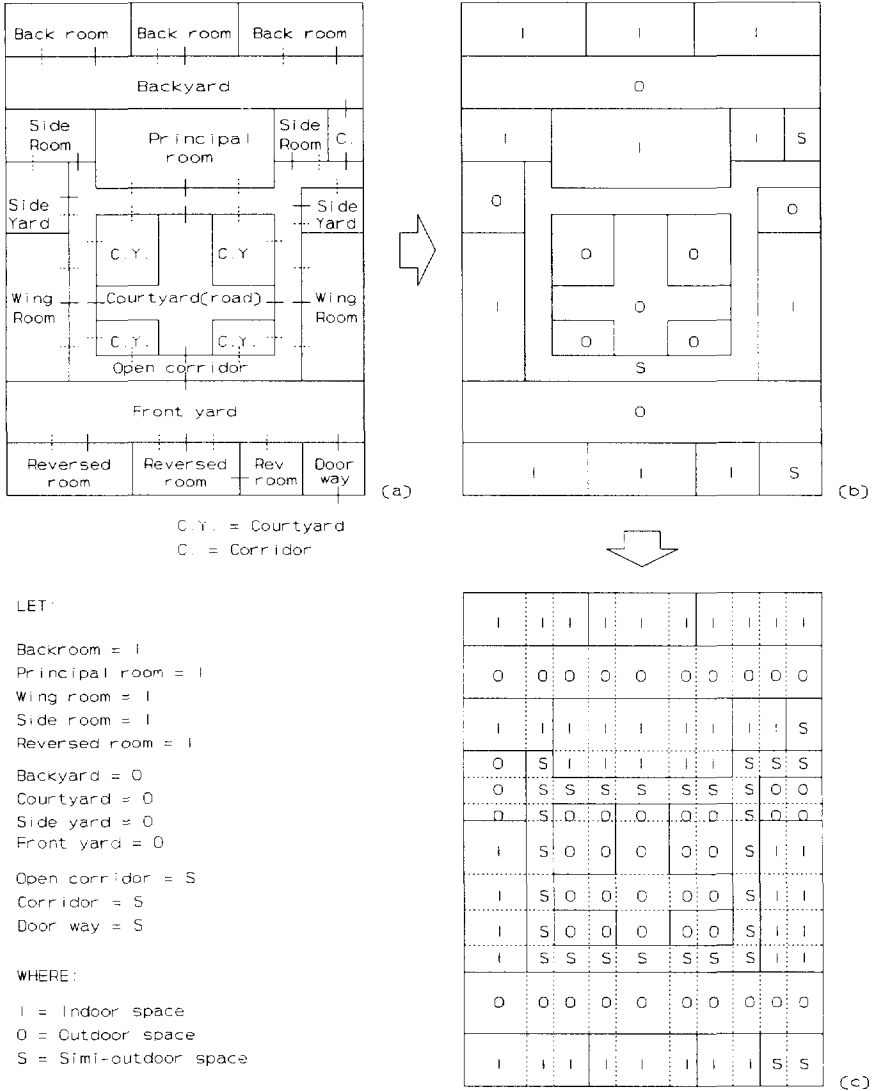
Figure 6-21 (a)-(b): Translating the labels of example (a) in Figure 6-14 into a set of more abstracted labels
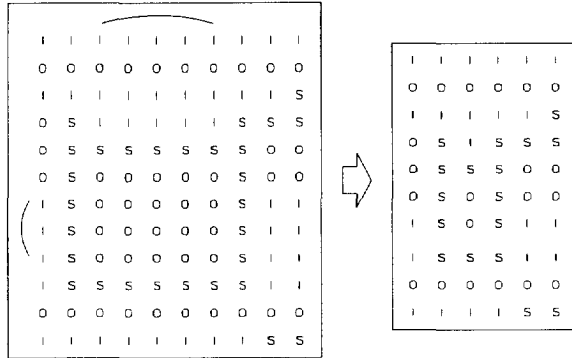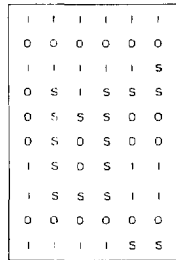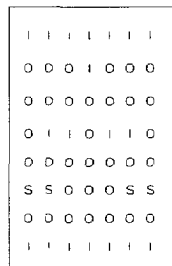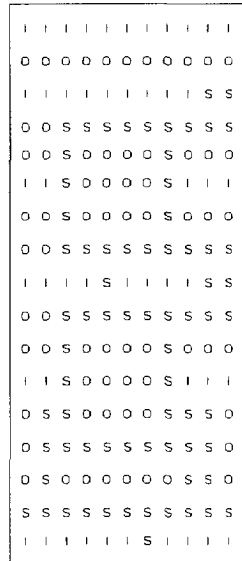(b)-(c): Dividing the plan into a grid pattern

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Figure 6-22 Rewriting Figure 4-21(c) as a matrix and then merging its columns and rows which have exactly the same elements

Example (a)

Example (b)

Example (c)

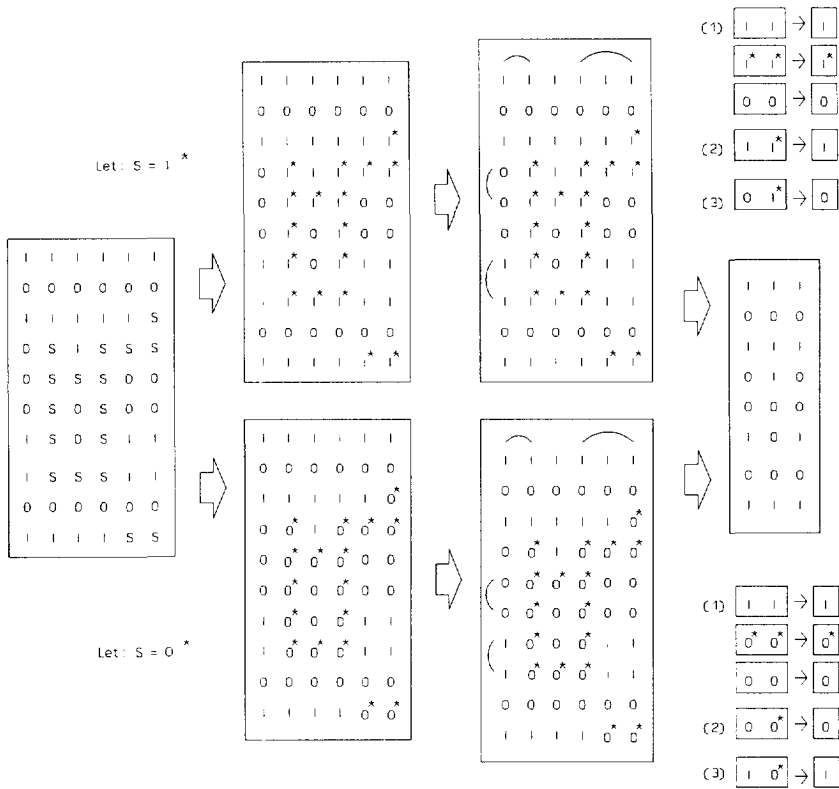**Figure 6-23** Result of plan abstraction of the three examples of the old courtyard house

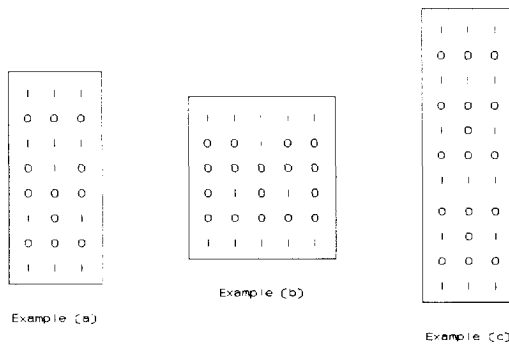**Figure 6-24** Further transformation of example (a) at the first step of generalization stage

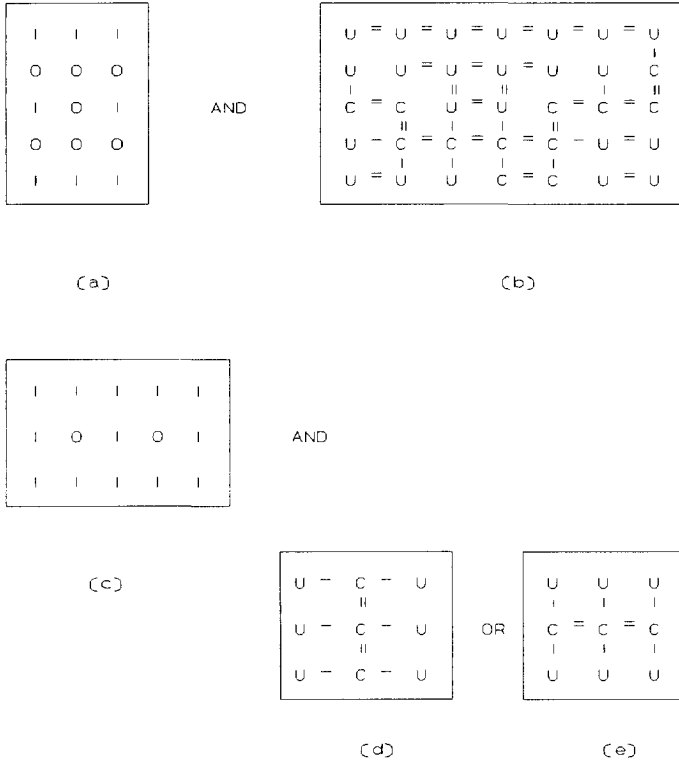**Figure 6-25** Results of the first step of generalization

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Figure 6-26 The results of learning "fitting the traditional urban fabric": two groups of descriptions each containing two aspects of morphology.
(a) and (b) are two aspects derived from the examples of Beijing's ordinary courtyard houses; (c) and (d) (or (e)) are two aspects derived from the Southern large mansions and the typical street-lane area in Beijing's old city. Among these descriptions, (a), (d) and (e) are the ones eventually applied by the designer of the "new courtyard house"

6.4.3 A framework of ARPRAN

The two example-studies have shown the major principles with which an architectural precedent analysis system would work. Based on those principles, a preliminary framework of ARPRAN can be sketched out as following (Figure 6-27).

First, the central part of ARPRAN is a perceptual module that contains at least three sub-modules which are responsible for the three major procedures of precedent analysis, i.e., frame construction, plan abstraction and generalization. As shown before, the process of analysis is carried out
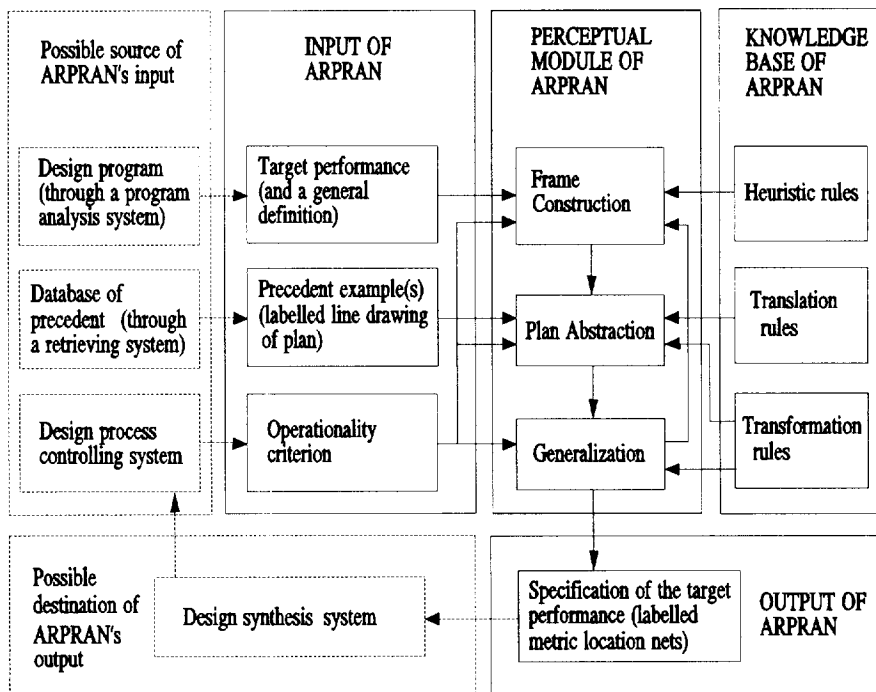

Figure 6-27 A preliminary framework of ARPRAN and the datastream

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generally from "frame construction" to "generalization" and, if necessary, it will start again from the beginning.

Second, the perceptual module is connected with a knowledge base which contains mainly three kinds of rules, i.e., the heuristic rules, the translation rules and the transformation rules. These rules are stored in groups and can be selected, replaced or modified according to the tasks of precedent analysis and the frames constructed at the beginning of analysis.

Third, the perceptual module must receive at least three kinds of information, i.e., target performance, precedent example(s) and operationality criterion, as its input. These input information can be supplied by other systems. For instance, the target performance usually comes from a design program, which can be processed by a program analysis system; the precedent examples can be stored in a database and be retrieved on request; the operationality criterion can be given by a controlling system of design process.

Finally, ARPRAN needs to exchange information frequently with a design synthesis system. On the one hand, ARPRAN's learning result is directly exported to the design synthesis system. On the other hand, ARPRAN receives also feedback from the design system through the controlling system.

It is noticeable that in the datastream of ARPRAN, there are at least two possible feedbacks, which connect ARPRAN closely to the design system it serves. Such connection contributes to a major characteristic of the approach developed in this work. As mentioned before, a fundamental distinction between ARPRAN and some other systems of using precedent lies at that ARPRAN adopts a reasoning approach to the use of precedent whereas the others mostly use a retrieving approach.

In illustrating the sketchy structure of ARPRAN, several issues must be emphasized. First, the framework described above is not the framework of a complete design system. It covers only the major constituents of ARPRAN and some components that are supposedly related with ARPRAN.

Second, the framework described above is a sketchy structure and

it will be remained as a sketch in this work. In other words, the framework presented above is still far from an algorithm and implementation scheme, whereas the algorithm and implementation are beyond the limits of this work.

Third, many important but unessential procedures of ARPRAN are not illustrated here. For example, how the plans and labels of precedent can be encoded and recognized by the perceptual module is an important computational problem, but it is not considered as so essential in respect to ARPRAN's learning task focused by this work.

Finally, in illustrating the framework of ARPRAN, we discussed very less about the efficiency of information flow. This is because the work is focused on the computational theory of a system, which concerns more about the effectiveness and efficiency in the general strategy of problem solving and representation and less about the efficiency of algorithm and implementation. In the present framework, for example, applying precedent knowledge in a reasoning manner in design can be regarded as a general approach to design computation which is both effective and efficient if it is compared with many other strategies. It is believed that once a good computational theory is developed, the efficiency of its implementation is a less difficult problem.

6.5 Summary

An important assumption adopted in this work is that architectural precedent analysis is primarily a learning process. This assumption leads to a perspective with which the computation of precedent analysis is treated as example-based learning.

This chapter first described the general task of precedent analysis from an information processing point of view, indicating that the input of precedent analysis should be a performance and a number of precedent examples and the output, a "working morphological description that accounts for the performance." Then, the chapter reviewed some major para-

digms of example-based learning, including similarity-based method, explanation-based method and the method combining the two.

Consequently, the chapter made a comparison between architectural precedent analysis and example-based learning, and pointed out that (1) precedent analysis is structurally similar to example-based learning that uses both similarity-based and explanation-based methods, and (2) precedent analysis has some distinctive features requiring a system for precedent analysis to use different tools of representation.

The comparative discussion was then exemplified by two exemplar problems of architectural precedent analysis to be solved by ARPRAN. Finally, based on the machine learning assumption and the two example studies, the chapter illustrated a sketchy structure of ARPRAN. In the following chapters, precedent analysis will be treated as a problem of representation. We shall discuss in some detail, and by applying cognitive theories, the representation system proposed for ARPRAN.
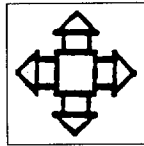
Part III

The Representation of Domain Knowledge
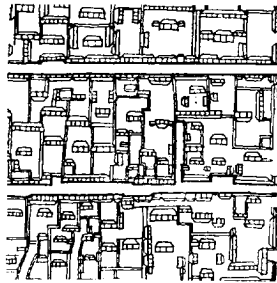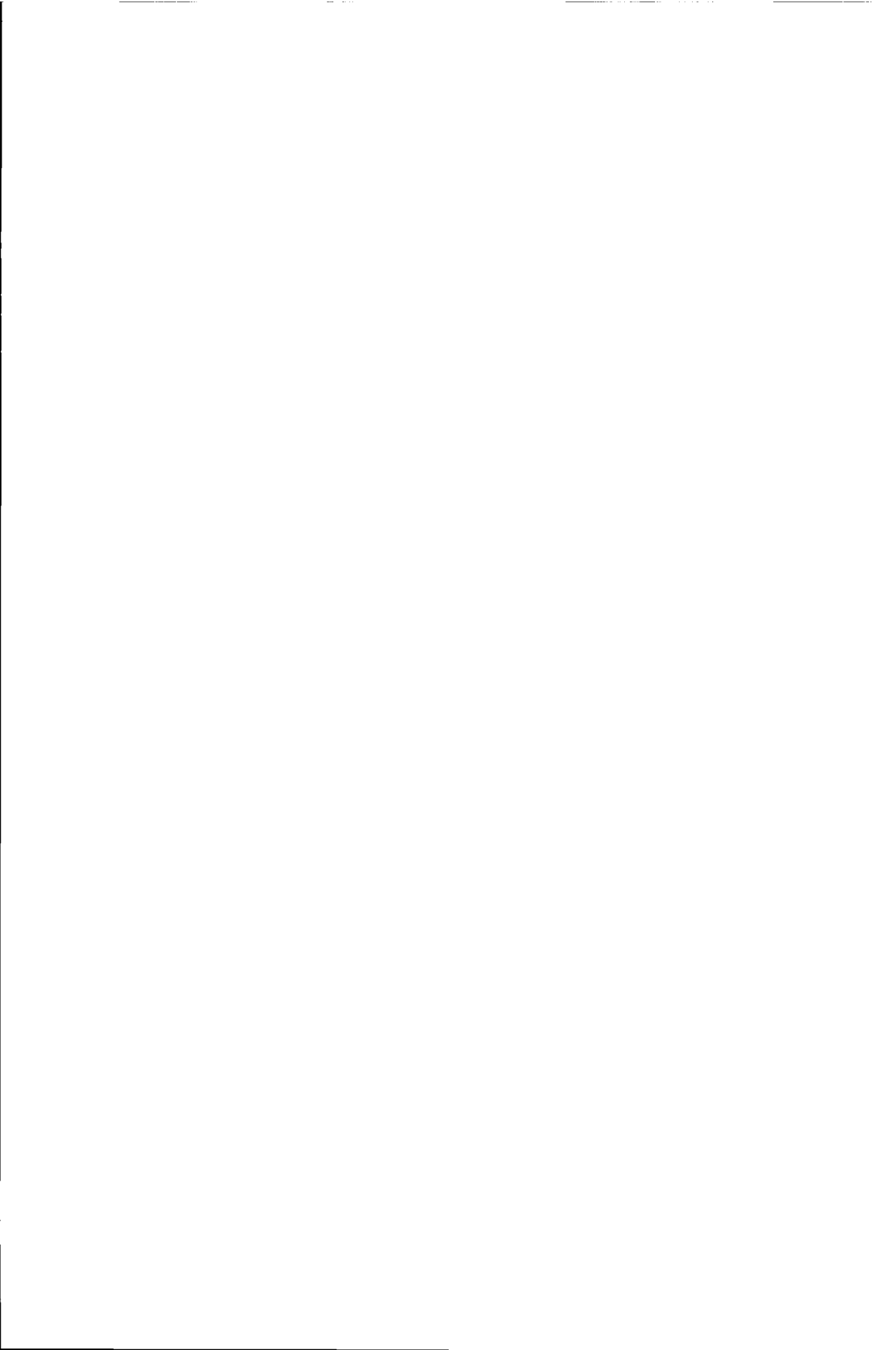
Chapter 7
From Drawing to
Structural Description

Like any other problem solving methods, architectural precedent analysis fundamentally depends on a process of representation: it concerns how a built environment can be *represented* so that certain properties can be disclosed with respect to a design objective. For the representation of built environment, there are several available systems, which we have reviewed in Chapter 3; but as discussed they are not satisfactory in respect to the task of precedent analysis addressed by the thesis. Firstly, none of these systems can comprehensively convey the kind of spatial concepts involved in the design case we studied. Secondly, within these systems it is difficult to structure a reasoning approach to the use of precedents, i.e., correlating the representation of precedents with particular design objectives, as we found in our case study and specified latter.

For these reasons, a new representation system is proposed in the last chapter through the design of ARPRAN. The new system involves several formats of representations, including not only a drawing-based representation (i.e., the labelled line drawing of plan, or the LLD) but also

some structured representations (i.e., the rules, the explanation structure, the frame, and the labelled location net, or the LLN). Whereas, transformation from the LLD to the LLN consists of the major process of representation.

In effect, the most important character of the new system lies at its integration with the principles of spatial cognition. The need of this new system can only be well understood through the explanation of its cognitive foundation. On the basis of morphology-operation-performance model, we have defined the general task of precedent analysis; with the framework of example-based learning, we have illustrated precedent analysis as a learning process. Yet, for studying the structure of domain knowledge that is dominated by spatial representation, the best approach is resorting on cognitive theories. This is not only because representation is a central topic in cognitive science, but also because the cognitive theories indeed can help us understand and reconstruct the recognition process in our case study, which has been serving as a criterion in the development of our precedent analysis system. The cognitive foundation makes the new representation system conspicuously different from those available representation systems, although it has absorbed many useful notions from them.

In this part of the work, I shall introduce some theories of spatial cognition and explain how they have been applied to ARPRAN's representation system. *Representation* can refer to both a process and the outcome of the process (Denis, 1991). These two aspects are covered respectively by the two chapters of this part: this chapter discusses the representation as an "outcome," while the next chapter treats it as a "process." However, the "process" of representation we talk here is not in the sense of computing algorithm. The process we mean is concerned with the general strategies with which different representations (i.e., input, output and knowledge base) could be related together.

This chapter is focused on the input, output and knowledge base of ARPRAN. To understand why ARPRAN takes the input and output forms displayed in the last chapter, however, we must first discuss some basic issues concerning spatial representation: What are the basic forms of spatial

representation? What information can each kind of representation convey? How are the representations interrelated to each other? These issues, although important to the design of a representation system, have been scarcely discussed in the architectural domain. Yet, they have been extensively explored in cognitive science, especially through a debate on the form of mental representation.

7.1 Proposition versus imagery representation

The history of psychology has been marked by debate on representation (Denis, 1989). A hotly debated issue, "Whether proposition or imagery is the basic form of mental representation for spatial thought," has been frequently mentioned by the literature on cognitive representation (e.g., Fodor, 1975; Kosslyn 1980; Johnson-Laird, 1983; Jackendoff, 1987; Putnam, 1988; Denis, 1991). Through out the debate, cognitive psychologists have discussed in depth and from different viewpoints about the properties of both proposition and imagery representation.

Presently, the debate is still continuing, but this work is not intended to take any position in the debate. In other words, our purpose of reviewing the notions of those cognitive psychologists is by no means to become involved in their debate. Instead, the purpose is to understand the distinction between different representation formats and to explain the role they play in the task of architectural precedent analysis.

7.1.1 Characteristics of proposition and imagery

Many writers on cognitive representation (e.g., Palmer, 1978; Paivio, 1986; Denis, 1989) discuss the nature of mental representation by analogy with physical representation, since physical representation can be easily described and classified in terms of the kinds of distinguishing characteristics. Obviously, it is this discussion, rather than the mental representation debate

itself, that is more relevant to our concern.

The most obvious distinction is that there are roughly two classes of physical representation: one is *language-like* and the other is *picture-like* (terms used by Paivio, 1986). Language-like representations include natural human languages as well as such formal systems as mathematics, symbolic logic, and computer languages. Picture-like representations include photographs, drawings, maps, and diagrams. In the literature, some other terms have been used variously referring to these two kinds of representation, for instance, *propositional format* and *quasi-pictorial imagery format* (Kosslyn, 1980), *propositional representation* and *analog representation* (Palmer, 1978), *algebraic* and *geometric structure* (Jackendoff, 1987). For the sake of simplicity, I use *proposition* and *imagery* in the following discussion.

While some theorists try to identify the features that distinguish proposition and imagery by describing them using such words as "non-iconic" versus "iconic", "discrete" versus "continuous", "interpreted" versus "non-interpreted", some others attempt at characterizing the two forms of representation from more fundamental distinguishing dimensions.

Palmer (1978) indicates that a fundamental difference between imagery and proposition lies at their different treatment of the relations among objects of the represented world. "Propositional representations are simply those in which there exist relational elements that model relations by virtue of themselves being related to object elements." (p. 294) Natural language is typical proposition representation. Words referring to objects (nouns, pronouns, etc.) are related in syntactically ordered strings through relational words (verbs, prepositions, etc.). For example, the sentence "The ball is on the box" specifies a relationship between the ball and the box that can only be understood by virtue of their syntactic relationship to the relational construction "is on." Consequently, imagery representations are those in which the relational elements are not existing or not indicated explicitly, instead, they are preserved as "spatial information" and "it is preserved (1) in a spatial medium, and (2) in such a way that the image resembles that which it represents." (p. 295) Palmer suggests that this distinction can be interpreted in terms of the *intrinsic-extrinsic* representational contrast.

Paivio (1986) interprets the intrinsic-extrinsic contrast in terms of a *degree of arbitrariness* of the mapping relation between the form of the representation and the form of the represented world. Besides arbitrariness-non-arbitrariness, he suggests other two dimensions characterizing the representations. One is that representation can be described as varying in *concreteness-abstractness.* Another is the *componential-holistic* dimension. He indicates that these two dimensions do not so perfectly correlate with the distinction between proposition and imagery, but they are helpful for us to understand the concepts of representation.

Figure 7-1 below shows a comparison made by Kosslyn (1980) between two forms of representation of "a ball on a box." The key distinction here rests on the difference between *description*—as is accomplished with proposition—and *depiction*—which is achieved with imagery.
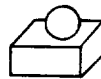
"A BALL IS ON A BOX"

Propositional Representation (Descriptive)	Quasi-pictorial Representation (Depiction)
ON (BALL, BOX)	
1. Relation	1. No distinct relation
2. Arguments	2. No distinct arguments
3. Syntax	3. No clear syntax
4. Truth value	4. Truth value only when under a particular description
5. Abstract	5. Concrete
6. Not occur in spatial medium	6. Occurs in spatial medium
7. No abstract spatial isomorphism	7. Abstract spatial isomorphism
a) No necessary part/whole relations	a) Necessary part/whole relations
b) Size and orientation optional	b) Size and orientation necessary
c) Arbitrary marks	c) Non-arbitrary marks
8. No abstract surface-property isomorphism	8. Abstract surface-property isomorphism
a) No necessary part/whole relations	a) Necessary part/whole relations
b) Shape not necessary	b) Shape necessary
c) Arbitrary marks	c) Non-arbitrary marks

Figure 7-1 Propositional and quasi-pictorial formats (after Kosslyn,1980)

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7.1.2 Architectural representation forms

The criteria for differentiating imagery and proposition discussed by cognitive psychologists, of course, can also be applied to distinguishing different formats of architectural representation. In architecture, three types of representation tools are often used; they can be generally classified as iconic, verbal, and symbolic representation. Obviously, the iconic representation of architecture (e.g., physical models, photographs, perspective renderings, etc.) is typical imagery representation, and the verbal representation of building belongs to propositional representation.

The symbolic representation, which includes various kinds of architectural plans, sections, diagrams, etc., however, cannot be simply regarded as either imagery or proposition, because it often entails arbitrary marks in a drawing or expresses discrete parts in a spatial medium (Figure 7-2). Nevertheless, we still can distinguish *imagery-based* symbolic representation from *proposition-based* symbolic representation in terms of their capacity of preserving spatial information. The plans in (a), (b) and (c), for instance, entail arbitrary marks—symbols standing for doors and windows, texts labelling the rooms; but they are still imagery-based representation because they have most characteristics of imagery: the objects (or locations) and relations are not indicated explicitly; they are still preserved as "spatial information"; the plan is still subject to more "arbitrary" representation. The diagrams in (d), (e) and (f), however, are primarily proposition-based because they have explicit objects (or locations) and relations, although the objects occur in spatial medium.

In fact, (c) and (f) are respectively examples of the labelled line drawing of plan (LLD) and the labelled location net (LLN), which we introduced in the last chapter. As will be further indicated, in ARPRAN, these two representations are used respectively as input and output to mark the essential of architectural precedent analysis, that is, using a proposition-based, *meaning-specified* description to represent the imagery-based, *equivocal* plan(s) of architectural precedent.
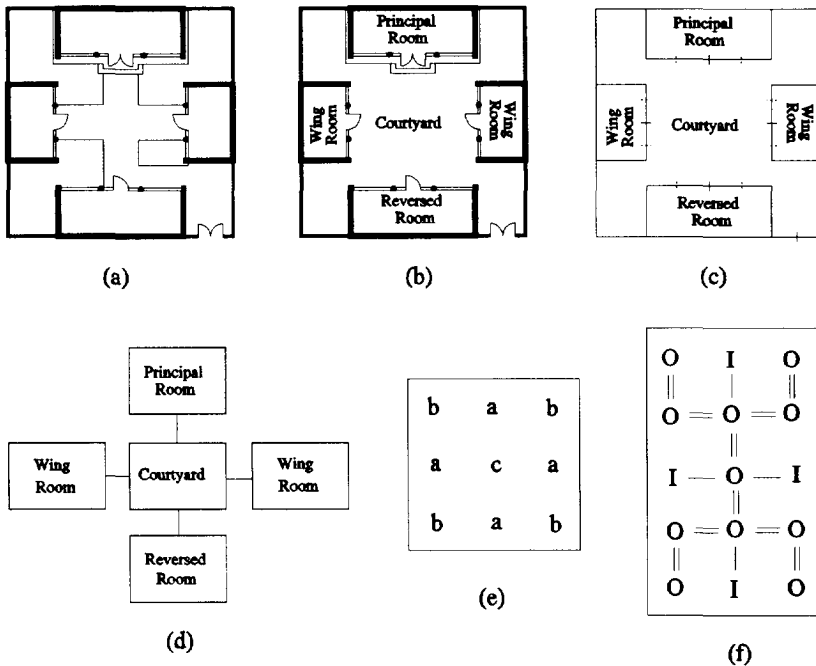
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Figure 7-2 Examples of symbolic representations
(a), (b) and (c): plans, imagery-based representation;
(d), (e) and (f): diagrams, proposition-based representation

7.2 The equivocality of architectural plan

From the same architectural precedent, ARPRAN is able to produce different interpretations according to different conditions (e.g., different target performances, operationality criterion, etc.). This is based on the *equivocality* of imagery representation of built environment: an architectural plan can be described in different ways according to different purposes and different principles. As will be augured, it is for making use of the equivocality of architectural plan that the LLD is introduced.

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7.2.1 Equivocality on perception level and description level

The equivocality of architectural plan can be explained on two levels. First is the equivocality on *perception* level, which can be best understood with some well-known ambiguous figures often used by cognitive psychologists in discussing visual perception (Figure 7-3). As indicated by many studies, these figures can be perceived as very different things when one uses different principles in the mind. Similar situation can also be found in architectural plans. For instance, the ambiguous plan in Figure 7-4 (a) may be perceived either as "Four buildings in one courtyard," as in (b), or as "One building with four courtyards," as in (c), depending on which part is thought as interior space. Of course, such possible vagueness is often reduced because the plan is labelled with details or texts. If a plan is labelled with some details (e.g., furniture or vegetation), then the space is less likely to be recognized as either interior or exterior. If the plan is labelled with texts that indicate the name of each space, as in Figure 7-2 (b) and (c), then the vagueness becomes even less.

Equivocality, however, still exists even when an architectural plan is labelled, although in the plan there is less ambiguity in terms of interiorness/exteriorness of space. Such equivocality can be understood on the *description* level: a built environment can be *described* in many ways. As was mentioned in Chapter 4, a building can be described with different hierarchies of organization, on different levels of organization and on different levels of abstraction. Consider the courtyard house in Figure 7-5. It can be described, in terms of physical elements, as the configuration of
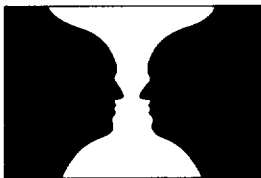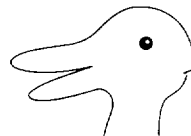
(a) Two faces or a vase?   (b) A duck or a rabbit?

Figure 7-3 Two famous ambiguous figures

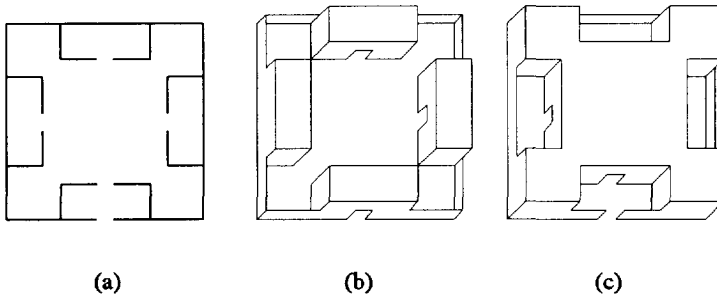(a)   (b)   (c)

Figure 7-4 An ambiguous plan can be perceived in two ways

"a set of columns plus a set of walls," or in terms of spaces, as the organiz-
ation of "a set of rooms and a set of courtyards." When it is described
spatially, it can be the organization of "four buildings and a courtyard," or
the composition of "twelve rooms, five courtyards and a doorway." If we
consider only the organization on the level of buildings and courtyards, we
still can describe it on different levels of abstraction: it might be as concrete
as "four rectangular buildings on the four sides of a courtyard," or as
abstract as "four indoor locations surround an outdoor location."

Similar to that on perception level, the equivocality on description
level is also caused by the use of different principles. More specifically, our
using different principles to describe an architectural plan is because of
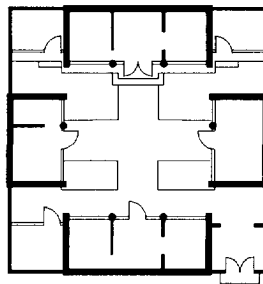

Figure 7-5 A plan of courtyard house which can be described
in different ways

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different purposes with which we describe that plan. For precedent analysis, as was emphasized, the purpose of description lies at specifying a particular performance of built environment. This will be further explored in the next section from the point of view of the meaning of object.

For now, my argument is: a system for precedent analysis should take advantage of the multi-possibilities of representation. In other words, with different rules or principles applied, the system should be able to draw from the same source (an example or a group of examples) many different conclusions that specify different performances or serve for different design phases. Ideally, the possible conclusions drawn from one source should be as many as possible. This is empirically coherent to the use of precedent by human designers: from the same precedent, different "things" can always be found by different designers or by the same designer when confronted with different design problems. Of course, it is unrealistic (at least at present) to expect the design of a system that can generate as many different conclusions as human designers can. Yet, it is possible to follow a principle with which human designers use precedent: they not only apply known rules to design, but also use these rules to extract new rules from precedent buildings or their documents. This is exactly the principle followed in the design of ARPRAN.

The idea of making use of the equivocality of architectural plan requires the system be able to accept imagery-based representation of built environment as input. This has lead to the use of the labelled line drawing of plan.

7.2.2 The labelled line drawing (LLD) as input

Using the LLD as input for ARPRAN, is firstly a consideration regarding to the task of architectural precedent analysis. In addition, it is also a measure to scale down research problem but without weakening the emphases of the work.

The LLD is essentially an imagery-based representation and has most

of the characteristics of imagery: the objects to be represented and the relations between objects are not indicated explicitly; they are preserved as "spatial information"; the plan is still subject to more "arbitrary" represent- ation. Yet, the LLD is not a "pure" imagery representation: it is labelled by texts and symbols, which are interpretations to the plan and which refer to some objects and relations (i.e., the rooms and their accessibility). Using such a double-featured representation as input, is corresponding to the nature of precedent analysis: on the one hand, precedent analysis makes use of the equivocality of architectural plan, and on the other hand, precedent analysis is based on the reasoning about how a built environment could be used.

Compared with conventional architectural plans, the LLD is obvious- ly a kind of more abstract and reductive representation (Figure 7-6). The abstraction is made to scale down the research problem. In principle, a precedent analysis system could use any kind of architectural plan as example input, given the representation satisfies two conditions: it is imagery-based and there is implication for the usage of spaces. In effect, from the point of view of taking advantage of equivocality, conventional architectural plans are more favourable for precedent analysis. Moreover,
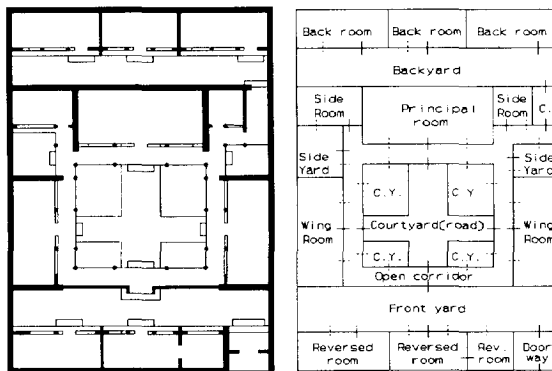

Figure 7-6 A conventional architectural plan and its LLD representation

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it is not impossible to design a perceptual module which accepts conventional plans as input.

However, such design has not been taken into consideration in the present version of ARPRAN, which is a down-scaled model to demonstrate barely the most central notions of architectural precedent analysis. Though a reductive representation, the LLD still keeps the most necessary information that would be used in the analysis at pre-parametric level, a level of abstraction focused by the present version of ARPRAN. Such information includes, position and division of spaces, accessibility between spaces, and the conventional name of each space (which reflects the major usage of the space). Other information, such as dimensions of walls and their openings (windows, doors) or layouts of furniture, is not indicated by the LLD, because the information is less relevant to the analysis of plan at the pre-parametric level.

In the LLD, there are two kinds of labels, i.e., symbols expressing door, windows, fences or low walls, and texts expressing names of spaces. These labels are considered as the minimum interpretation required in precedent analysis. In other words, the architectural plans serving for precedent analysis must provide information from which descriptions could be drawn about the usage of each space or each location in a space, and some primitive relations like accessibility among the spaces or locations. Of course, the interpretation could be made directly from a conventional plan depicted with more details. In that case, an additional sub-module is required to be increased which could translate the drawing details in a plan into texts or symbols. The design of such a sub-module has not been considered in the perceptual module presently proposed for ARPRAN, because it is a problem concerning more general techniques of computer vision rather than architectural domain knowledge.

To summarize, the present study emphasizes on the distinction between architectural plan, as imagery-based representation, and the description of the plan, as proposition-based representation. The LLD, as an imagery-based representation of architectural plan, can appropriately stress this

emphasis. Transformation from imagery to proposition, in fact, marks the essential of the precedent analysis: to *re-present* the continuous, iconic, less-arbitrary representations of built environment (i.e., the plans) as discrete, non-iconic, arbitrary representations. Such transformation, as was emphasized, is aimed at relating the precedent(s) to a given performance. In order to understand why the output has to be proposition-based representation, we further introduce an important notion, structural description.

7.3 Structural description and meaning

The representation by which meaning is assigned to a spatial object during perception, as Olson & Bialystok (1983) would suggest, must be a structural description—a proposition-based format. This notion is very important to precedent analysis. I would suggest that the outcome of precedent analysis, i.e., the morphological description, must be a kind of structural description.

The notion of structural description constitutes the cornerstone of not only Olson & Bialystok's theory but also many other pro-proposition theories of spatial perception (e.g., Palmer, 1975; Pylyshyn, 1973, 1977). A typical argument of these theories is that "structural descriptions are not to be seen as an alternative to images and prototypes; rather they are to be seen as an underlying form of representation from which both images and prototypes may be generated." (Olson & Bialystok, 1983, p. 9). In Pylyshyn's (1973) words, all characteristics of images can be described propositionally, so there is no argument for a separate representation.

We should, however, be clear about that these theories deny only the role of image as mental representation, or the representation during spatial thought; it is by no means the negation of the distinction between imagery and proposition formats in the physical world, as we discussed earlier. What these theories have emphasized is that "at some point in the perception and interpretation of the physical world, spatial information must be translated, recorded, or transformed into relational structures . . . " and "there is little doubt that the end product of this operation (i.e., perception and interpreta-

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tion) is a set of categorical, semantic distinctions . . ." (Bialystok & Olson, 1987 p. 511). This view is coherent with that of Jackendoff's (1987), who has proposed many levels of mental representation, some of which are imagery but the end product, or the highest level, of perception is propositional. It is with this view that we are legitimated to make use of various notions developed by cognitive psychologists without having to be involved in their debate about mental representation of space.

7.3.1 The structural description of objects

A structural description, according to Olson & Bialystok, is composed of a set of propositions which jointly specifies the meaning of objects and the spatial information appropriate to the perception of these objects. A structural description is similar to a feature list except that the features are not assumed to be constructed from a set of list but an ordered, hierarchically organized set of descriptions. In addition, structural descriptions are assumed to be constructed from a set of elements which constitute the language or code for the mental representation of experience.

The proposition expressing spatial information can be represented as a relation between a predicate and one or more arguments. The specific form of such spatial proposition can take the predicate calculus format discussed by Miller & Johnson-Laird (1976):

predicate (referent, relatum)

For example, to express the situation "a cup on a table," there would be a set of propositions, including:

on (cup, table)

This representation could also be expressed by a sentence, "The cup is on the table."

Olson & Bialystok suggest that objects are perceived and patterns are judged as similar because they take the same structural description. Consider a simple example. The two pairs of display in Figure 7-7 (a) might be judged as very similar; but if they are superimposed as in (b), the
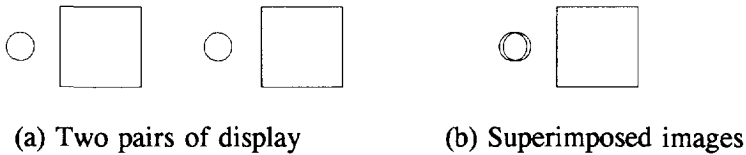
(a) Two pairs of display   (b) Superimposed images

Figure 7-7 An example for discussing structural description (after Olson & Bialystok, 1983)

images do not fit. The images appear similar because they both satisfy the description "small circle to the left of the larger square." Of course, they satisfy some other descriptions as well: "circle and square," "two figures," and so on. The judgement of similarity would not happen, however, if the images were not represented as any structural description.

In fact, structural description has played the most important role in the design of the "new courtyard house." The new design has *abstractly inherited* the features of the old city, because it has been so designed that it can be represented with some "structural descriptions" equivalent to that of the old city. In Chapter 3 (p.57), we illustrated some of these structural descriptions, such as the so-called "courtyard-building pattern" and the "fishbone circulation pattern." They are responsible for the new design being recognized as fitting in with the old environment, because both the new design and the old building satisfy those structural descriptions. Of course, *the structural descriptions we illustrated in the case study are not* sufficient for the success of the new design. In other words, more properties, such as dimension, colour, texture, etc. are responsible, hence more structural descriptions could be constructed than the ones we have shown. This work is focused only on the global spatial organization aspect.

7.3.2 The meaning of objects

A "representation-*of*" something is also a "representation-*for*" some purpose (Denis, 1991). The purpose of structural description, as Olson & Bialystok (1983) put it, is reflected in the *meaning* system. They suggest, "If an

object or event or display can 'take' a particular structural description, that object or event is assigned the meaning associated with the structural description." (p. 12)

"Meanings," as they explain, "represent the intentions, purposes, and goals of the perceiver, while the structural descriptions of objects reflect the properties appropriate to assigning that object to a meaning category." Therefore, "Meanings are not represented as part of the structural descriptions of objects but rather they are the criterion in terms of which features are selected, detected and added to a structural description." (p. 21)

Although a more adequate treatment of meaning may be needed (which is beyond the subject of this work), the above elucidation on the relationship between meanings and structural descriptions is clear enough for us in understanding the nature of architectural precedent analysis and the role of structural description.

Consider the meaning of a house as something to live in. The meaning is not a part of the structural description; rather it is the criterion in terms of which we assemble distinguishing features into a structural description. The features which enter into the structural description are those which are clues to its meaning as a livable object—its spatial organization, its size, its material and the like. In a perception process, the search for distinguishing clues will end as soon as the livable object can be readily recognized and discriminated from the unlivable ones.

Up to now, we may easily find the correspondence between meaning/structural description and—what we have been putting forward as the basic elements of the precedent analysis—performance/morphology of built environment. A performance can be regarded as the meaning with which a built environment is described, while a morphology is the structural description which specifies the meaning in the built environment. In our first example-study presented in the last chapter, the meaning of the walk-up apartments is "having good sense of privacy"; all the procedures of learning can thus be summarized as (1) to find features in the input plans which are related to that meaning, and (2) to assign to the plans a structural description which can specify that meaning. Of course, the search for those fea-

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tures, which may enter the structural description, is accomplished via some other features, i.e., the operations, which do not enter the structural description. The structural description of environment is characterized by relational specification between locations.

To conclude, structural description is destined to be used in spatial representation when such representation is associated with certain meaning. Architectural precedent analysis is a process of assigning a meaning, a kind of performance of built environment, to the precedent plans. A labelled location net, or LLN, can thus be seen as an "interpretation" of a LLD or a group of LLDs. It is through the LLN that the meaning, which is implicitly related to the equivocal LLD(s), can be "defined" and "understood."

For the present version of ARPRAN, I distinguish two kinds of LLN, i.e., the *local description* of a plan and the *global description* of a group of plans. These two kinds of LLN are respectively the results of "plan abstraction" and "generalization," two of the three general operations of ARPRAN's perceptual module (see Section 6.4). Chapter 8 will discuss the formation process of these descriptions.

I shall further suggest in this chapter that the kind of meaning, which a structural description would assign to a built environment, requires not only specification of relations between locations, but also some discrimination, or *semantic distinctions*, among those locations. This is why ARPRAN's output is a kind of *labelled* location net, and consequently, the input is also attached with some labels.

7.4 Semantic distinctions and schematization by structural descriptions

A basic feature of structural description is that it impose a fixed form of structure on virtually every spatial scene. The fixed form of structure means not only the unified syntax of spatial propositions (as discussed earlier), but also the limited vocabulary to make semantic distinctions. The benefit of

such fixed form of representation can be understood with a principle of categorization, called "cognitive economy," suggested by Rosch (1976): "as an organism, what one wishes to gain from one's categories is a great deal of information about the environment while conserving finite resources as much as possible." As I shall further discuss, the formation of structural description is virtually a process of categorization.

The structural description is constructed by selecting from a "vocabulary of available concepts" to form an appropriate representation (Olson & Bialystok, 1983; Pylyshyn, 1977). This makes every structural description a kind of schematized representation. Then, where do those "concepts" come from? And what determines the selection?

Many scholars agree that these "concepts" are basically innate: both animals and humans have a profound bias towards seeing and interpreting objects in space in terms of primary categories such as *front/back, up/down, left/right, in/out* and so on. Clark (1973) has argued that it is our asymmetrical body structure—with eyes at the front and gravity pulling in one direction—that are responsible for our representation of the primary spatial dimensions in the environment. The perceptual bias has been systematically discussed by Jackendoff through his "Conceptual Structure Hypothesis."

7.4.1 Conceptual structure: the source of semantic distinctions

Jackendoff (1983, p. 17) assumes: "There is a *single* level of mental representation, *conceptual structure*, at which linguistic, sensory, and motor information are compatible." Although there is no logical necessity for the existence of such a unified level, Jackendoff notes that at worst it is "a plausible idealization; at best, it is a strong unifying hypothesis about the structure of mind." Because of the conceptual unity, we are able to talk about what we see, and similarly, to carry out verbal instructions.

The conceptual structure, according to Jackendoff, consists of a number of *basic primitives* and *principles of combination* (or *formation*

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rules). For instance, there are a set of basic primitives called *ontological categories*, or "semantic parts of speech," which include such entities as [THING] (or [OBJECT]), [EVENT], [STATE], [ACTION], [PLACE], [PATH], [PROPERTY], and [AMOUNT]. These basic categories can be expanded into more complex expressions via formation rules, like

$$[\text{PLACE}] \rightarrow [_{\text{Place}} \text{ PLACE-FUNCTION(THING)}].$$

It says that [PLACE] can be related to [THING] through a place-function. For instance, [PLACE] may be a complex expression, expressed by "on the table," which contains as a subconstituent the [THING] expressed by "the table." In addition, these category features may be associated with one of the other two conceptual primitives, [TOKEN] and [TYPE]. Thus, a perceived object will be represented as an [OBJECT TOKEN], and a category of objects as an [OBJECT TYPE]. Similarly, a perceived event will be represented as an [EVENT TOKEN], and a category of events as an [EVENT TYPE]. As for how these ontological categories and their combinations could be applied to architectural spatial thinking, it might be a problem worth further investigation. What we are interested in now is the principles presented by the theory of conceptual structure.

An important principle is: both the object we are perceiving and the object we are describing must be a reflection of the constituents of the conceptual structure or their combinations. In other words, everything we see or talk about must fit to our conceptual structure; if not so, then the object cannot be seen or talked about. This is why Jackendoff (1983) distinguishes between the *projected world* and the *real world*, and argues that "One can not perceive the 'real world as it is,'" (p. 26) and "*the information conveyed by language must be about the projected world.*" (p.29, emphasized by Jackendoff)

7.4.2 Categorization and type

Closely related to the Conceptual Structure Hypothesis, is the problem of categorization, which is also relevant to the precedent analysis we are

studying. Harnad (1987) notes, categorization "plays a critical role in perception, thinking, and language and is probably a significant factor in motor performance too."

Categorization happens at every turn of cognition. Two kinds of categorization are usually studied: one kind, about *generic knowledge categories*, involves the judgement of the type of an object, such as to classify an animal as a fish or a bird; another, *sensory perception categories*, has to do with sorting out a continuous stimulation into discrete categories, such as to impose category boundaries on colours or musical pitches (Medin & Barsalou, 1987). Both kinds of categorization are involved in the architectural precedent analysis we study. As a general process, precedent analysis can be seen as categorical perception of spatial information, i.e., to turn a continuous plan into a discrete description (this will be discussed in the next chapter as *spatial categorization*). In some procedures, precedent analysis involves also in generic knowledge categorization, such as translating "Living Room" into "Private" location, "Principal Room" into "Indoor" location.

Although two kinds of categorization are usually studied separately, there are many similarities between them (Medin & Barsalou, 1987). Jackendoff's Conceptual Structure Hypothesis is in fact intended to provide principles unifying the studies on both generic knowledge categories and sensory perception categories.[1]

Jackendoff (1983, 1987) has identified some common characteristics of categorization. First, categorization is essentially "to judge that a particular thing is or is not an instance of a particular category," hence there is a distinction between [TOKEN] and [TYPE]. Second, categorization has the nature of creativity: one can categorize novel tokens as instances of known type as well as create new [TYPE] concepts at will. Third, most categoriza-

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[1] Devitt (1991) suggests a third kind of categorization. In his opinion, the kinds that Jackendoff's theory covers take a classic, or Constructivism, view towards categorization. Still, in this work, we are not intended to get involved with their debate but to apply the theories which are useful for the design of our system.

tion involves in *fuzzy categories*: in many cases, the membership of a [TOKEN] cannot be simply judged with a yes or no.

These observations lead to an important principle about [TYPE] concepts: a [TYPE] is not something existing rigidly in the mind, as a template, a list containing all the [TOKENS], or a group of necessary and sufficient conditions; rather, a [TYPE] concept is a finite set of conditions and formation rules in the conceptual structure, which constitute a *preference rule system* and which can not be projected as an entity in the mind. "The process of concept acquisition can then be thought of as using environmental evidence to help select or construct a [TYPE] concept from the possibilities provided by the conceptual structure." (Jackendoff, 1987, p. 138) In order to further understand the nature of [TYPE] concepts, I briefly introduce as following the concept of preference rule system discussed by Jackendoff.

Preference rule system

The notion of preference rules in cognition is based on ideas from Gestalt psychologists, and was first developed by Lerdahl and Jackendoff (1983) in analyzing music cognition. Jackendoff (1983) then extended the application of the notion to semantics.[1]

Jackendoff describes the notion by citing Wertheimer's study on how the perceptual principles organize collections of shapes into larger units. With the circles in Figure 7-8 (a), for example, the organization that is most salient and that one perceives most spontaneously is that of three circles to the right of two other circles ("2+3"). Here, relative proximity is the principle that determines which circles will form a visual group. In Figure 7-8 (b), the grouping is "2+3" by virtue of similarity of size of the circles; so, relative similarity becomes the principle that determines the grouping. Jackendoff (1983) calls these principles *grouping preference rules*, "because

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[1] A similar idea has been proposed independently by Lakoff (1987), in which he discusses how word meanings and other reflections of cognitive categories may be determined by *clusters of interactional properties*.
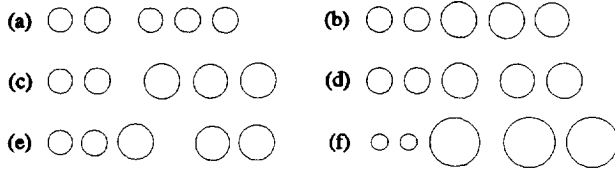
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Figure 7-8 Wertheimer's study on how the perceptual principles group the shapes

these rules establish not inflexible decisions about structure, but relative preferences among a number of logically possible analyses" (p. 132).

Often encountered is the situation where several principles apply, such as in Figure 7-8 (c) and (d), both proximity and similarity are applicable. In (c), both of the principles analyze the configuration as "2+3," so a still stronger grouping judgement can be made. In (d), however, by proximity the configuration is judged as "2+3," but by similarity it tends to be "3+2"; the outcome is an ambiguous judgement that may even switch interpretations spontaneously. In Figure 7-8 (e) and (f) the two principles are also conflict; but proximity is more dominant in (e) and similarity in (f).

The conditions of proximity and similarity and their interaction in grouping judgements constitute a simple case of a *preference rule system.* Jackendoff suggests that each [TYPE] concept is a preference rule system, which contains a number of conditions. These conditions are not collectively necessary and sufficient, so they may not be used at the same time in a categorical judgement. In case of ambiguous judgement, like Figure 7-8 (d), some other conditions must be found and applied. This can explain why we can always make a judgement although sometimes categorization involves in fuzzy categories.

I shall suggest in the next chapter that the notion of preference rules has been particularly used in the "generalization" operation of ARPRAN. For now, I should like to indicate that the hypothesis of conceptual structure and the principle of type formation have been generally applied to ARPRAN's representation system. This can be understood from several perspectives.

First, the knowledge base of ARPRAN contains a conceptual struc-ture which determines the semantic distinctions among the spatial relations and locations that constitute the structural description of precedent plans. For example, there is distinction among *east, west, north* and *south*, or between *indoor* and *outdoor*.

Second, the basic vocabulary of spatial relations and locations can be seen as primitives forming a number of basic [TYPES] of built environ-ment. These [TYPES] are not explicitly existing in the knowledge base, just as they have no projection in the mind. Yet, they are "there" and directing the analysis and description of the precedents.

Third, the precedent analysis can be seen as the construction of new types. The new types are formed according to the evidence of input as well as the available possibilities provided by those basic [TYPES]. This is perhaps the most distinguishable feature of the approach presented by this work.

In the next subsection, I shall explain the basic semantic distinctions constructed in the knowledge base of ARPRAN.

7.4.3 Semantic distinctions in the knowledge base of ARPRAN

The semantic distinctions in ARPRAN are mainly derived from the case study, the "new courtyard house" design. Particularly, the distinctions are constructed in order to account for the global spatial organization patterns that are crucial to the case design, namely, the "courtyard-building pattern," the "fishbone circulation pattern" and the spatial organization patterns of the walk-up apartments. These semantic distinctions are therefore part of the basic [TYPE] concepts which are used in the categorization of architectural precedents related to our case design. Yet, to what extent they are general-izable enough so as to be applicable to other cases is still a problem worth investigation.

The most fundamental distinction, of course, lies between those

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primitives for locations and those for relations, which are two kinds of primitives forming the structural descriptions. Among the primitives for locations, there are several sets of semantic distinctions, i.e., *indoor* versus *outdoor*, *circulation* versus *utility*, and *private* verses *public*.

Indoor vs. Outdoor

Distinction between *indoor* and *outdoor* is constructed mainly according to the "courtyard-building pattern." Obviously, without a distinction between *indoor* and *outdoor*, there would be no sense to talk about locations where a building can stand and locations where a courtyard can be placed. We might notice that such a distinction is also fundamental in SAR's zoning diagram, where the distinction is made between zones rather than locations (see Chapter 3).

Circulation vs. utility

Distinction between *circulation* and *utility* is derived from the so-called "fishbone circulation pattern." Since this pattern is about circulation, it must contain some locations where people only pass through: they may stay at these locations temporarily to make choice for further movement, but these locations are not somewhere regarded as a destination of the movement. Correspondingly, there must be some other locations where are the destination of people's moving.

Circulation and *utility* are constructed to make these two kinds of locations distinguishable. Utility locations are mostly those spaces used for some activities other than travelling, for instance, rooms, courtyards, or squares; but they are not necessarily so—an utility location can also be a circulation location at a lower level of built environment. Consider the apartment house illustrated by Figure 7-9. At the building level, a public corridor is regarded as a circulation location and the internal corridor of an apartment attached to this corridor can be regarded as an utility location; but at a lower level, i.e., the living unit level, the internal corridor becomes circulation location, while the rooms are the utility locations.

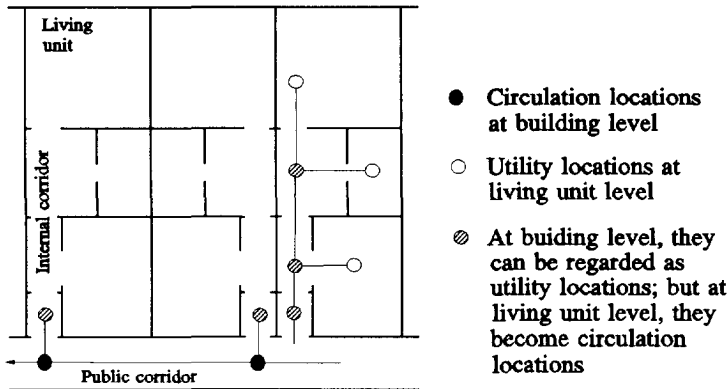The distinction between *circulation* and *utility* locations has been

Figure 7-9 At different levels, the internal corridor can be regarded as different locations.

inspired also by Lynch's (1960) distinguishing among district, node, landmark, path, and edge, the five spatial elements in the cognitive map of a city. However, whether these two systems have any correlation, can be a problem for further research.

Private vs. public

Distinction between *private* and *public* is constructed to account for the spatial organization patterns of walk-up apartment. This pair of primitives are in fact frequently used in conceptualizing architectural spaces (e.g., Habraken, 1982; Hillier & Hanson, 1984).

Again, both public and private spaces are relative concepts. We can have public space on all levels of the territorial hierarchy. For instance, the public space in a house is, in turn, private, when we step our into the street. It is this relativity, as Habraken notes, that accounts for the confusion of terms we often encounter such as "public," "semi-public," "private," and "semi-private."

The above semantic primitives for the locations are part of the basic categories for recognizing architectural spaces. However, not all the spaces

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can be simply classified as *indoor/outdoor*, or *circulation/utility*, or *public/private*. In effect, most spaces need to be categorized as something in between. For ARPRAN's knowledge base, therefore, some combined concepts have been introduced, such as *semi-outdoor*, *mixed* (circulation and utility), *semi-public* and *semi-private*. These categories are used in this study to cover all those categories between the basic primitives. However, more categorical distinctions could be made.

Semantic primitives for relations between the locations are further divided into two classes: those for labelling the relativistic positions, i.e., *east, west, north, south*; and those for describing the connectivity of the locations, i.e., *access, no-access, visual-access*, etc. Based on these basic distinctions, spatial predicates could be constructed relating two locations together. For example, positional relations can be expressed by predicates such as TO-THE-NORTH-OF, TO-THE-EAST-OF, etc.; connective relations can be as ACCESS-TO, VISUALLY-ACCESS-TO, IN-THE-SAME-SPACE-WITH, etc. In a LLN representation, these predicates are not explicitly written down. The connective relations are noted by symbols, while the positional relations are simply omitted and expressed instead through the spatial layout of the locations. This of course does not mean that those semantic distinctions are not existing in the LLN representation.

East/west, north/south

That these semantic primitives are chosen for expressing the relativistic positions among locations, is mainly because this version of ARPRAN deals with the analysis of precedents in Beijing's old city, where the environment is orthogonal and cardinal directions are dominant in spatial conception and representation. As a convention of orientation, the residents of Beijing's old city are used to show way to strangers by using words like "go straight forwards," "then turn west," "then turn north," etc. In an old tourist guide book, we may even find an index of places which is full of such records:

"*Shitiao Hutong*: Turn west from the south part of *Dongzhi-mennei Street*;
Sandai Hutong: Turn west from *Jinshifang Street*, to the

south of *Wudinghou Hutong*; . . . "
(Translated from ZT, 1917)

Whether such a convention of orientation has any deeper cultural reason, or it was solely out of the orthogonal environment, can be a topic of further investigation. However, some cognitive psychologists did indicate that the most directly perceivable spatial relations are such as north/south, east/west or left/right, front/back relations. In other words, these are basic positional relations; all the other complex relations can be derived from or schematized into these basic relations (Olson & Bialystok, 1983; Miller & Johnson-Laird, 1976).

The perceptual bias, or the [TYPE] concepts, for structural description is often investigated by means of nature languages. Olson & Bialystok (1983, p. 47) notes, "Language, being an explicit set of representation of spatial information is one of the primary means for making that spatial information explicit and hence, for the development of spatial cognition. . . . The structure of language, therefore, is a window to the structure of the recognition routines we have called structural description." The language of space has been examined by many scholars (e.g., Leech, 1969; Bennett, 1975; Olson, 1975; Miller & Johnson-Laird, 1976; Talmy, 1983; Cienki, 1989), whose findings as well as methods would be undoubtedly an important source for our investigation into the semantic of space.

7.5 Summary

Two basic forms of representation can be distinguished: proposition and imagery. A fundamental difference between the two formats lies at their different treatment of the relations among objects of the represented world: the relations are indicated explicitly in proposition, but not in imagery. This leaves imagery representation to be "equivocal" and it can be interpreted "freely."

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This distinction between imagery and proposition has been reflected in ARPRAN's representation proposal, as a distinction between the input of precedent example (i.e., the LLD) and the output of analysis (i.e., the LLN). The LLD is primarily an imagery representation, while the LLN is basically propositional. The essential of the architectural precedent analysis is thus to *re-present* the imagery representations of architectural plan(s) as propositional representation—or a kind of structural description—so as to assign a *meaning* to the plans of precedents. The meaning of a precedent is related to how it would be used or perceived.

The assignment of meaning to a plan as well as any objects is always schematized, because of the perceptual bias towards seeing and interpreting objects in space. Such perceptual bias has been systematically discussed by Jackendoff through his "Conceptual Structure Hypothesis," which is a cognitive foundation for the construction of ARPRAN's knowledge base.

In the next chapter, I shall explain the process of drawing/structural description transformation.

Chapter 8
Frame-directed
Spatial Categorization
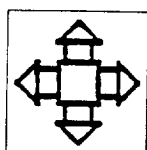
Jackendoff (1987) has asserted: "what we see is in part affected by what we know about the world and what we expect to see" (pp. 187-188). Similar notions have been expressed also by many other scholars (e.g., Olson & Bialystok, 1983; Ullman, 1986). These notions can be summarized—using Minsky's (1975) concept of frame—as "frame-directed perception." Correspondingly, ARPRAN's representation of architectural plan can be termed as "frame-directed spatial categorization." Spatial categorization, as already mentioned in the last chapter, is a process of turning a continuous, imagery-based architectural plan into a discrete, structural description of the plan; and through such a process, a meaning associated with a performance of built environment is assigned to the plan.

The "frame-directed spatial categorization" has been illustrated in Chapter 6 as a kind of example-based learning, which consists of three major procedures, i.e., "frame construction," "plan abstraction" and "generalization." In this chapter, I present some cognitive principles underlying these procedures.

Two issues are worth being emphasized again. First, ARPRAN is not intended, nor possible, to imitate the human mind. By referring to the cognitive principles, we are developing ARPRAN's own "perception" mechanism that is both specific for performing the architectural plan abstraction task and generally acceptable by digital computers. Second, the thesis is about the computational theory rather than the computing algorithm of ARPRAN. The process discussed in this chapter is thus only in terms of the principles of domain knowledge structure rather than the algorithm for implementing ARPRAN.

8.1 Visual perception and frames

8.1.1 Some principles of visual perception

Based on his multi-level theory of mental representation, Jackendoff (1987) has assumed a complicated process of visual processing, which is illustrated as the operations of three sets of processors. First, there are a set of bottom-up processors that can translate perceived information from lower-level visual representation form into higher level: from retinal array into primal sketch, and from primal sketch into 2½D sketch, etc.[1] Then, there are a set of top-down processors that translate conceptual information from higher level into lower-level: from conceptual structure into 3D model, and from 3D model into 2½D sketch, etc. Finally, there are a set of integrative processors which integrate on each level information coming from both bottom and top. Information translation between each two levels is governed

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[1] The *retinal array*, the *primal sketch*, the *2½D sketch* and the *3D model* are different levels of visual representation identified by Marr (1982). The retinal array is the lowest level, which represents simply the light intensity at each point in the image at each moment; while the 3D model is the highest, in which objects are represented as occupying volume in space, by contrast with the surface representations of the lower levels. Jackendoff suggests that the 3D model is actually connected with an even higher level of perception, the conceptual structure, so to explain why visual information is compatible with the information from other modalities (see Chapter 7, subsection 7.2.1).

by some internal rules which Jackendoff calls *correspondence rules*. Although Jackendoff has indicated that in this theory there are still many gaps to be filled in, one principle is clear: both the top-down and the bottom-up process are necessary in visual processing.

This principle can also be found in the work of Ullman's (1986), who advances a two-stage process of perceiving spatial relations. The first is the bottom-up creation of certain representations of the visible environment; it is similar to Jackendoff's notion. The second stage involves the top-down application of visual routines to the representations constructed in the first stage. These routines can establish properties and relations that cannot be represented explicitly in the bottom-up representations. Underlying the visual routines, there exists a fixed set of elemental operations that constitute the basic "instruction set" for more complicated processes. The perception of a large variety of properties and relations is obtained by assembling appropriate routines based on this set of elemental operations.

We might notice that Ullman's "visual routines" are not identical to Jackendoff's operations of the top-down processors. Yet, I should suggest that they have similar functions in visual perception, and the notion of "fixed set of elemental operations" plays a similar role to Jackendoff's "correspondence rules." These notions, among others, are the main sources inspiring the use of "translation rules" and "transformation rules" in ARPRAN's abstraction of architectural plan.

Moreover, the "visual routines" or the "top-down processors" are functioning as an intermediary between the visual representations and some "higher-level cognitive functions." In Jackendoff's words, the higher cognitive functions are in charge of wilfully creating internal contents that bias the selection function toward one interpretation or the other. In Ullman's work, the correspondents of these "higher-level cognitive functions" are something called "higher-level components of the system," which determine the application of the visual routines according to the goals of cognition.

I shall use Minsky's (1975) word *frame* to name these "higher-level cognitive functions," because frame is a more familiar concept and not

fundamentally different from Jackendoff's or Ullman's correspondent notion. In fact, both Jackendoff and Ullman have mentioned the relationships between their notions and the frame concept. Jackendoff (1983, p. 141) emphasizes the selection task and the use of default values of frames and hence connects these usage directly to his notion of *preference rule system*, which we briefly introduced in the last chapter. Ullman (1986, p.177) indicates that the theory of frame does to solve the same problems that he concerns, i.e., guiding the perceptual activity and selecting the appropriate routines, but frame is not satisfactory enough because it emphasizes on detailed expectations (or default values). In my opinion, however, such a gap between the frame notion and Ullman's theory is not an essential one when we apply them only as the general principles for the developing our own system.

A note about frame should be made here. Frame has been found very useful in both artificial intelligence and cognitive psychology. In AI application, frames are important intelligent data structure and frequently used in expert systems or other AI systems (Parsaye, Chignell, Khoshafian and Wong, 1989; Jackson, 1990). What we are interested in the concept here, however, is its application in cognitive psychology. In other words, we use frame as a device to study the abstract representation (see Chapter 1), which certainly has the potentiality to be developed into concrete representation in the future.

To summarize, we can learn from the cognitive theories a set of important principles: (1) visual processing contains both bottom-up and top-down processes, (2) the top-down operations are directed by some frames, and (3) the operations are executed and constrained by a number of "rules" that are selected by the frames according to the purpose of cognition.

8.1.2 The frames constructed in ARPRAN

The first major operation of ARPRAN's perceptual module is "frame construction," which is to build a frame according to an explanation
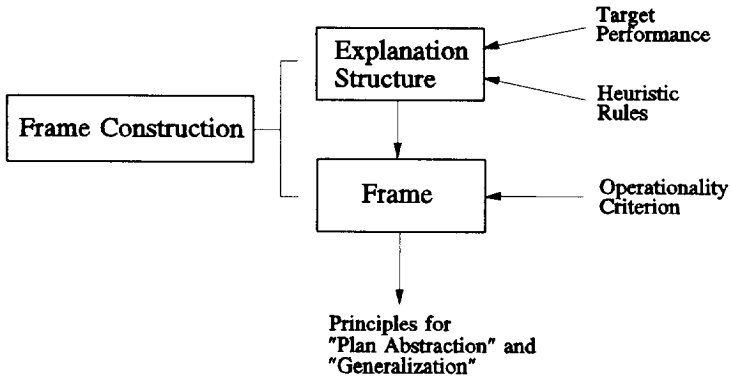
Figure 8-1 According to target performance, heuristic rules and operationality criteria, "frame construction" sets principles for "plan abstraction" and "generalization"

structure of the input target performance and the given operationality criterion. Although this procedure is derived analogically from an explanation-based learning paradigm (see Chapter 6), it is embedded with an important cognitive principle—what we see is affected by what we know about the world and what we expect to see (Jackendoff, 1987).

In ARPRAN, constructing a frame is setting a series of principles for plan abstraction and generalization. These principles are set according to the "known" heuristic rules and the "expected" level of morphological specification (Figure 8-1). Generally, the principles indicate a direction along which the precedent analysis proceeds; they regulate which [TYPE] concepts would be applied in a particular analysis task. Specifically, they manifest three matters concerned:

> (1) what information in the input plan is relevant to the specification of the target performance and hence expected to be preserved during the course of abstraction and generalization,

(2) how the locations and their labels will be categorized, and

(3) which set(s) of transformation rules should be used in plan abstraction and generalization.

Consider again our first example-study, learning the "good sense of privacy" (see Chapter 6, sub-section 6.4.1). The explanation structure indicates that four morphological aspects are probably relevant to "good sense of privacy," i.e., "separated living units," "short corridor," "no visually accessible windows from two adjacent living units" and "sound insulating walls and windows." This information, together with the operationality criterion (which requests the description of "global spatial organization of the plan"), forms a frame which suggests that several kinds of information are expected to be conveyed in the final result of target performance specification:

(1) spatial relation between the living units,

(2) spatial relation between the living units and the public corridor(s) connecting the living units, and

(3) accessibility (both physical and visual) between the living units, the public corridors and the outside space.

As should be emphasized, frame construction is not only based on the explanation structure, but also affected by the operationality criterion, which is given according to the stage of the design for which the current precedent analysis serves. According to a given operationality criterion, some morphological aspects that are less relevant to the current design stage might be abstracted out during the plan abstraction. For example, one might have noticed that in the explanation structure of the first example-study, one of the morphological aspects is "sound insulating walls and windows." However, in the plan abstraction stage, information about this aspect does not appear. The reason is as the following.

According to the available heuristic rules, morphology which may cause sound insulation is expected to be specified; but following the operationality criterion, which requests the description of "global spatial organization of the plan", this aspect of morphology is not necessary to be appear in the current precedent analysis (because the specification of the morphology causing the sound insulation implies the material and construction detail of walls and windows, which are not relevant to "global spatial organization"). The operationality criterion used here is obviously corresponding to the so-called "pre-parametric design." The morphological description results from this criterion is thus a pre-parametric description. Similar case occurs also in the second example-study.

Corresponding to a constructed frame, in the plan abstraction of the first example-study, (1) the labels for accessibility between the spaces are preserved as aspects of relations between the locations; (2) the labels showing the use of spaces are translated into a set of more abstracted labels which categorize the spaces according to their scale of privacy with respect to a living unit; and (3) a set of rules for the merger of various types of locations are used to transform the labelled metric location net.

In the second example-study, learning "fitting the traditional urban fabric," (see sub-section 6.4.2), the explanation structure and the operationality criterion jointly indicate that two morphological aspects are relevant to the target performance, i.e., the "building-space pattern" and the "circulation pattern." These suggest that the plans of the precedent examples could be abstracted and generalized along two directions. On the one hand, the typical building-space relation in the old houses should be described; and on the other hand, the typical circulation pattern in the old houses and the old street should be captured. Consequently, the plans are respectively categorized with two sets of location categories: one set reflects the building-space relation, including "Indoor," "Outdoor" and "Semi-outdoor" locations; another set shows the circulation relations, containing "Circulation," "Utility" and "Mixed" locations. Corresponding to the two ways of categorization, as we have seen, the relevant labels and transformation rules are selected for abstraction and generalization.

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So far, we have discussed the principles in frame construction and use. Several questions would surely be raised here: What is the exact form of the frame constructed? How is information from the explanation structure and operationality criterion mapped into the frame? How does this frame give instruction in plan abstraction and generalization? These questions, I should indicate, are concerned with the "concrete representation" and the algorithms for carrying out the computation task; they need some further investigation beyond this thesis.

8.2 Spatial categorization and plan abstraction

Architectural precedent analysis, as mentioned in the last chapter, can be understood as a process of spatial categorization. The process is defined by Bialystok & Olson (1987) as representing essentially continuous physical space in terms of spatial predicates which are discrete codes or categories and which form part of a structural description. Spatial predicate takes the format of predicate calculus, usually consisting of a predicates, a referent and a relatum:

predicate (referent, relatum).

Therefore, the basic problem of spatial categorization can be stated in three operations, each having an output that specifies one of the three constituents of the required spatial propositions of the general form:

(1) Select referent: Identify critical features of display.

(2) Find relatum: Assign axis or locate reference object in the display.

(3) Assign predicate: Determine the spatial relationship between the referent and the relatum. (Bialystok & Olson, 1987, p. 521)

Certainly, each of these operations would be involved in very complicated procedures in the actual human cognition, which Jackendoff, Ullman and

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many others have attempted to illustrate. However, if we treat these operations only as some major procedures in spatial cognition, and do not attempt to reconstruct the much more complicated mental process associated with them (in fact, Bialystok & Olson have treated them in this way), we find that they can be analogically applied to explaining ARPRAN's plan abstraction.

As for what determines the selection of referent, relatum and predicate that will be assigned to a particular situation, we suggested in Chapter 7 and Section 8.1 that it is firstly determined by the perceptual bias in the conceptual structure, and secondly, by the frames constructed according to the particular purposes recruited by the task.

8.2.1 Abstraction of the labelled line drawing of architectural plans

The second major operation of ARPRAN's perceptual module is "plan abstraction," i.e., to transform the labelled line drawing (LLD) of a plan into labelled location net(s) (LLN). The LLN which results from "plan abstraction" can be called *local description*, in contrast with the global description resulting from "generalization" (see Chapter 7, sub-section 7.2.2).

The abstraction process consists of three sub-processes of transformation, i.e., dividing a plan into locations, categorizing labels in the plan and merging locations and relations (Figure 8-2). The goal of plan abstraction is to form a structural description that shows the spatial organization of an individual precedent (i.e., the *local description* of LLN). However, the abstraction starts from a "low-level" description of plan. This is obviously a bottom-up strategy and can be understood with the bottom-up process in visual perception.

When a plan is divided into discrete locations, the three operations of spatial categorization are simultaneously being carried out. Each location is a referent and at the same time is a relatum for the other locations next
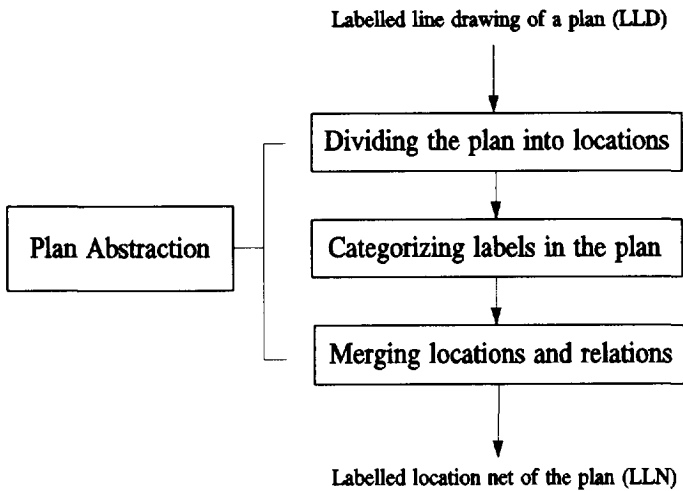
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Labelled line drawing of a plan (LLD)

Dividing the plan into locations

Plan Abstraction

Categorizing labels in the plan

Merging locations and relations

Labelled location net of the plan (LLN)

Figure 8-2 Three sub-processes of plan abstraction

to it, and the relationships between the two neighbouring locations become the primitives of the predicates. The subsequent procedures are transforming such a "low-level" description into a more abstracted description by further selecting referents, finding relatum and assigning predicates.

8.2.2 Dividing a continuous plan into discrete locations

An important initial procedure in ARPRAN's plan abstraction is dividing the plan according to the position of the walls or the other recorded boundaries of space (e.g. roads, fences, etc.) so as to form a griding pattern (Figure 8-3).

The fundamental aim of dividing the plan is to initiate the general transformation in spatial categorization, i.e., to change a continuous space into discrete categories. Evidently, for such an initiation, we may take any
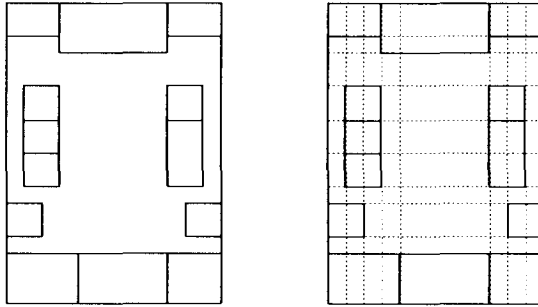
Figure 8-3 Dividing a continuous plan into discrete locations
by imposing grids on the plan

method, provided it allows distinction of *locations* in space. In other words, the initial procedure is not necessarily dividing a plan into grids as we have used in ARPRAN, but it must be a procedure which enables the plan to be divided into discrete space primitives, or "parcels of space" (Tzonis & Oorschot, 1987). The division can be made according to the natural rooms, activities, or any other distinguishable features of a space. In Koutamanis' (1990) plan recognition system, the initial division of plan is along the wall of each room, and the consequent recognition procedures are based on the distinction of individual rooms.[1]

For the several reasons discussed below, the present version of ARPRAN uses the rectangular grid to initiate spatial categorization.

First, in ARPRAN's precedent analysis, the ultimate interest is not a description of those physically defined rooms and their relations in an

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[1] We are talking here about the central task of the first module of Koutamanis' CHAP system, which is to describe a plan as a set of locations that are virtually a set of rooms. We should distinguish the division of plan here with what discussed by Koutamanis (1990) as the "preprocessing" of the plan, that is, how to digitize a scanned image into abstracted binary image (pp. 60-64). For preprocessing, griding method is also used, but it is irrelevant to the griding we use in ARPRAN. It is conceivable that the preprocessing method developed by Koutamanis is also applicable for ARPRAN.

architectural plan. Instead, the goal is to represent the plan through selecting and categorizing information concerning the usage of all kinds of spaces (not only rooms, but also open spaces). Obviously, categorization based upon the usage of the spaces does not have to be confined by the physical boundaries of individual rooms. Therefore, the space primitives of categorization is not necessarily to be the natural rooms in a plan; it can be part of a room or a group of rooms. Yet, without following the physical divisions in a plan, it seems that there is no other effective way to initiate the division. In other words, the description of a plan has to be based on some divisions existing in the plan, although the divisions are not necessarily walls defining the rooms. Consequently, dividing a plan into grids according to divisions in the plan is a reasonably good approach (if not the only approach) to spatial categorization.

Second, division with rectangular grid is an approach to the schematization of the spatial relations. By using rectangular grid, spatial relations between the locations can be characterized with semantic distinctions in terms of *east, west, north* and *south*. Whereas, as was emphasized in the last chapter, these semantic distinctions are characteristic in spatial conception and representation in the environment of Beijing's old city, with which this version of ARPRAN deals.

Third, using rectangular grid as coordinating system for recognition and manipulation of architectural plans is a very practical method and hence a potentially generalizable method. This is not only because most architectural plans are orthogonal (Steadman, 1973), but also because rectangular grid is a basic framework in environmental recognition and development. Martin (1972) calls the grid of streets "the framework of urbanisation"; It is often a "controlling factor of the way we build whether it is artificial, regular and preconceived, or organic and distorted by historical accident or accretion" (p. 10).

Finally, from a computational point of view, the griding patterns and the corresponding location matrix is relatively easy to be processed. This is probably a reason why some early computation work on architectural plans has applied matrix representations (e.g., Hawkes & Stibbs, 1976).

8.2.3 Categorizing labels in the plan

In a labelled line drawing of plan, there are basically two kinds of labels, i.e., symbols expressing doors, windows, fences or low walls, and texts expressing names of spaces. Both kinds of labels imply the potentiality of how a built environment could channel activities, how it could be used or perceived—that is, imply the *operation* of the built environment. Therefore, the aim of label categorization is to get an organized morphological description of a built environment with respect to an operation and hence to the performance concerned by the task of precedent analysis (i.e., the target performance). Corresponding to these two kinds of labels, label categorization is also divided as symbol categorization and text categorization.

Text categorization

This is a process of organizing locations according to the attributes of spaces implied by their text labels. The attributes are distinguishable because of the basic semantic distinctions embedded in the conceptual structure. In other words, the text labels of space can be decomposed into semantic primitives expressed by *indoor/outdoor, circulation/utility* or *public/privacy*. For example, if a building in a courtyard house is labelled as "Principal Room," it is implied that every location within this building is, among others, an "Indoor" space and can be treated as an "Utility" space in respect to the circulation on the house level. Consequently, when the plan of the courtyard house is manipulated with an "Indoor, Outdoor, Semi-outdoor" (I-O-S) category system (this is instructed by the frame), the "Principal Room" is translated into "Indoor" and each location as part of that building can be treated as "Indoor" location (Figure 8-4). If the plan is processed with a "Circulation, Utility, Mixed" (C-U-M) category system, then, the same locations would be treated as "Utility."

The translation rules

Text categorization is carried out with a group of *translation rules* stored in the knowledge base and selected by the frame constructed at the begin-
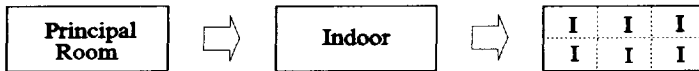
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| Principal Room | ⇨ | Indoor | ⇨ | I I I / I I I |

Figure 8-4 Every location is labelled with "Indoor" when a "Principal Room" is categorized as "Indoor" space

ning stage of each analysis. Translation rules are responsible for identifying the semantic attributes of each space and then, according to an instruction from the frame, imposing on the space a label out of one category system— for instance, imposing "Indoor"(I) on the "Principal Room."

In the present version of ARPRAN, the translation rules are simply expressed in the IF-THEN form and stored in groups. Which group of rules will be ignited in a particular situation, depends on the instruction from the frame. For instance, two groups of rules may be stored for courtyard house,

> (1)　IF "Principal Room," THEN "Indoor";
> 　　　IF "Wing Room," THEN "Indoor";
> 　　　IF "Side Courtyard," THEN "Outdoor";
> 　　　IF "Open Corridor," THEN "Semi-outdoor";
> 　　　. . .

and
> (2)　IF "Principal Room," THEN "Utility";
> 　　　IF "Wing Room," THEN "Utility";
> 　　　IF "Side Courtyard," THEN "Utility";
> 　　　IF "Open Corridor," THEN "Circulation";
> 　　　. . .

Using various category systems in label categorization is one of the most important notions developed by the thesis. Certainly, more careful investigation is needed on the category systems and translation rules. This would lead to a study on the semantics of various spaces.

Symbol categorization

This is a process of categorizing connective spatial relations between the locations. The present version of ARPRAN distinguishes three types of connective relations, i.e., (physically) ACCESS-TO (expressed in the LLD as "—"), VISUALLY-ACCESS-TO ("·······"), and IN-THE-SAME-SPACE-TO ("="); and these relations are only categorized as either relevant or irrelevant (to an operation). The irrelevant symbols are then eliminated during further transformation. For example, in learning "fitting the traditional urban fabric," when a constructed frame indicates that the building-space pattern in the old courtyard house is an aspect that should be described and the connective relations ACCESS-TO and VISUALLY-ACCESS-TO should be categorized as irrelevant to this aspect, both of these relations are then omitted (Figure 8-5).

The way of symbol categorization presented here is obviously a simplified method, which has been adopted primarily for the sake of scaling down the research problem. Ideally, the symbols should also be treated with more categorical variations.
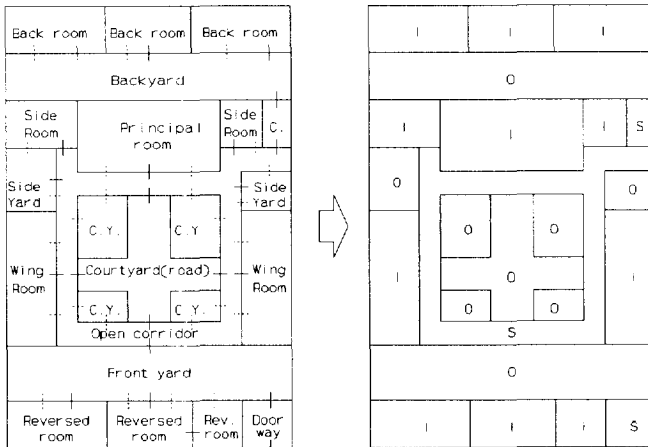
Figure 8-5 Relations irrelevant to a the target performance are eliminated during transformation

8.2.4 Merging locations and relations

Merging locations and relations is a subsequent process to label categorization; it is virtually the merge of columns or rows in a location matrix. Such an operation aims at simplifying the LLN local description while keeping the positional relations distinguishable. For the merger, *transformation rules* are responsible; they regulate which locations and hence which columns or rows of locations can be merged, and what will be the result of merger.

The transformation rules
The transformation rules can be divided into two groups: one group is for plan abstraction, another is for generalization.

During plan abstraction, when two columns or rows contain the same arrangement of locations, they can be merged into one column or row. Having same arrangement of locations is a necessary and sufficient condition for the merge of two columns or rows. In other words, if two columns or two rows can be merged, they must have the same arrangement of location but may not have the same pattern of relations between the locations. For instance, the two location columns in Figure 8-6 (a) can be merged into one because they have the same arrangement of locations, although the relations among the two rows of locations are not identical.

When two columns or rows are merged into one, the relations between the locations are merged too. If the correspondent relations in two columns or rows are identical, then they simply remain the same during the merge. If they are not identical, then their merge depends on the degree of the connectivity of the relations.

The three kinds of connective relations, i.e., VISUALLY-ACCESS-TO, ACCESS-TO and IN-THE-SAME-SPACE (they are respectively represented by the symbols "⋯⋯", "—" and "="), are considered as having different degree of connectivity: IN-THE-SAME-SPACE has the highest degree of connectivity and VISUALLY-ACCESS-TO, the lowest. When two different relations are merged into one, the result will be the relation with a higher degree of connectivity (Figure 8-6, c).
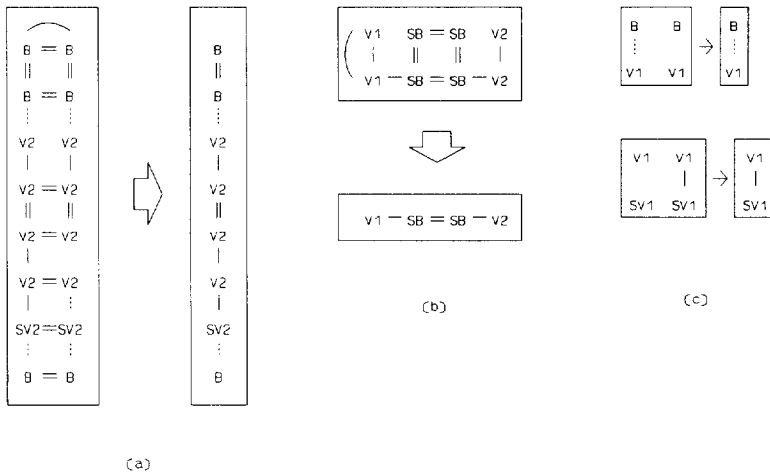
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Figure 8-6 Two location columns or rows can be merged into one, when they contain the same arrangement of locations

Similar transformation rules are applied also in the generalization stage of precedent analysis.

8.3 Generalization: from local description to global description

The third major operation of ARPRAN's perceptual module is "generalization," in which the local descriptions of the individual plans are compared and further categorized so as to form a generic description, called the *global description* of the LLNs.

A prerequisite for the precedent examples in architectural precedent analysis is that the examples must bear large similarity. This is not only a necessary condition derived from a similarity-based learning paradigm (see Chapter 6), but also a condition piratically available. In our design case, for instance, the precedents used for the specification of a particular perform-

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ance are all belong to the same type of buildings. For example, "privacy" is specified with walk-up apartment buildings, "community" is referred to with courtyard houses, etc.

Similarity among examples provides the basis for generalization. Recall Olson & Bialystok's (1983) notion that objects are perceived and patterns are judged as similar because they take the same structural description (see sub-section 7.2.1 of the thesis). We might also say that if a group of examples are known of having similarity, than they must be able to be described by the same structural description. Generalization is virtually a process of finding *the* structural description which makes the examples regarded as similar to each other.

The whole process towards the generic structural description has in fact partially fulfilled during the "plan abstraction" stage. For example, describing each plan with the same coordinating system (i.e., the griding system) and the same category system (i.e., I-O-S, or C-U-M, or B-SB-SV-V) can be seen as an operation that makes the plans share some common elements and hence comparable with each other. In other words, "plan abstraction" and "generalization" can be seen as two phases in the entire process of capturing the generic structural description; the two phases are respectively concerned with catching *elements* and their *organization*, two aspects of a structural description.

For catching the common organization, ARPRAN's "generalization" operation entails two recursive suboperations on the LLN local descriptions which have used the same category system: transformation and comparison (Figure 8-7). The general aim of these operations is to bring the LLNs describable by the same structural description.

Two kinds of transformation are probably needed in the generalization. First, the LLNs need to be transformed respectively so as to have the same number of columns and rows. This could be carried out by inserting columns or rows in those LLNs which have less elements, as presented in the example-studies in chapter 6.

Second, some of the locations in the LLNs may need to be re-categorized. In this case, those locations which have already been catego-
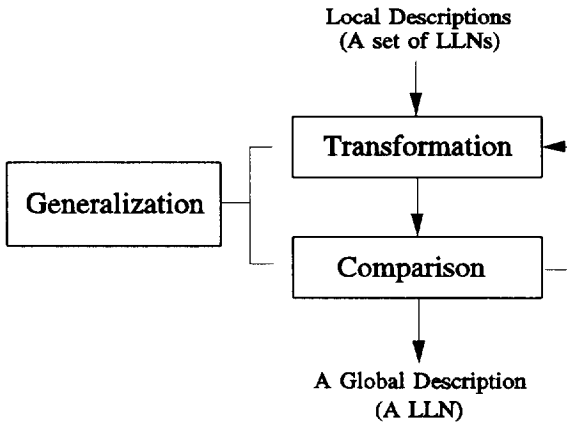
Local Descriptions
(A set of LLNs)

Transformation

Generalization

Comparison

A Global Description
(A LLN)

Figure 8-7 Generalization contains two recursive operations

rized as something between the basic semantic distinctions are re-categor-ized by using only the basic semantic distinctions. For example, "Semi-outdoor" locations may be re-categorized as either "Indoor" or "Outdoor" locations; "Mixed" locations, as either "Circulation" or "Utility."

Re-categorization
The purpose of re-categorization can be understood, again, through the general objective of precedent analysis and the particular purpose of abstrac-tion. As was indicated earlier, precedent analysis is virtually a process of searching for a structural description which can be applied to all the prece-dent examples concerned. We may think of this process as being conducted through a step-by-step abstraction. Each step of abstraction brings to the precedent examples some common elements and makes their descriptions more close to the common structural description we are searching for.

Of course, the most abstracted structural description applicable to all precedents may be something like: "There are locations." Obviously, this kind of analysis is virtually of no use in the design synthesis for which the precedent analysis serves. Therefore, a principle for analysis is to find the

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least abstracted description which however is applicable to all the precedent examples concerned. This principle can be further explained with the three similar plans in Figure 8-8. A least abstracted structural description that is applied to (a) and (b) may contain three kinds of locations: "Indoor"(for buildings), "Outdoor"(for courtyards), and "Semi-outdoor"(for open corridors). However, such a description can not be applied to (c), because it has no corridor. Therefore, to cover all three plans, a least abstracted structural description should not contain "Semi-outdoor" locations. The semi-outdoor locations in (a) and (b) must be re-categorized into "Outdoor" or "Indoor" in order to get a global description for all three plans.

(a)   (b)   (c)
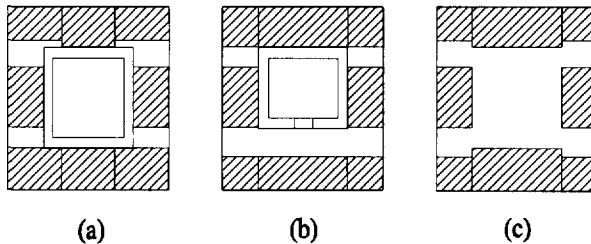
Figure 8-8 Three plans of courtyard house, (a) and (b) with open corridors, (c) without corridor.

LLN descriptions in which locations are categorized with only the basic category distinctions can be considered more abstract than those in which locations are categorized with not only the basic categories but also some categories in between. Therefore, as a first step of categorization, locations are naturally categorized with more categories (e.g., I, O, S). If based on this categorization a common structural description could be found, then it is not necessary to conduct a re-categorization. Otherwise, a re-categorization is needed in order to find the structural description at a more abstracted level.

8.4 Summary

Architectural precedent analysis is a spatial categorization process directed by a frame which is constructed on the base of pre-existing knowledge. "Frame construction," as the first major procedure of ARPRAN, is to establish a set of principles which connect the target performance to their precedent examples. The frame is responsible for selecting rules for "plan abstraction" and "generalization," two other major procedures of ARPRAN. This is an application of the top-down principle of visual perception.

In contrast, "plan abstraction" and "generalization" can be seen as two operations in a bottom-up process. Plan abstraction is to turn a LLD plan into a LLN local description through dividing a plan into locations, categorizing the labels in the LLD, and merging the locations. Generalization is to form a global description on the basis of the local descriptions.

Chapter 9
Concluding Remarks
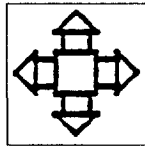
This chapter summarizes the major ideas, contributions and limitations of the thesis. In the final section, the potential extension and generalization of the present work will be discussed.

9.1 A reasoning approach to the use of architectural precedents

It was pointed out at the beginning of Chapter 1 that this work aimed to describe from a computational perspective the characteristic features of precedent knowledge and its usage in architectural design. Towards this end, one might proceed with two completely different approaches, i.e., a *retrieving* approach versus a *reasoning* approach. With a "retrieving approach," a work would describe how precedents could be decomposed simply into a number of elements or rules, stored orderly in a database and retrieved passively for use. With a "reasoning approach," however, a work

describes how precedent knowledge is actually used in a design, how a precedent could be analyzed according to a particular design task and how a system could learn precedent knowledge according to given examples and instructions. Obviously, it is the reasoning approach that has been followed by this work. A number of ideas are central to the reasoning approach:

(1) Architectural precedent analysis is an indispensable procedure for most architectural design actions. Particularly, it is useful for the specification of non-quantifiable objective, for precedent-constrained design and for design by analogy (Chapter 2, 5).

(2) Morphology, operation and performance of built environment constitute a model of precedent knowledge. The architectural precedent analysis is a process of finding the morphological description that may plausibly account for a known perform-ance (Chapter 2, 4).

(3) Architectural precedent analysis is a learning process, in which new principles for design are learned from precedent examples. Thus, a system for precedent analysis can be treated as a machine learning system that uses both inductive and deductive learning methods (Chapter 6).

(4) A learning system for architectural precedent analysis, how-ever, requires representational tools different from most of commonly studied learning systems, because it must deal with spatial representation which is central to the architec-tural domain (Chapter 6).

(5) Spatial representation is founded on some cognitive prin-ciples. Architectural precedent analysis can be regarded as spatial categorization, basically a process of turning imagery-based depictions of precedents into proposition-based struc-tural descriptions of the precedents (Chapter 7, 8).

(6) As an important feature, the structural description of built environment entails semantic distinctions among both

locations and their relations. These semantic distinctions make a description meaningful with respect to the performance of a built environment (Chapter 7).

(7) Semantic distinctions are basic perceptual biases towards the recognition of architectural space. Such distinctions—for instance, the distinctions between *indoor/outdoor, private/ public, circulation/utility, east/west, north/south*—should be constructed in the knowledge base for the architectural precedent analysis (Chapter 7).

(8) Architectural precedent analysis is a plan recognition process entailing both bottom-up and top-down processes. As a top-down process, a frame is constructed and rules are selected for plan transformation. As a bottom-up process, plans are transformed step-by-step in order to be describable by a structural description (Chapter 6, 8).

These ideas have been developed from the study of a practical architectural design case and exemplified through a sketchy design of a knowledge-based computer system, ARPRAN (ARchitectural PRecedent ANalyst). The case selected for study is the design of the "new courtyard house" in Beijing's old city, in which architectural precedents have been used and analyzed successfully according to particular design objectives (Chapter 2). The design of ARPRAN is based on the reconstruction of two precedent analysis processes extracted from the design case (Chapter 6).

ARPRAN is proposed to be able to produce—according to the plans of precedents—pre-parametric descriptions of spatial organization that may account for a given performance of built environment. It accepts as input a target performance, a group of plans in the form of labelled line drawing (LLD) and an operationality criterion, and returns as output one or several labelled location net(s) (LLN). Three major procedures, "frame construction," "plan abstraction" and "generalization," constitute the plan recognition process of ARPRAN (Figure 9-1).
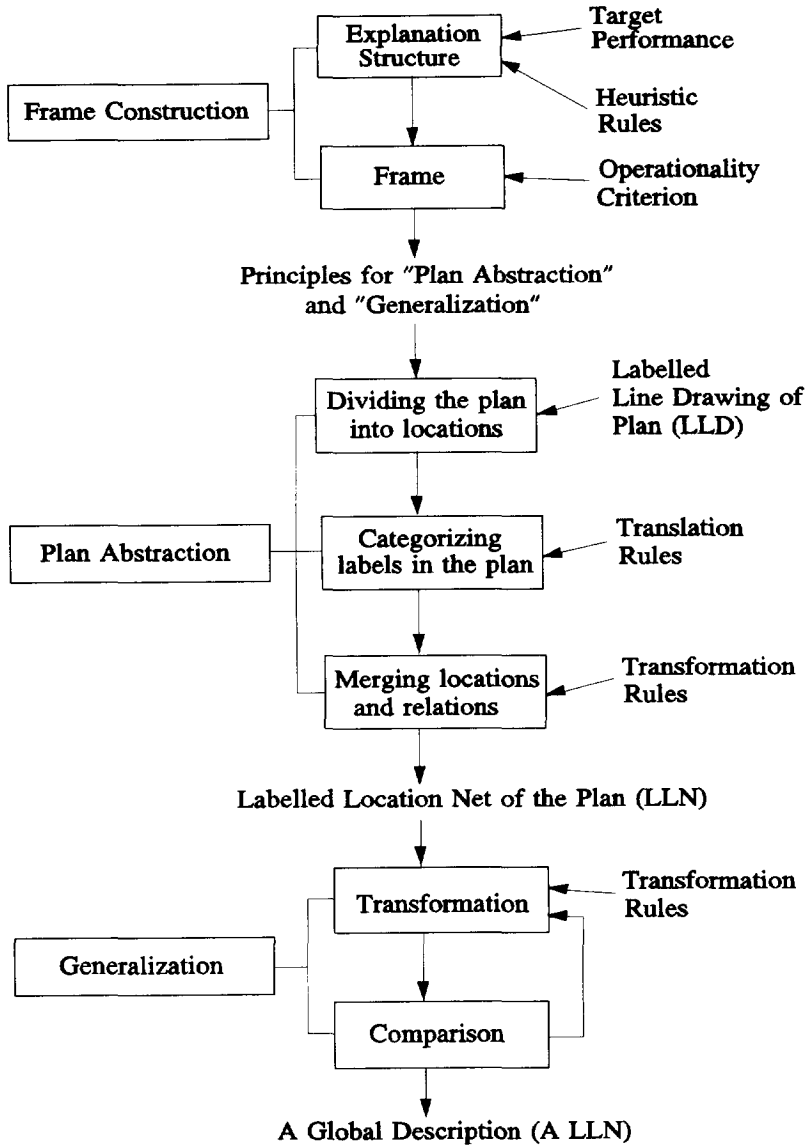
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Figure 9-1 The plan recognition process of ARPRAN

9.2 ARPRAN and the Intelligent Architect

The result produced by ARPRAN is expected to be used by a design system. An example of the design system is the *Intelligent Architect*, a system for the automated production of design solutions on the basis of a collection of stored precedents. The potential contribution of ARPRAN to the Intelligent Architect can be understood in comparison with that of CHAP, the plan recognition system proposed by Koutamanis (1990).

CHAP is designed to select architectural plan of precedents for the Intelligent Architect. The basic capacity of CHAP is to evaluate the well-formedness of an architectural plan with respect to the principle of tripartition, one of the principles of classical canon advanced by Tzonis & Lefaivre (1986) (see Chapter 3). Compared with the systems based on the rectangular dissections of plan, shape grammars or similar techniques, CHAP is evidently a more comprehensive tool because it is integrated in selection with "high-level" formal recognition and analysis (i.e., three partitioning principle), and may improve the ability to match programmatic requirements with precedent solutions on more abstract levels and hence more efficiently. Yet, compared with CHAP, ARPRAN seems to be a more promising system.

First, ARPRAN selects and analyzes plans of precedents according to not only stylistic criteria but also the possible operations and performances the plan may offer. This ability of ARPRAN has been expected by the developer of CHAP. Yet, it is unclear how CHAP correlates morphological aspects with performances other than stylistic requirements.

Second, ARPRAN can not only select plans from a database, but also process selected plans into abstracted descriptions which may be used directly in design synthesis. This capacity of ARPRAN results from its reasoning or learning approach. In contrast, the way CHAP selects precedent plans is still somewhat a retrieving approach, despite that CHAP uses "higher-level" formal criteria which have been less considered by most other retrieving systems.

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9.3 On the generalizability of the approach

In this work, the approach to architectural precedent analysis is developed on the basis of a particular design case, the design of the "new courtyard house." A question would be consequently raised: How generalizable is the approach? Indeed, the generalizability of the approach is questionable; it would be a major limitation of the approach presented in this work.

Although it has been emphasized that the case selected for study is typical in terms of the use of architectural precedent in design, we must recognize that by opting for the case of Beijing's old city we have in fact largely limited our investigation scope. For instance, the built environments in this case, either the precedents or the new design, have exclusively orthogonal plans. Then, what about the non-orthogonal environment? More-over, We have identified a number of semantic distinctions for the description of precedents. Are these semantic distinctions applicable to the other cases? Are they culture-bounded or cross-cultural? To answer these questions we have to enlarge our investigation scope to include many other cases and probably we need to introduce another investigation approach rather than the case study method currently adopted in this work.

Nevertheless, we should never underestimate the importance of the case study method, although the generalizability of the result out of such a method may be questionable. As was emphasized before, architectural design is application-oriented and diverse in nature; it is hence difficult to talk of an "architectural design problem" abstractly. Case study, however, allows one to specify the design task and to focus in depth and in detail on the domain problem without loosing applicability. The case-study method is particularly important to development of the reasoning approach to the use of architectural precedent, because an essential principle of the reasoning approach is that precedent analysis must be closely related to a particular design task.

The generalizability of this work would be hardly satisfactory if we only gaze at the specific procedures or rules developed according to our

case study but ignore the principles underlying those details. In effect, the most important role the case plays is a *heuristic device* to understand the use of precedents. McNeill (1985) asserts, the value of a case study lies at that it "may prompt further, more wider ranging research, providing ideas to be followed up later." Indeed, through the case study in this work we did find some useful notions associated with the use of precedents; their usefulness lies at their encouragement for new investigations.

9.4 Future work: generalization and extension

In addition to the limitation on generalizability, there are some other limitations in this work. Like many other research work, the limitations of this work are precisely caused by the investigation scope adopted by the work. Therefore, any effort aimed at enlarging the scope of the present research would contribute to the extension of the present work. As I would suggest, there are several potential directions in which extension work could be carried out.

Generalization test
The approach developed in this work is based on a specific design case. Although the design case has displayed strong typicality in using precedent knowledge, a question still remains: Is the approach developed in this work generalizable enough? To answer this question, the best way is to test the approach with some other design cases.

Extension in computation
The approach developed in this work is confined to the investigation level of computational theory. Questions related to this level of study can always be asked: Is this approach feasible with respect to the available computing techniques and devices? Is this approach efficient enough? To answer these questions, studies at an algorithm level is required.

Extension in spatial semantics

This work has inferred some basic semantic distinctions for the recognition of architectural space, such as indoor/outdoor, private/public, etc. Certainly, they are far less than the whole primary elements that necessarily related to architectural thinking; more such elements are expected to be identified.

Extension in pattern recognition

A necessary procedure at the outset of precedent analysis is the recognition of the usage of architectural spaces. In this work, this procedure has been simplified by using labelled line drawings (LLD) as the input of analysis. In the LLDs, the usage of each space is explicitly indicated by a text label. However, it would be more practical if interpretation of the usage of spaces could be made directly from a conventional architectural plan depicted with more details. In this case, an additional sub-module is required to be developed which could recognize the drawing details in a plan and translate them in into texts or symbols which describe how each space is used. The design of such a sub-module has not been considered in this work, but it can be an extension of the work.

Appendix A
Beijing's old city and
its development

Today's old city of Beijing (about 62 km^2) was formed in the Ming (1386 ~ 1644) and the Qing (1644 ~ 1911) dynasties, and was constructed by transforming Dadu of the Yuan dynasty (1271 ~ 1368). As a work of art, the old city strikingly presented the classical Chinese city-planning principles, which were characterized by walled enclosures, rectangular layout, strong axises, north-south orientation and the grid network of streets.

The plan of Beijing's old city is clear and easy to grasp (Figure A-1). It had four main walled enclosures: the Outer City (7950m x 3100m) to the south, the Inner City (6635m x 5350m) to the north, the Imperial City within the Inner City and within that again the Forbidden City. Today, the walls of the Forbidden City are still well-preserved but the walls of the other three enclosures no longer exist.

The whole city is centred by a south-north axis (8 km long), along which all important buildings are organized. To stress the supremacy of the emperors, the Forbidden City, with the royal palaces in it, is located at the central part of the axis. In the old times, the closed Imperial City formed an enormous barrier to the east-west traffic in the Inner City. Behind the Forbidden City, is the 50 metre-high Jingshan hill, which was the highest point in the city.

The street system of the city is composed of several main streets stretched out from the city gates, a number of sub-streets and hundreds of lanes (or *Hu Tong*). This street-lane system, together with large amount of gray-colored courtyard houses, composed the unique vernacular scene in Beijing's old city.

A. Inner City
B. Outer City
C. Imperial City
D. Forbidden City
1. Tiananmen
2. Imperial Ancestral Temple
3. Altar of land and Grain

4. Jingshan Hill
5. West Garden
6. Altar of Heaven
7. Altar of Earth
8. Altar of Sun
9. Altar of Moon
10. Altar of Agriculture
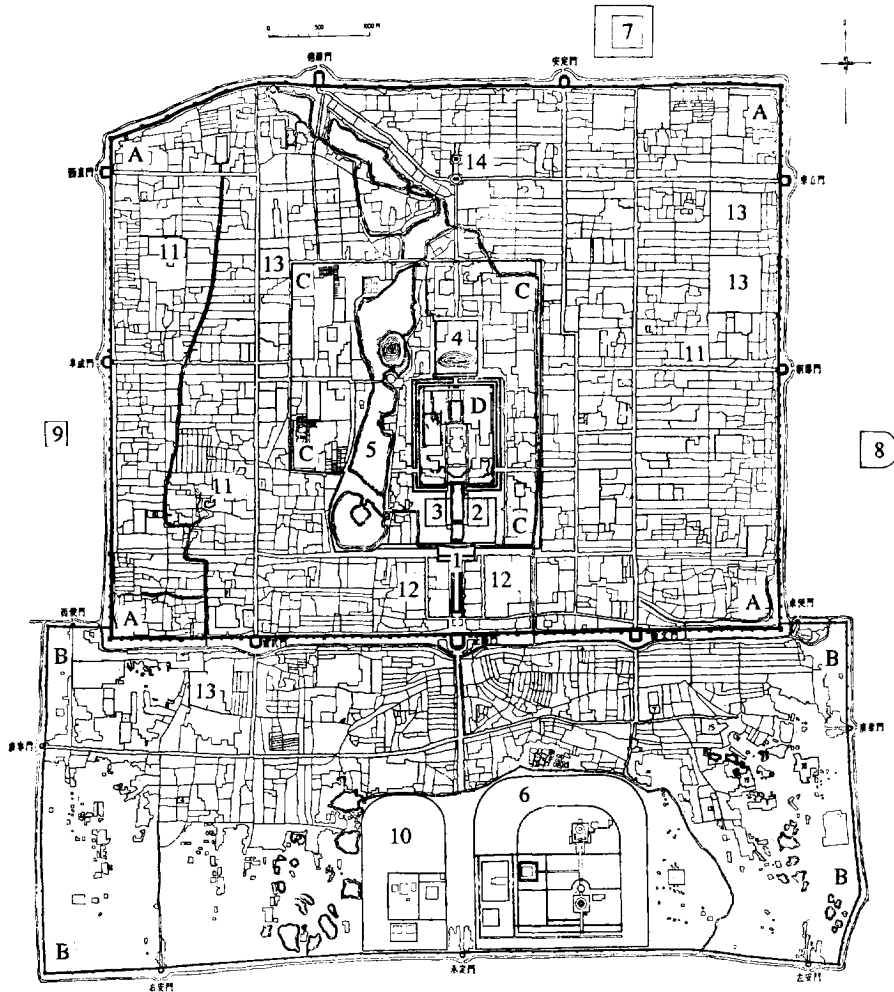
11. Residences of Princes
12. Government Office
13. Warehouses
14. Bell and Drum Towers

(Chinese characters refer
to gate names)

Figure A-1 The Ming and Qing's Beijing City (Source: Liu, 1980)

A brief history of Beijing

The urban history of Beijing started more than 3000 years ago (Tong *et al.*, 1985). In the third and fourth centuries, B.C., Beijing was ever the capital of Yen, one of the "Warring States." In 1153, Beijing was chosen again as the site of a capital city, when Zhongdu of the Jin dynasty was built (Figure A-2, a). In 1264, a new city centred on a palace to the north-east of Zhongdu was built by the Yuan dynasty. Years later this city became the capital of the Yuan, known as Dadu, or the Khanbalik City. According to historic records, around 1293, the city was already a flourishing metropolis (Figure A-2, b).

In 1403, the Ming dynasty decided to move its capital to Beijing and started the construction of Beijing City. Ming's Beijing City was transformed from the city of Dadu. The major transformation included the southerly parallel movement of the city walls and the reconstruction of the Imperial City. In 1421, Beijing City (the Inner City) became Ming's capital.

In the 16th century, a large area of residential and commercial was formed outside the southern wall of the Inner City. A larger walled enclosure, later called the Outer City, was then proposed to surround the Inner City. However, the construction of the Outer City was not completed as it was planned because of the financial problems. This resulted in the present shape of Beijing's old city (Figure A-2, c). By the end of the Ming dynasty, the total population in Beijing City was already near to one million.

The Qing dynasty (1644 ~ 1911) inherited entirely Ming's Beijing City as its capital. While there was no much change in the urban structure, most of the buildings have been rebuilt during the Qing. In the times of the Republic of China (1911 ~ 1949), only part of the buildings were rebuilt.

In 1949, Beijing became the capital of the People's Republic of China and since then a series of planned, large-scaled reconstruction projects have been carried out. Among the major changes in the old city, are the demolition of the city walls, the expansion of several east-west streets and the construction of the Tiananmen Square. Present development of Beijing is directed by a master plan which was formally adopted in 1982 (Figure A-3).
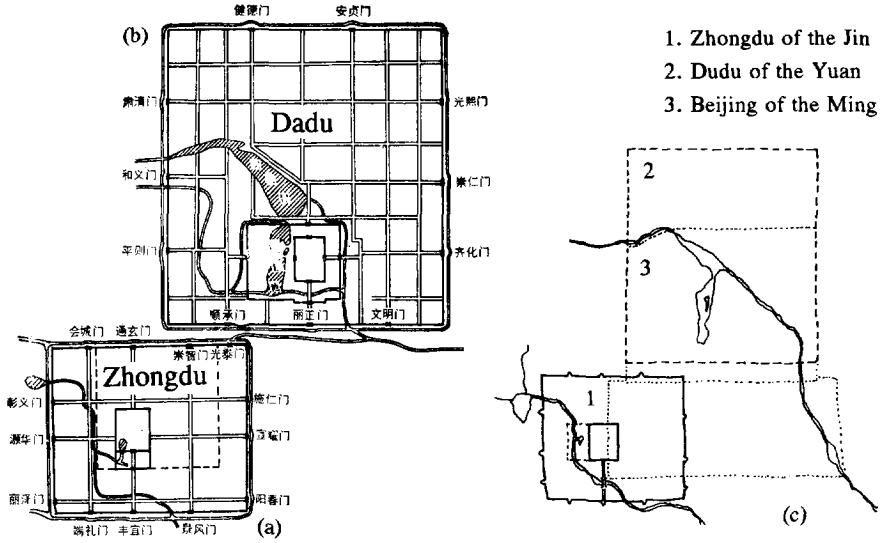
Figure A-2 (a) Zhongdu of the Jin, (b) Dadu of the Yuan
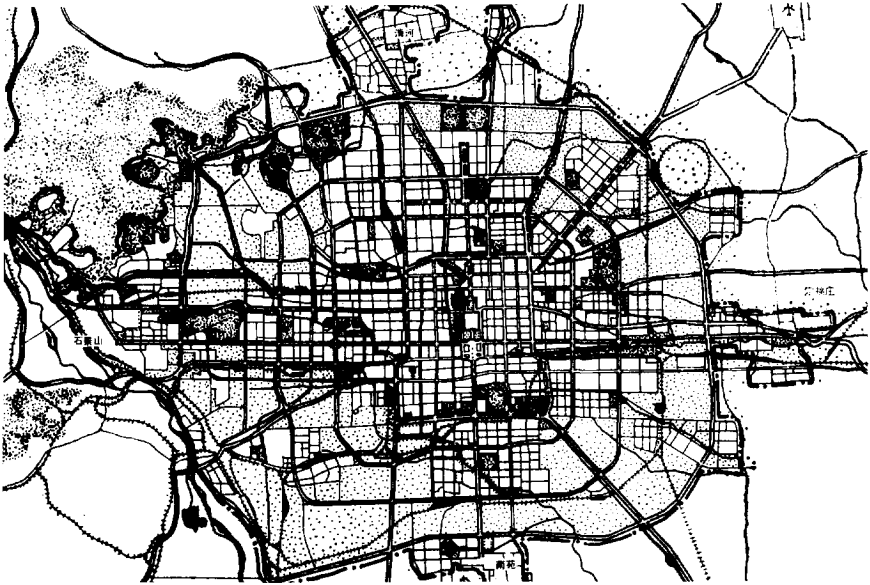and (c) The spot change of the cities

Figure A-3 The master plan of Beijing, formally adopted in 1982
(Source: Tong *et al.*, 1985)

Appendix B
The "new courtyard house"
project and its background

Since 1978, a series of studies of Beijing's urban development have been carried out in the Department of Architecture (now School of Architecture) of Tsinghua University, in cooperation with the municipality of Beijing and several governmental planning and construction agencies. Through out the studies, a general strategy for the rehabilitation of the old city and some design concepts of the "new courtyard house" type have been gradually formulated. As a result, in 1990, an experimental housing compound (with 2760 m^2 total floor area) based on the "new courtyard house" concept was realized at Ju'er Lane, in cooperation with Beijing Housing Reform Office and Beijing East District Government. Following is a summary of the project and its background.

B.1 The problems with the old houses

The reconstruction and preservation of Beijing's old city were started in as early as 1949. However, the work was focused mainly on the monumental buildings, the public areas and some large residences; the treatment of the mass ordinary courtyard houses in the old city has long been a problem under careful study.

This problem, however, appeared more and more eminent in the late 1970's. First, the living conditions in the old houses declined swiftly. Second, many new constructions were carelessly inserted in the old city by simply demolishing the old houses; this seriously damaged the unique

feature of the old city. Third, the inappropriate housing investment policy resulted in serious financial shortage in housing renewal.

Decline of the old houses

By the time of 1976, 90% of the population in Beijing's old city were still living in the traditional courtyard houses. These houses were characterized by high density of residents, small indoor spaces and shortage of service utilities (kitchens, toilets, etc.).

Before 1976, most of the houses still had relatively satisfactory outdoor environment: the spacious courtyards, the abundant sunshine, the activity places for children and elders. However, after a big earthquake in 1976 near Beijing, the situation in the old houses was swiftly worsen. This was not only because some of the old buildings have been damaged by the earthquake, but also because most of the courtyards were filled with temporary "anti-earthquake sheds" and these temporary sheds were gradually turned into permanent constructions as the extension to the crowded living space. Consequently, the building density largely increased and the living condition sharply declined. Most courtyard houses virtually lost their courtyards (Figure B-1).

The built area:

(a) 2440.5 m² in 1949
(b) 3196.5 m² in late 70's
(c) 3786.5 m² in 1987
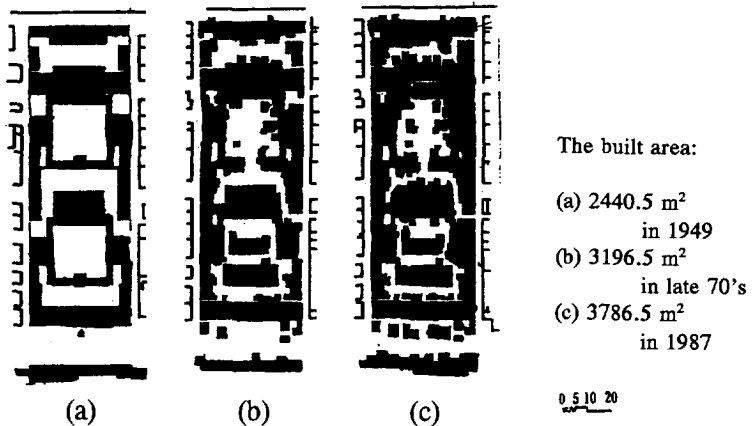
Figure B-1 The decline of the traditional courtyard house: an example (Source: Wu, 1989)

At the same time, many structures were collapsing, the drainage systems in the courtyards were out of work and the roofs were leaking. A survey in 1983 indicated that there were 29 decayed areas in the old city, covering 435 hectors of land and 1.9 million m^2 of floor area (Zhang *et al*, 1983).

Careless new constructions
Lacking of a well-studied strategy of urban renewal in the old city, the development of the residential areas were mainly based on mass construction of walk-up apartment blocks or careless insertion of such buildings in the old neighbourhood. Although few projects of mass construction have been carried out in the old city, they had shown a dangerous tendency of destroying the harmony and unity of the historic city (Figure B-2).

Though several old areas had been designated as the preservation zones of traditional courtyard houses, the building area under such legal preservation was only more than 0.3 million square metres, which took only a small part of the total area of the old houses—more than 10 million square metres—in the whole city. Obviously, if no appropriate measure was taken, most of the old sectors would be gradually changed into featureless areas and this would be a disaster to the historic city.
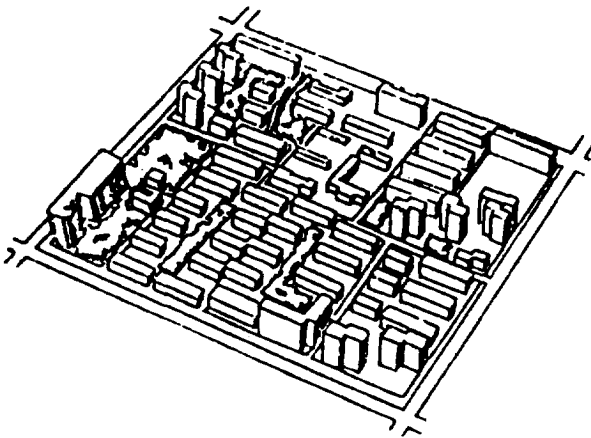
Figure B-2 A new area in the old city resulted from the mass construction of the common walk-up apartment blocks (Source: Wu, 1989)

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Inappropriate housing policy

In China, houses have for long time been a kind of social welfare supplied by the government to residents at an extremely low rent. The rent revenue was usually too less to support the maintenance of houses, let along the reimbursement for the construction investment. Such inappropriate housing policy left large amount of decaying houses in Beijing's old city unable to be repaired or replaced. Of course, to solve this problem thoroughly was a matter related to the entire economic reform undergoing in China, but urban renewal of the old city had to be started by introducing some new systems of housing investment.

All the problems suggested that it was urgently needed a careful study on the renewal of the residential areas with respect to the preservation of the old city. A new strategy must be searched and the old paradigms of construction should be given up.

B.2 A strategy of urban renewal

Since 1978, a general strategy of urban renewal in Beijing's old city has been explored through a series of studies, including the research on the Master Plan of Beijing, the urban design of an area in the old city and the design and improvement of the concept of the "new courtyard house." Some key principles have been summarized by Wu (1989):

The integral conservation of the old city calls for continuity in the courtyard building system

The conservation of historic cities should not be narrowly understood as the preservation of a few monumental buildings. More attention should be paid on the integral conservation of the organic order of urban environment. The order of Beijing's old city is based on the courtyard building system, in which individual buildings are relatively simple but courtyards have rich variations. Such a building system is very different from the building systems in most of the Western cities, in which the building facades are colour-

ful and variable. It is the distinctive building system rather than the individual buildings should be in the focus of conservation.

The law of "organic replacement" should be applied
A city is always metabolizing. As the cells of a city, houses need to be replaced from time to time. At any time, the relatively good houses should be remained, and the bad ones be replaced. It is normally conducted by inserting new cells in an old tissue. Only very occasionally, a large operation is needed. This is the order of urban reconstruction. In Beijing, most of the houses could not be preserved as historical relics as those in the European cities (because there are differences in the quality and the tissue), nor could them be completely removed and replaced by new sectors as those in Singapore. The "organic replacement" seems to be the best way.

The new prototypes of courtyard house are required
Obviously, the traditional courtyard houses, as the production of the old society, can not perform properly as a common dwelling type for nowadays. They are destined to be gradually abandoned during social development. However, it is conceivable to develop a new type of courtyard house which is based on the traditional urban fabric but meets the contemporary living standard. The new type of courtyard house should provide enough privacy for the families as the walk-up apartments do, while keep the community atmosphere provided by the courtyards. It should also accommodate nearly as much residents as usually in the walk-up apartments, otherwise it has no enough competitive capacity.

The original community structure should be kept
Urban renewal in Beijing's old city should avoid mass immigration of the local residents to the suburb areas. At least, in the near future, immigration should not be taken as a major policy. On the one hand, less immigration, can reduce the pressure on the traffic and the land use. On the other hand, it can keep the original community structure in the old city. In order to reduce immigration, local residents should be encouraged to move back

after renewal. This can be achieved by encouraging local residents to purchase the new houses.

B.3 The project at Ju'er Lane

In 1987, Ju'er Lane was chosen as an experimental site for implementing the urban renewal strategy and the concept of the "new courtyard house." The first phase experiment was carried out in the courtyard No. 41 and several neighbouring small courtyards, where 139 residents in 44 families were living (Figure B-3, 2-3). This was a typical decayed courtyard house area urgently needing renewal and it was considered an ideal site of experiment. For example, the living conditions in the courtyard No. 41 was very poor: the building density was as high as 83%; 2/3 of the families had no sunlight; nearly 80 people shared only one water tap and one sewer; a public toilet was a hundred metre away from the courtyard. In addition, the hight control of this area was 9 metres, appropriate for implementing the new concept of courtyard house, which was characterized as a low-rise building with high density of floor area. Finally, the residents welcomed the reform in housing investment and were willing to purchase the new houses.

The construction work of the first experimental compound started in October, 1989 and finished in May, 1990. The new compound (with 46
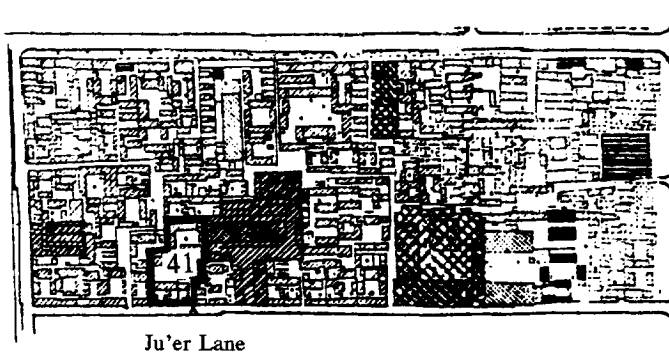
Ju'er Lane

Figure B-3 Ju'er Lane area and the site of first experimental project

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living units) has four courtyards, including two larger courtyards surrounded by two- and three-storied buildings and two smaller courtyards with only two storied buildings (Figure B-4). The buildings are characterized with white walls and dark grey tiled roofs. Each living unit has a private outdoor space (a balcony, a roof terrace or a garden). In the larger courtyards, two old trees have been preserved, which contribute largely to the intimate atmosphere in the new courtyards. Table B-1 is a comparison between the new compound and the old courtyard.

Table B-1 The site situation of the first phase experimental project before and after renewal (Source: Wu, 1991a)

	Before renewal	After renewal
Land area	2090 m² (7 courtyards)	2090 m² (4 courtyards)
Number of households	44	46
Total floor area	1085 m²	2760 m²
Average living floor area	5.2 m²/person	12.0 m²/person
Number of rooms	64	92 (excluding halls)
Plot ratio	1:0.8 (including self-constructed buildings)	1:1.32
Number of storey	1	2~3
Living standard	26.66 m²/family; 1.45 room/family	60 m²/unit; 2 room/unit (8 one-room units: 39~49 m²/unit; 28 two-room units: 54~66 m²/unit; 12 three-room units: 66.5~76 m²/unit)
Service	No private toilet, no private water supply, no central heating system	Private kitchen, toilet; central heating system
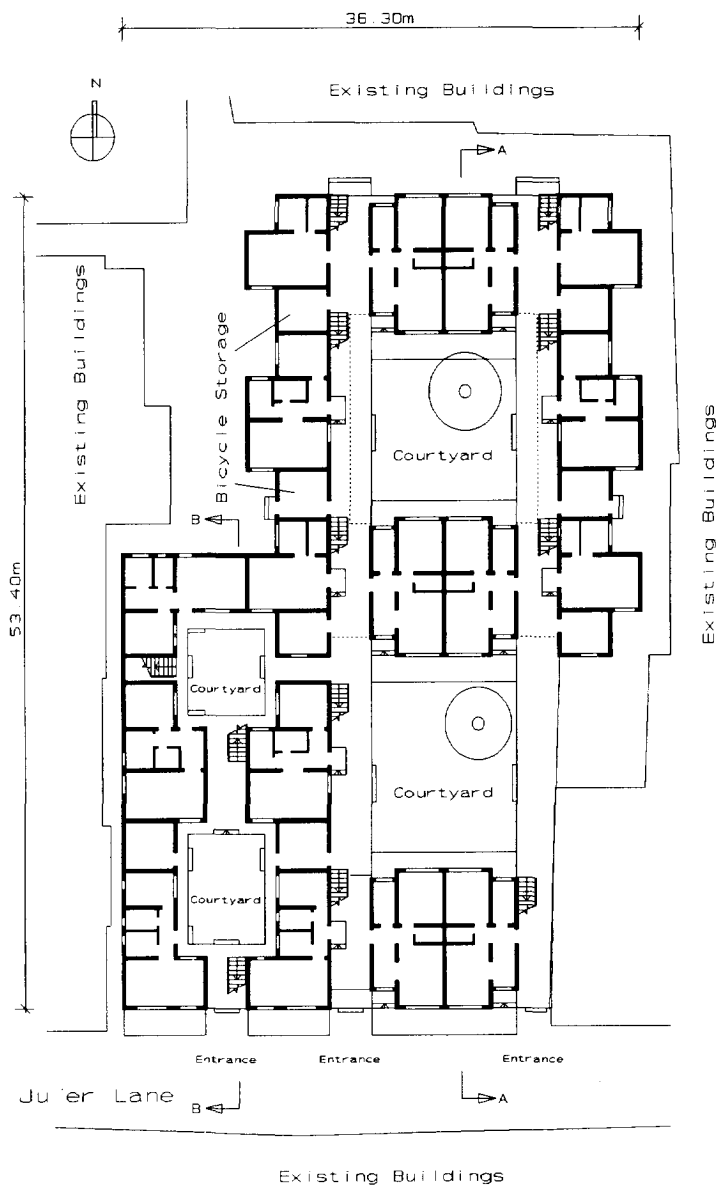
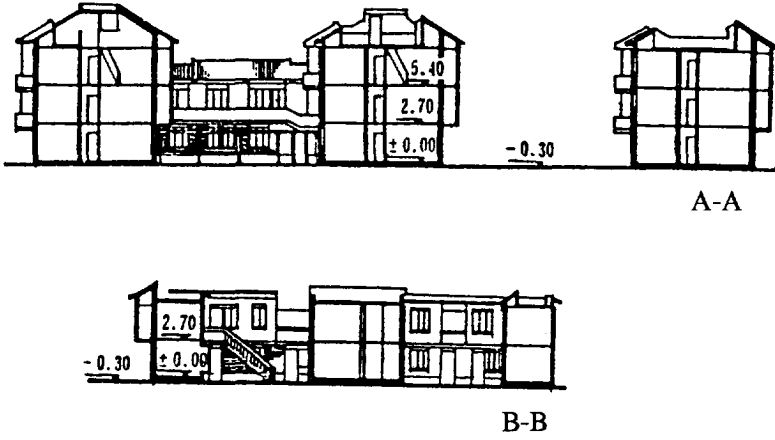**Figure B-4** (a) The ground plan of the first phase experimental compound at Ju'er Lane (Redrawn after Wu, 1991b)
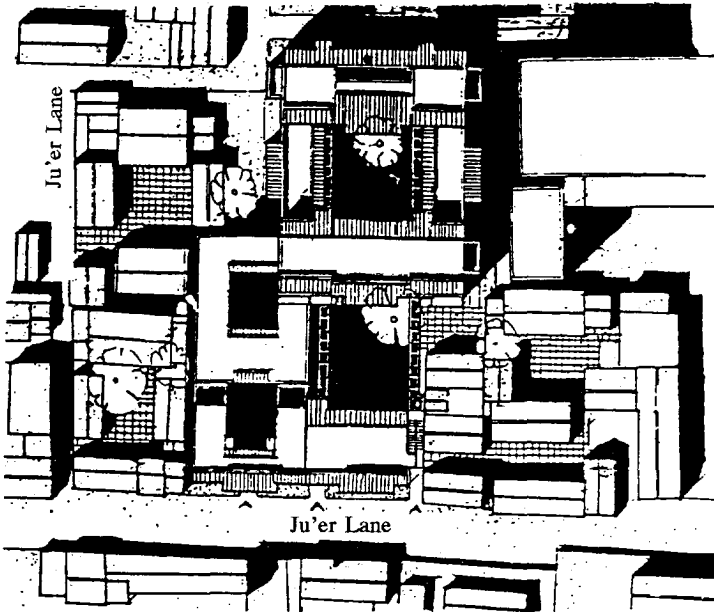
Figure B-4 (b) Sections A-A, B-B (Source: Wu, 1991b)

Figure B-4 (c) The site plan (Source: Wu, 1991b)

B.4 Evaluation of the project

The first phase experimental project at Ju'er Lane started gaining attention from both home and abroad even before its construction work was finished. In both the public and the professional opinions, the project has been a successful one because it has provided an effective approach to urban renewal and housing design. For Beijing's municipality, the project has been regarded as a model for future work (Bai & Wu, 1992). Started in 1987, the experiment at Ju'er Lane has been continuing at an increasing scale. After the first phase experiment (46 living units), the second phase (160 units) was completed in 1992 (Figure B-5) and the third is still going on. A much larger area is also under planning and design in some other quarters in Beijing's old city.

Existing Building

The First Phase   Ju'er Lane
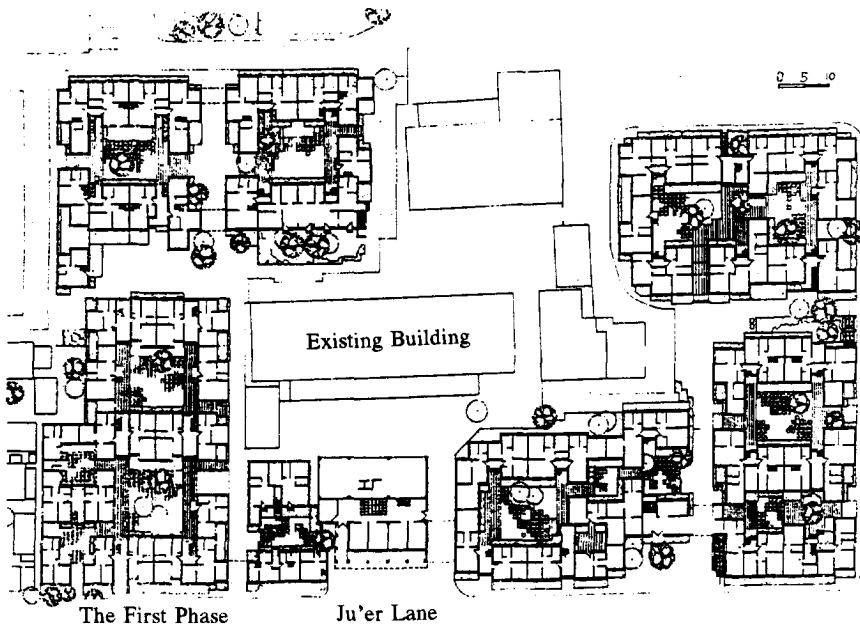
Figure B-5 *The second phase experimental project at Ju'er Lane*
(Source: Wu, 1991a)

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A sampling survey of the residents in the first experiment, made in 1992, after one-year occupation, has shown that the design objective of improving the living quality has been realized satisfactorily (Liu, 1992). Here are some data out of the survey:

On density
83% of the residents consider the basic courtyard (15m x 13m, surrounded by 30 living units, 3-storied buildings in north/south and 2-storied buildings in east/west) has a good atmosphere of living; no one thinks the courtyard has accommodated "too many households." 96% feel the courtyard is "not crowded" or "crowded only occasionally (mainly in the weekend)." However, 15% of the households (mainly at the ground floor) are not satisfied with the natural lighting of their living units.

On privacy and security
67% of the residents feel the environment is quiet. 70% close their window curtains only in the evening. These show that the visual and auditorial disturbance has been kept at a satisfactorily low level. In the old courtyard house, quarrels between the residents are often caused by the ambiguous borders between the private territories; in the new building, such quarrels have totally disappeared. In addition, 89% of the residents consider it is safe to live in the new building.

On community
After one-year living in the new building, 46% of the residents consider the new courtyards where they are living as their own neighbourhood, while 35% think their neighbourhood include not only their own courtyards but also the whole Ju'er Lane. 19% do not think they have a fixed neighbourhood, but they still have the sense of living in a community. 46% of the residents can identify almost all the people living in their neighbourhood; 29% can recognize some. Each resident has been well acquainted with at least 2 neighbouring families.
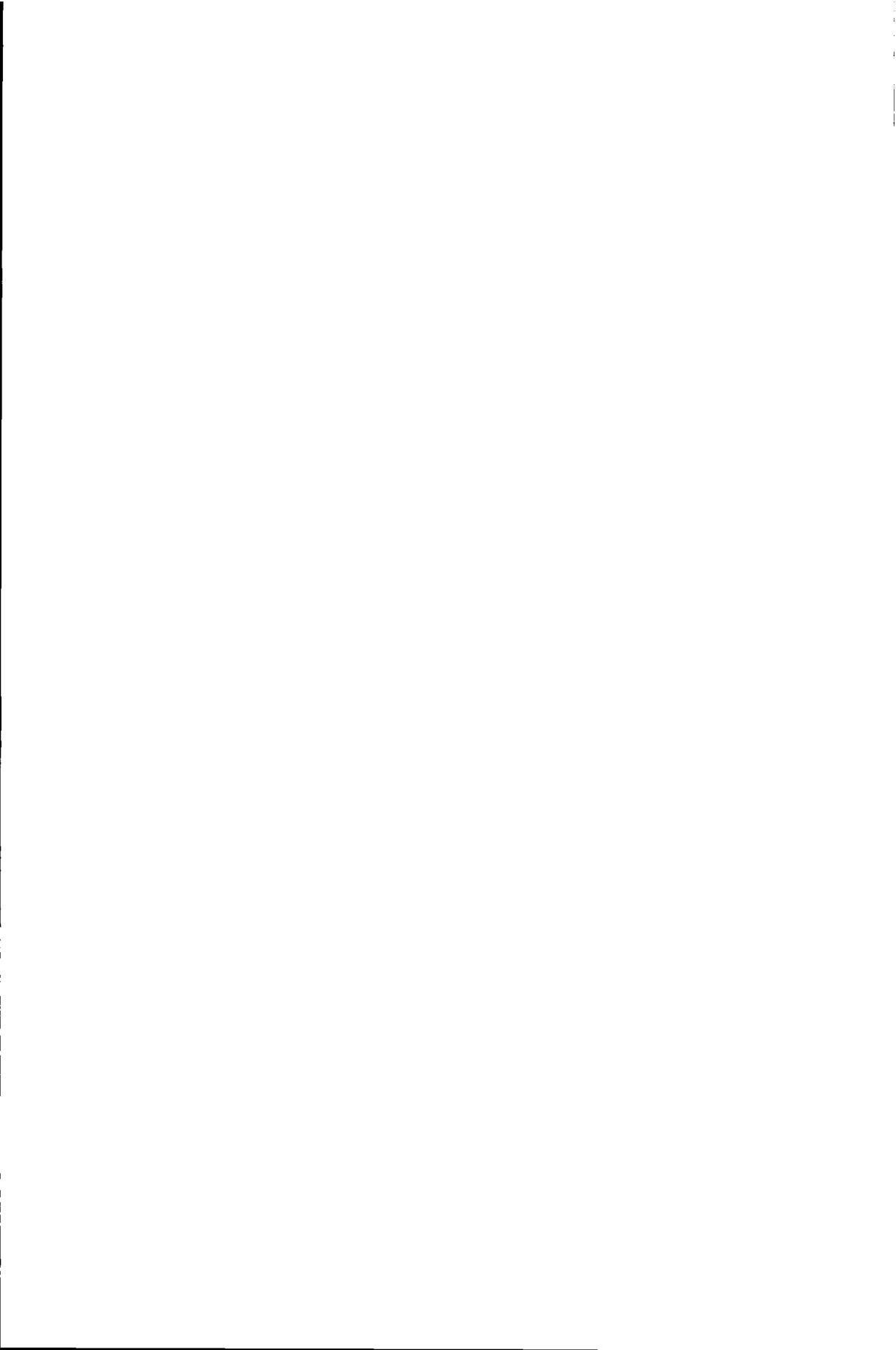
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Samenvatting

Het proefschrift presenteert een aanpak voor het gebruik van precedenten kennis voor het architectonisch ontwerpen door onderzoek van de computationele theorie van een systeem voor architectonisch precedenten analyse. Enkele ideeën zijn centraal te benaderen:

(1) Architectonisch precedenten analyse is een onmisbare procedure bij de meeste architectonisch ontwerp uitvoeringen. Het is met name nuttig, voor het specificeren van niet kwantificeerbare objectieven, voor door precedenten beperkt ontwerpen en voor ontwerpen naar analogie (Hoofdstuk 2, 5).

(2) Morfologie, werking en verrichting van de gebouwde omgeving vormen een model van precedenten kennis. De architectonisch precedenten analyse is een proces waarbij het gaat om het vinden van een morfologisch beschrijving die waarschijnlijk een geleende verrichting zou kunnen teweegbrengen (Hoofdstuk 2, 4).

(3) Architectonisch precedenten analyse is een leer proces, waarin nieuwe ontwerp principes geleerd worden vanuit precedenten voorbeelden. Zodoende, kan een systeem voor precedenten analyse behandeld worden als een machine kennis systeem, dat zowel inductieve als deductieve leer-methodes gebruikt (Hoofdstuk 6).

(4) Echter, een leersysteem voor architectonisch precedenten analyse eist representatie middelen die verschillend zijn van de meest gangbaar bestudeerde leersystemen, omdat het moet omgaan met ruimtelijke representatie die centraal staat in het architectonisch domein (Hoofdstuk 7, 8).

(5) Ruimtelijke representatie is gebaseerd op enkele cognitieve principes. Architectonisch precedenten analyse kan gezien worden als ruimtelijke categorisatie, voornamelijk een proces waar de op een plaatje gebaseerde afbeelding van precedenten wordt omgezet in, op voorstelling gebaseerde, structurele beschrijvingen van de precedenten (Hoofdstuk 7,8).

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(6) Als belangrijk kenmerk, brengt de structurele beschrijving van de gebouwde omgeving semantisch onderscheidingen tussen zowel lokaties als ook hun onderlinge relaties met zich mee. Deze semantische onderscheidingen maken een beschrijving betekenisvol ten aanzien van architectonisch precedenten analyse (Hoofdstuk 7).

(7) Semantische onderscheidingen zijn fundamentele perceptuele bias-es tot de herkenning van architectonisch ruimte. Zulke onderscheidingen—bijvoorbeeld de onderscheiding tussen binnen/buiten, privé/publiek, circulatie/utiliteit, oost/west, noord/zuid—zouden geconstrueerd moeten worden in de kennisbasis voor architectonisch precedenten analyse (Hoofdstuk 7).

(8) Architectonisch precedenten analyse is een plattegrond herkenningsproces welk zowel bottom-up als top-down processen met zich mee brengt. Als top-down proces is een frame gevormd en worden er regels geselecteerd voor plattegrond transformatie. Als bottom-up proces, worden plattegronden stap voor stap veranderd zodat ze te beschrijven zijn door middel van een structurele signalement (Hoofdstuk 6, 8).

Deze ideeën zijn ontwikkeld vanuit de bestudering van een feitelijk architectonisch ontwerpgeval en toegelicht door middel van een schetsmatig ontwerp voor een op kennis gebaseerd computer systeem ARPRAN (ARchitectural PRecedent ANalyst). De geselecteerde studie casus is het ontwerp van het "nieuwe hof huis" in de oud stad van Beijing, waarbij architectonische precedenten gebruikt zijn en met succes zijn geanalyseerd overeenkomstig bepaalde ontwerp-doelen (Hoofdstuk 2). Het ontwerp van ARPRAN is gebaseerd op de reconstructie van twee precedenten analyse processen gehaald uit de ontwerpcasus (Hoofdstuk 6).

ARPRAN wordt voorgesteld om volgens de plattegronden van precedenten, pre-parametrische beschrijvingen van ruimtelijke organisatie te kunnen produceren, die een gegeven verrichting van de gebouwde omgeving zouden kunnen teweegbrengen. Het accepteert als input, een doel-verrichting, een groep plattegronden in de vorm van een labelled line drawing (LLD) en een operationele criteria, en geeft als output een of meer labelled location net(s) (LLN). Drie hoofd procedures, "frame construction," "plan abstraction" en "generalization" vormen het plattegrond herkenningsproces van ARPRAN.

(Translated from the English version by Catharine Visser)

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Definitions or Explanations of
the Major Concepts

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About the Author

Mr. Nan Fang was born on January 29, 1963, in Zhejiang, China. In Beijing he received his primary and secondary education. In July 1986, after a five-year study, he graduated from the Department of Architecture of Tsinghua University in Beijing and received a bachelor's degree in engineering. In the same year, he entered the Post-graduate School of Tsinghua University, majoring Architectural Design. During his post-graduate study, he was involved in the design of several public buildings in Beijing.

Since December, 1987, he has been working as an assistant-in-training in the Faculty of Architecture, Delft University of Technology in the Netherlands. From December, 1987 to May, 1989, he worked in the TUDARC group, where he gained some experiences with a computer-aided architectural drafting system. From June, 1989 to April, 1990, he worked in the OPM group, where he had chance to study a computer-aided planning and design decision-making system. In May, 1990, he joined the AKS group, involving in the research project Artificial Intelligence for the Intelligent Architect (AIIA), which has resulted in this thesis.

During his studying in Beijing and working in Delft, he often took part in architectural design competitions and has won a number of prizes. In 1989, cooperated with Mr. Li Yu, he won a prize of honourable mention in Japan's Central Glass International Architectural Design Competition (the result was published in *Japan Architect*, January, 1990).