# 5. Design Education with Computers

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*This paper summarizes a teaching project carried out by the CAAD Chair in the Department of Architecture at the ETH in Zurich during the last one and a half years. The approach adopted for the design education with computers focuses on two major issues: design representations and design strategies. The alternative representations that computers can provide are discussed in the first part of the paper. The core of this first part is a detailed description of a course in which hierarchical structures were used to teach some of the alternative design representations that are unique to computers. The second part of the paper proposes that understanding design as the interplay of systems is a design strategy which can lead to an effective integration of computers in design. A brief description of the content of another course developed around this concept is included.*

## Introduction

Unlike the sculptor or the painter, the architect is detached from the actual artifact he is trying to create. While the work of the sculptor and the painter are results of direct interaction with the object itself, the architect does not create a building through the direct manipulation of real objects in space. Architecture is conceived in a world of abstractions; it is essentially a product of the intellect, a mental process dealing with symbols that refer to the real world where the building is built.

There are some simple, pragmatic reasons behind the detachment of the architect from the object of his creation, among them, the fact that raising a building represents a collective effort that requires a huge investment of time and money. A more significant reason, however, is that the existence of architecture as a discipline and the position of architects as central figures in the creation of the built environment are intimately related to the division between 'design' and 'construction' as it was established after the Renaissance. Significantly, Alberti started his treatise On the Art of Building (Alberti 1452) by describing the division between lineamenta and structura:

*"The whole matter of building is composed of lineaments and structure. All the intent and purpose of lineaments lies in finding the correct, infallible way of joining and fitting together those lines and angles which define and enclose the surfaces of the building. Jet lineaments be the precise and correct outline, conceived in the mind, made up of lines and angles, and perfected in the learned intellect and imagination."*

## The Abstract and Real Worlds

The architect's realm lies between two worlds: the abstract world in which the building is conceived and the real world in which it is experienced. The abstraction of design by architects has a similar purpose as formulas have for physicists: it allows them to capture some relevant aspects of reality in order to manipulate them in the realm of the intellect. Le Corbusier talked about this similarity in Vers une Architecture (Le Corbusier 1923):

*"Le plan est la determination du rout; il est le moment décisf. Un plan n'est pas foil a dessiner comme le visage d' une madone; c'est une austere abstraction; ce n' est qu' une algébrisation aride au regard. Le travail du mathématicien resre tout de même une des plus hautes activités de l'esprit humain".*

The ultimate purpose of the activity of the architect is the real object, the creation of space. In this regard, the architect must be aware of the impact that decisions made in the realm of the abstract will have in the real world of the built environment. Le Corbusier was also aware of the link between the two worlds when he wrote (Le Corbusier 1923):

*"L' homme voit les choses de 1' architecture avec ses yeux qui sont a 1 m. 70 du sol. On ne peut compter qu'avec des buts accessibles a l'oeil, qu'avec des intentions qui usent des éléments de l'architecture".*

## Conceptual Tools of Design

Abstractions of a design are something more than a link between the individual world of the designer and the outside world; they create a reality of their own. Architecture often becomes trapped in this world of abstractions that was actually meant to represent it. Moreover, some architectural concepts belong exclusively to the abstract world and do not necessarily have a place in the physical world.

The order we try to find in the composition of a facade, for example, may be the result of using a specific orthographic projection to capture some of the properties of the real building.

The mechanisms we use to design a facade (to play with the proportions of openings, to create tensions and balances between parts of the composition) are consistent with the properties of the conceptual tools that we are using to conceive the building. Moreover, the very concept of 'facade' exists because orthographic projections were developed as a way of controlling the geometric properties of real objects before they are built. Therefore, the conceptual decompositions that an architect makes in order to conceive a building are consistent with the design representations that are known to the architect.

The interdependence between what we can think of and the characteristics of the tool that we have to think with is such that we cannot escape the use of the representations of design that we know, even when we are facing complex design problems that exceed the limitations of those representations.

## Alternative Design Representations with Computers

The possibility that computers might provide alternative design representations was recognized in the first applications of computers in architecture. For Ivan Sutherland, the attraction of using computers in design lay in the structured nature of computer drawings (Sutherland 1975):

*'To a large extent it has turned out that the usefulness of computer drawings is precisely their structured nature. The drawing itself has properties quite independent of the properties of the object it is describing."*

The new representation possibilities offered by computers for design inspired Herbert Simon to develop a new theory of design (Simon 1969). In his book The Sciences of the Artificial, he explains the relationship between the kinds of representation that can be made of a problem and the solutions that can be found. He concludes that solving a problem simply means representing it so as to make the solution transparent. Following Simon it is possible to imagine that, at some moment, computers will be able to provide new representations that help a designer to better understand the actual complexity of design issues.

Although these alternative representations have not yet been realized in practice, the basic assumptions are still valid. In order to define the role of computers in design, it is not enough to recognize a computer's capability to produce new representations. The critical point is how architects can actually use those representations to conceive and represent design in a different way. Thus, a clear definition of the role of computers in architectural design cannot emerge until computers offer new representations of design that architects can use to conceive and represent a building.

## Alternative Design Representations: The Reality of Current Systems

Current computer-aided design systems do not provide alternative design representations that the architect can use to conceive a design. The representations of design that we find in today's computer-aided design systems have not broken any new ground (Madrazo 1991). They rely too heavily on the conventional representations that we know through hand drawings and physical models. Because of this, current systems are used to emulate tasks that were previously done manually, for example, creating a set of construction drawings or a three-dimensional model for visualization purposes.

Today, a large gap exists between what a computer should be able to do in order to become an irreplaceable tool for design, and what current commercial systems actually can do. The situation is such, that it is even difficult to justify the term 'computer-aided design' when the capabilities of the available systems are considered. Rather, the use of expressions such as 'computer drafting', 'computer modeling' or 'computer animation' better describe the possibilities offered by computer systems in architecture at this time.

As a result of this situation, educators who are interested in teaching about the unique potential that computers offer for design, face a paradoxical situation: there are no computer tools that prove that computers have a place in architectural design. In this context, the alternatives are whether to adjust design teaching to the capabilities of those systems (which means to teach drafting and modeling with computers and to make students proficient in the use of selected packages) or to create some new conceptual tools that support a specific approach to design (Schmitt 1989).

### Computers in Design Education: Teaching New Design Representations

The education of design with computers should concentrate on those aspects of a computer that make it a unique tool for addressing design issues, for example, its different design representations.

The course that took place during the Wintersemester 1990 at the ETH introduced a method of computer representation for design that cannot be implemented with traditional tools. Rather than using a standard system to teach, we created our own environment and tools for the students to use during the course.

Although most of the ideas that were presented in the course belong to the world of object oriented languages, the task of providing a completely new set of tools outside one of the commercial packages was beyond our possibilities. For this reason, the new tools and their corresponding environment were programmed in AutoLISP and interfaced with AutoCAD (Version 10).

### Course Content

The goal of the course was to focus on understanding some of the basic concepts related to the representation of design with computers. We purposely avoided specific architectural references by developing exercises based on the representation of abstract three-dimensional objects. Although we considered the simplification of design issues advantageous for making the basic ideas clearer, it was not intended to suggest that a trivialization of design is necessary in order to bring it into the realm of computers.

Three fundamental ideas served as a basis for the presentation of the capabilities of computers as unique tools for design: *design vocabulary, multiple representations and hierarchical structures.*

### Design Vocabulary

With the computer, the designer is more aware of the fact that the representation of a design idea takes place within a closed universe of objects. These objects make up the design vocabulary. Because the vocabulary is restricted, more attention is paid to the exploration of spatial relationships between elements of the vocabulary and to the ways in which the existing vocabulary can be enhanced by the creation of new elements.

The concepts of types and instances are used to explore the representation of design within a design vocabulary. The objects created by the provided functions are extruded shapes made in two steps: first a two-dimensional profile is defined and, second, a complete three-dimensional objects is created within the boundaries of a lx1x1 unit cube. Instances of these objects are used to create more complex objects thus enhancing the initial vocabulary. The instances also can be assigned different scale values.

## Multiple Representations

Typically, each abstraction of a design is an expression of a particular set of issues filtered out of the overall complexity of the design. Working with traditional tools, each abstraction becomes unique. A detailed section of a facade is a separate drawing with no link to the floor plan. Massing studies are done with physical models which have no real link to the drawings. One significant capability that the computer offers is the ability to interrelate the different representations of the same object.

We use different levels of detail for the same object to illustrate this idea. Different representations for every type in the vocabulary are created with a function that cuts and adds rectangular sections to a given square. An instantiation menu makes it possible to select an instance of a type and increase or 'decrease' the level of detail according to the structure of the design vocabulary.

## Hierarchical Structures

The idea of creating a hierarchical structure of a design is the main objective of the course. Although architects have long been familiar with the concept of hierarchies in design, it is only now, with the computer, that we can actually have a representation of those hierarchies that we can use to design.

The proposed hierarchical structure is the result of instantiating the elements of the design vocabulary to create more complex elements. At the top of the structure, the most basic elements are created as single unit types organized according to their levels of detail. The operations to create those types are embedded in the functions that create them. In a second level, new operations are applied to the instances of those objects to create more complex ones.

At every level of the structure, different kinds of objects and operations are used to create compositions with existing objects or new ones that are then added to the vocabulary. The criteria for creating the most basic objects, for example, is fundamentally different than that of the more complex object. In the first case, the most relevant issue for the creation of simple objects is the operation used to give them form. For more complex objects, however, it is crucial to define the spatial relationships between the instances of the simpler objects. Thus, at every level of the hierarchy different design considerations can be isolated and treated separately.

The most important aspect, however, is the dynamic character of this hierarchical representation of design. The changes performed at the top of the hierarchy (for example, redefining some elements in the first vocabulary) will propagate down through the other levels. Thus, it is not necessary to question the overall design process in order to explore different alternatives of design.

## Description of the Exercises

The exercises for this course have been designed to allow the students to progress in the understanding of the basic principles involved in a regulated fashion. In order to complete the exercises, the students need only the provided set of tools and a basic knowledge of the most generic operations of the commercial package.

## Exercise 1: Creating Form with the Computer

The first two exercises introduce students to three-dimensional space. In the first, the three-dimensional space is introduced by exploring the relationship between the plane and the vertical dimension.The three-dimensional objects are extruded shapes whose outlines are defined using a 30 grid interface (Figure 1).

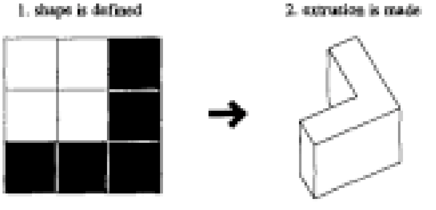


**Figure 1**. The interface used to create extruded objects.

The function CREATE-OBJECT creates an object with surfaces on all sides (note that in AutoCAD version 10, creating a complete 3d object involves more operations than just a simple extrusion). Within the same function, the resulting object is then defined as a 'block' and a slide of the object made to be used in an icon menu. A series of objects created with this function make up the first design vocabulary (Figure 2).

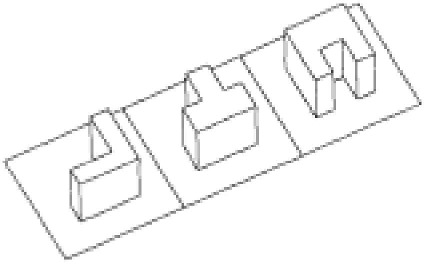

**Figure 2.** The first design vocabulary.

In the second part of the exercise, different compositions are made by placing combinations of the objects over a plane (Figure 3). When the function INSERT-OBJECT is invoked, an icon menu appears on the screen displaying the existing objects. Each inserted object is an instance of the original type. Each instance can be individually scaled at the moment of insertion. Special editing functions are provided to modify the position of the inserted object or redefine the scale factor. With X_FLIP, Y_FLIP it is possible to change the orientation of the inserted object with one mouse-click. Z_ROT rotates the object through an axis passing through the center of the section. Z_RESIZE modifies the height of the object.

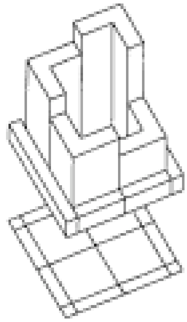

**Figure 3.** Composition of extruded objects over a plane.

### Exercise 2: The Three Dimensions

In this second exercise, the operations that were restricted to the relationship between the plane and the vertical dimension are expanded to all three dimensions of space.

The function INSERT _OBJECT allows one to insert an object with any orientation in space. Similarly, scale factors can be applied to any of the three axes of the object. The editing functions are also enhanced to allow modification in all three dimensions. FLIP, ROT and RESIZE replace their two-dimensional counterparts from the first exercise. The function RESIZE is particularly useful since it circumvents the necessity in AutoCAD of manually deleting and reinserting blocks in order to rescale them. With RESIZE one can select an instance of the block and modify graphically any dimension along the three axes of the block.

The goal of this exercise is to create complex objects out of simpler ones. Every type defined in the vocabulary can be scaled and placed in any position in space. To illustrate the idea, we provide a function that allows the student to build different cube constructions out of one of the types of the vocabulary created in exercise one (Figure 4). With the function CREATE _CUBE, a pop-up menu displays three different cube constructions: a cube defined as a single instance of a type, six instances defining the faces of a cube and twelve instances defining the edges of a cube. A second menu follows which displays the existing objects. After the second selection, the function prompts for some scale factors and the cube is created.

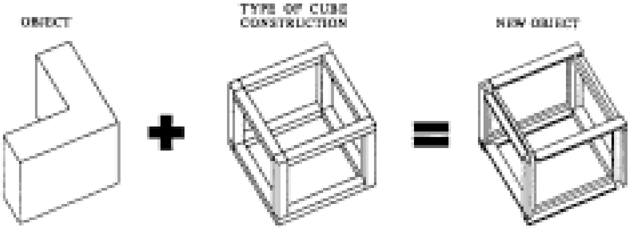


**Figure 4.** The function CREATE-CUBE creates a cube from a vocabulary type by instanciating it as the twelve edge elements.

In the second part of the exercise, the student uses the new editing functions to modify the configurations of the cubes obtained with CREATE-CUBE (Figure 5). The different transformations are the result of changing the orientation and scale factors of the instances using a few interactive tools (the functions FLIP, ROT and RESIZE).

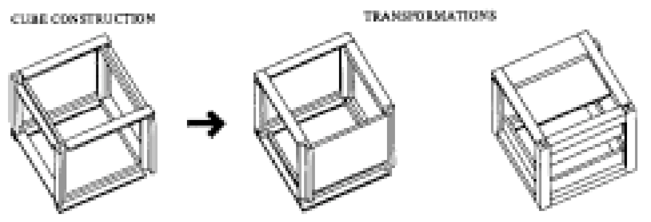


**Figure 5.** Two different transformations of a cube construction previously created with the function CREATE-CUBE.

## Exercise 3: Levels of Detail

After three-dimensional space and the concepts of types and instances have been introduced, the main core of the course begins. In the third exercise, objects can be created with a new function (EXTEND _PROFILE) with which two-dimensional rectilinear shapes can be created by cutting and adding sections to an initial lx1 square (Figure 6). As in the first and second exercises, the function CREATE-OBJECT automatically extrudes the two-dimensional shape, inserts surfaces on all sides, defines the resulting objects as a block and makes a slide for the pop-up menu display.

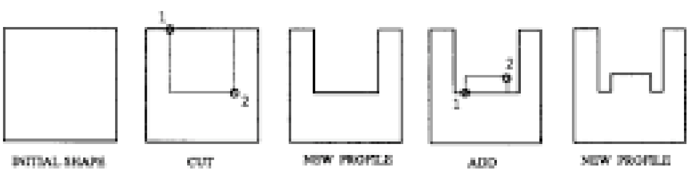


**Figure 6.** The interface to create two-dimensional profiles with cutting and adding operations.

The concept of multiple representations is established and developed with the inclusion of different levels of detail for every object in the design vocabulary (Figure 7). The purpose of the exercise is to complete a table of objects, organized horizontally as a collection of types and vertically according to levels of detail. The table works in combination with an INSTANTIATION menu, which allows the manipulation of the objects when they are inserted. Thus, it is possible to select an instance and 'increase' or 'decrease' its level of detail, or substitute one type with another while maintaining the same level of detail. Also, any modification of the scale factors of an instance at any level of detail are inherited by its replacement.

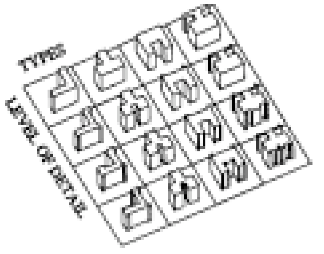


**Figure 7.** The enhanced vocabulary with types and levels of detail.

### Exercise 4: Building a Hierarchical Representation

The goal of this exercise is to explore possibilities for creating new objects within a restricted design vocabulary (Figure 8). New objects are the result of creating combinations of instances of the original single unit types with different scale factors. The spatial relationships between the objects of the first vocabulary determine the characteristics of the more complex ones of which they are a part. The initial vocabulary is then expanded by the new, compound objects.

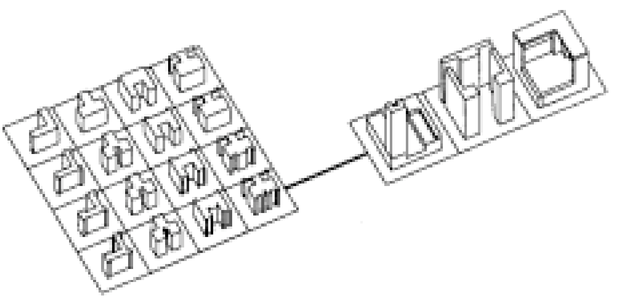

**Figure 8.** The design vocabulary is enhanced by more complex elements.

The transformation of a simple object into a complex one can be described in terms of the application of an operator to an object. The objects in the hierarchy are made up of two components: the geometric properties of the object (OBJECT) and the operations that determine the spatial properties of that object (OPERATOR). Recursive application of the operations on the vocabulary results in a hierarchical structure as seen in Figure 9.

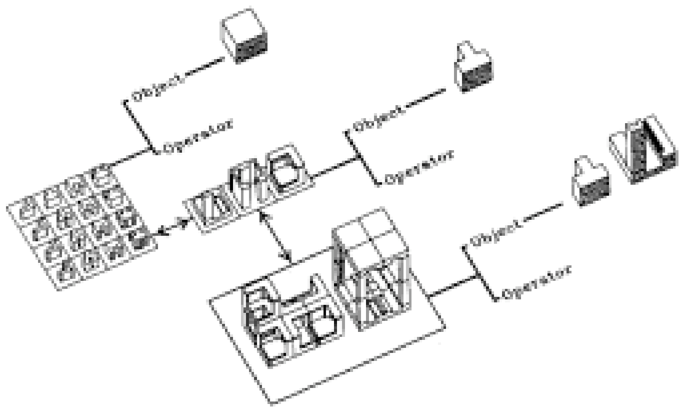


**Figure 9.** A hierarchical structure based on objects and operators.

It is possible at this point to create a composition with the most simple elements of the first vocabulary, for example, a cube (Figure 10). After having created new complex elements in the vocabulary, the instantiation menu can be used to automatically replace the most simple cubes by more complex ones. In order to explore different formal expressions based on the first volumetric schemes, one must simply select a cube and use the function 'increase' level of detail or 'substitute' types.

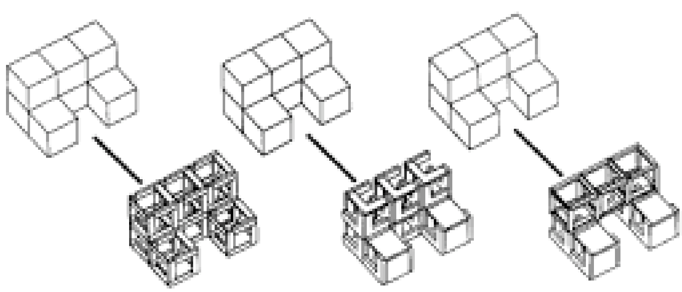

**Figure 10.** Replacing simple elements with more complex ones.

### Exercise 5: Using the Hierarchical Representations

Building up a representation in this way results in a hierarchical structure made up of the objects of the first design vocabulary and objects created by applying operations to them. The purpose of this exercise is to use the concept of instantiation to create design alternatives within the hierarchical structure already created. For example, it is possible to go to the top of the hierarchy and redefine one of the types and levels of detail. In Figure 11, the redefinition of the L-shape in the first vocabulary results in the automatic update of all the instances in all levels of the hierarchical structure.

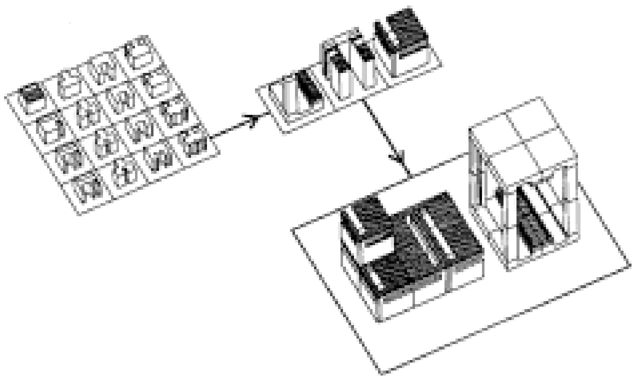

**Figure 11.** Exploration of design alternatives within the hierarchical structure.

It is also possible to explore alternatives from any level within the hierarchy. A new solution might require the enhancement of the vocabulary at an intermediate level of the hierarchy. At this point, the design vocabulary needs to be enhanced in the upper levels of the hierarchy (Figure 12).

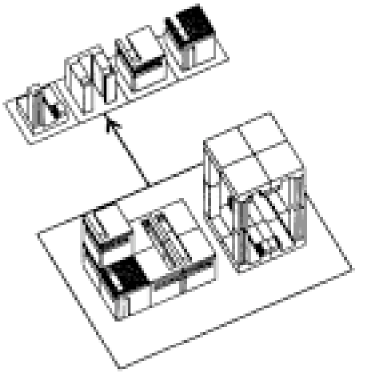

**Figure 12.** New elements are added to different levels of the hierarchy.

Another way to creatively exploit the representation of design with this hierarchical structure is to create multiple decompositions of a compound object. Figure 13 shows four possible decompositions which are based on different interpretations that a designer might have for a design. In each case, new elements can be created to reflect the concepts behind each decomposition and added to the vocabulary.

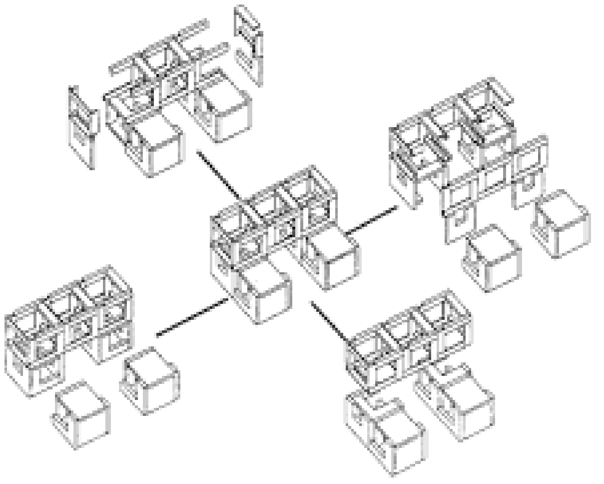

**Figure 13.** Decompositions reflecting different perceptions of the same scheme.

## PART TWO: DESIGN STRATEGIES

The first part of the paper focused on the issue of design representation in isolation from any references to architectural design. This second part specifically addresses the role of computers in architectural design. The central point of the discussion is that architects will need to develop certain design strategies in order to use the representations provided by computers to conceive a design. One of those strategies is understanding design as the result of the interplay of systems.

### Creation and Representation of Architectural Knowledge

Typically, an architect starts a design with sketches in order to communicate an idea from his or her mind to the outside world. At the early stages of the design process there is a necessity to think freely about a design without much interference from the medium used to represent it. However, such an intimate connection between ideas and tools cannot be achieved with the conventional computer systems. As soon as the architect moves to the computer to continue the design that was started with sketches the tool starts to mediate the ideas. The exact geometry of every element and the level of abstraction of each object have to be defined. The design also has to be broken into parts that can be implemented in the computer as symbols, layers or files. Attributes and names have to be assigned to the elements and groups of elements in the design.

With sketches the architect is creating knowledge; then that knowledge must be transferred to the computer. Although during this transition a new understanding of the original idea may emerge, it is difficult to continue designing working exclusively with the computer. The critical issue is how to enable an architect to create knowledge while working with the computer, rather than simply using it to represent what is already known. In this context, it can be argued that the role of computers in architectural design *is to capture the design logic* *of an individual architect by representing the design process itself, rather than the output of that process.*

## The Dialectic Between Form and Context

According to Christopher Alexander, a design is the result of the dialectic between form and context (Alexander 1964). The architect moves from one to the other in the process of design, establishing the boundaries between the definition of the problem (context) and the formal solution to that problem (form). Being unable to understand completely all of the complexities of the context in which the form has to fit, the architect begins by making a formal hypothesis. In this way, the form proposed by him becomes the description of the problem and, at the same time, its solution. By acting in this way, Alexander contends that the architect loses the chance to really understand all of the complexities of the problem he is supposed to solve.

The response of the architect to a given problem takes place in the realm of form. Faced with the objective description of the design task (a single family house in the countryside, an office building in front of a public square in an historical district, the design of an exhibition) the architect 'invents' (or reinvents) the problem in order to bring it into a territory in which he can handle it according to his own skills. Once a design problem has entered the territory of individual forms, formal solutions to the problems are created. From that moment, the search for the solution of a problem is mixed with the search for the internal order of the forms.

A computer tool should be able to increase the awareness of the architect about the boundaries between the two worlds, context and form, where design takes place. The representation of the context does not necessarily have to occur in the realm of form. A computer tool could maintain separate representations of the context and the form and make the architect aware of the possible links between them. A project developed for the CAAD Futures '91 exhibition will be used to illustrate the dynamic interaction between form and context in the process of design.

## Design as the Interplay of Systems: A Project for an Exhibition

This exhibit, conceived of as part of the CAAD Futures' 91 conference, is the expression of the ideas developed for the courses of the CAAD Lehrstuhl at the ETH in Zurich. The exhibition was to be located in the lobby of the Department of Architecture at the ETH, a residual space where multiple paths to different parts of the building intersect.

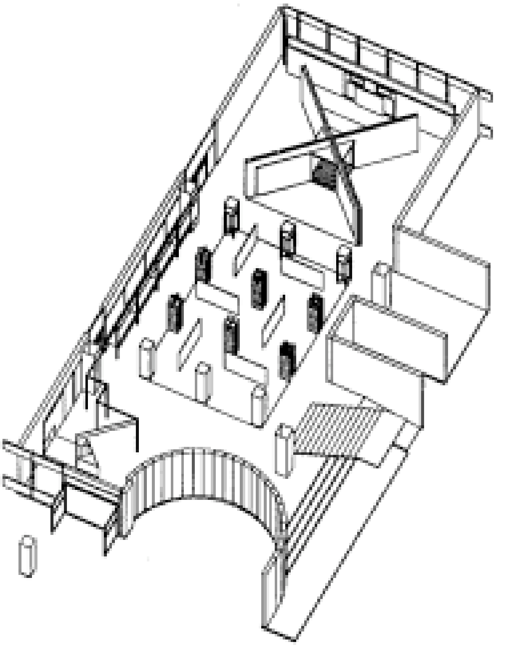

**Figure 14.** First proposal for the CAAD Futures '91 exhibition. Project by Leandro Madrazo.

As a response to the partitioned character of the space, different systems of elements were introduced that could accommodate the areas delimited by the existing circulation patterns. Figure 14 shows the four basic systems of the design: a 3x4 arrangement of 'columns', a 'portico', a 'cross' and a system of transparent 'panels' hung from the ceiling.

The part of the project that will be used to illustrate the dynamic interaction of context and form in the process of design is the one that deals with the relationship between the system of the 'cross' and the system of the 'columns'. The system of the columns is the materialization of the concepts of design vocabulary and levels of detail that were described in the first part of this paper. The cross divides the end of the room into four spaces, two of which are designed for viewing slides projected on the walls of the room from projection shelves located in the upper part of the center of the cross.

The system of the columns has some well-defined properties. The columns start out as simple boxes. In the second row they acquire the classic decomposition of base, shaft and capital. In the third row, the detailing of the joints and the capitals is more refined. In the last row, however, the columns no longer represent an increase in the level of detailing. The reasoning behind this is that, at that point, the system of columns starts to interact with the system of the cross (Figure 14).

Working at the level of the context, following Alexander's terms, an important consideration was that a visitor moving within the system of columns should perceive the last row as a threshold to the system of the cross. Thus, rather than keeping the criteria of increasing the level of detail for each successive row, the last columns became more transparent, as a way of creating a transition from the column system to the cross system. Formal solutions the contextual problem 'make a transparent row of columns to mark a threshold with the next system' are numerous. Figure 15 shows two of the alternatives considered.

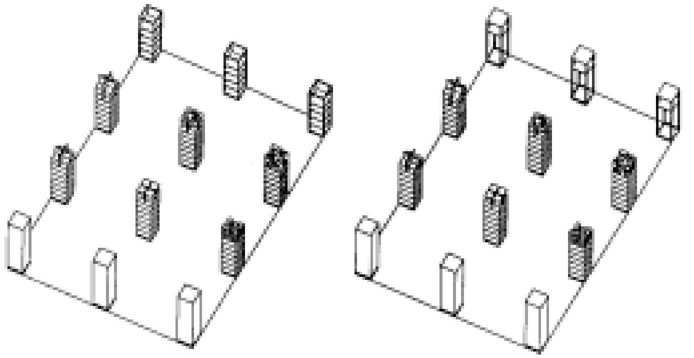

**Figure 15.** Two formal solutions for the last row of columns.

Other alternatives are possible if, instead of focusing on the geometric characteristics of the columns, the material of the columns is considered. For example, by using glass the columns could remain transparent while at the same time maintaining a progression in the level of detail. The final option transfers some of the geometric attributes of the 'cross' to the columns. Thus, the cross-shape is also reflected in the base and shaft of the columns in the last row (Figure 16).

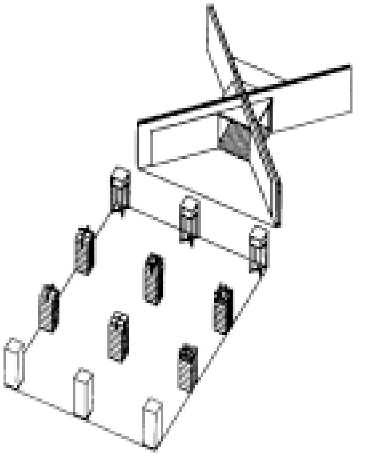

**Figure 16.** The interaction between the systems of the cross and the columns.

A similar reasoning is behind the formal definition of the portico. Initially, the portico ran parallel to the wall in order to create an intermediate space between the two existing columns, the room and the wall (Figure 14). A relationship was established between the portico and the main entrance to the lobby, which is also the main entrance of the exhibit space. The portico was to grow towards this 'gate' as though being attracted by it. On its way towards the gate, the portico breaks away from the wall, finds an equilibrium and confronts the gate at a 45 degrees angle. The recognition of the gate as an element of the problem is, in this case, part of the context. The portico itself is the system in the design which specifically responds to that contextual problem.

The computer tool used for this simple design was a standard three-dimensional modeling program. The articulation of the design thinking occurred using only the tools that were developed for the course described earlier (the INSTANTIATION menu for instance, was used to modify the levels of detail in the column system). At this point it is interesting to consider what would be the characteristics of the optimal computer-aided design system, for this type of design strategy.

An ideal system for this design problem would have to be able to create a representation of the problems discovered at the level of the context (for example, the representation of the condition 'make a threshold'). Then, the different formal solutions given to that condition would have been recognized in relationship with the representation of the context. In this example, the formal answers to the contextual condition 'make a threshold' were three different formal solutions for the columns (excluding the possibility to making them out of glass, which was discarded as impractical in terms of the budget).

Also, the computer tool should be able to maintain a description of the attributes of every system of elements. This way would have enabled one to transfer attributes from elements and/or systems of elements inter alia, in much the same way that the geometric attribute of the cross was applied to the last row of columns to express the interaction between the system of the cross and the system of the columns.

If such a reasoning could be articulated with a computer tool, then it would be possible to claim that design is taking place within the computer environment. It would be the design process itself that is captured in the computer. The representation of the design using the computer can then allow one to have access to that structure that Sutherland recognized as the genuine value of computer representation.

## Design as the Interplay of Systems: A Course in Design Strategies

The implementation of new design representations made possible by computer tools will require architects to create or adopt certain design strategies in order to make effective use of the new tools for design. Thinking of design as the interplay between systems is one of many strategies that could be explicitly supported by future computer tools. In a separate course, a design strategy was introduced based on the interplay of systems, similar to that used to the design the exhibition space described above.

The four systems that the course focused on were: structure, circulation, interior space and exterior enclosure. After an introductory exercise dealing with massing studies, the volumes of the preliminary design were replaced by structural elements made up of columns, porticos and/or walls. The circulation elements were considered next, including among others: stairs, ramps and corridors. Figure 17 shows an intermediate stage of a student project in which the connection between the different circulation elements and the structural frame were of primary concern.

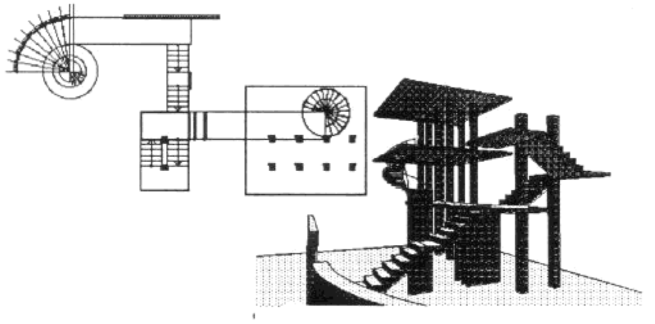

**Figure 17.** Creating a scheme with the structure and circulation systems. Project by Thomas Kaempfer.

The next stage in the process was to consider the interior spaces that were implicated by the earlier schemes that focused on the structural and circulation systems. Figure 18 illustrates two different spatial compositions by the same student, generated around the scheme that he had developed during the previous exercises. In figure (a) the stair-ramp is enclosed in a new space that becomes a pavilion and other spaces adjacent to the spiral stair (which intersected the rhythm of the structural system) were also defined. In the second example, figure (b), a different approach was taken. Two spaces, one with a square plan and another with a curvilinear wall were located along the spine created by the structural frame.

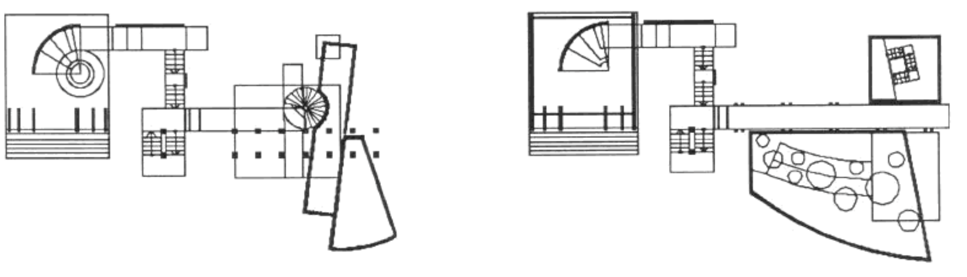

**Figure 18.** Two different approaches for creating the interior spaces based on the structural and circulation systems.

The quality of the spaces that were being created needed to be taken into account at this stage. Inside the space defined by the curvilinear wall, for example, a relationship between the round openings in the ceiling and the ramp was established (Figure 19). Issues such as light penetration began to be taken into account.

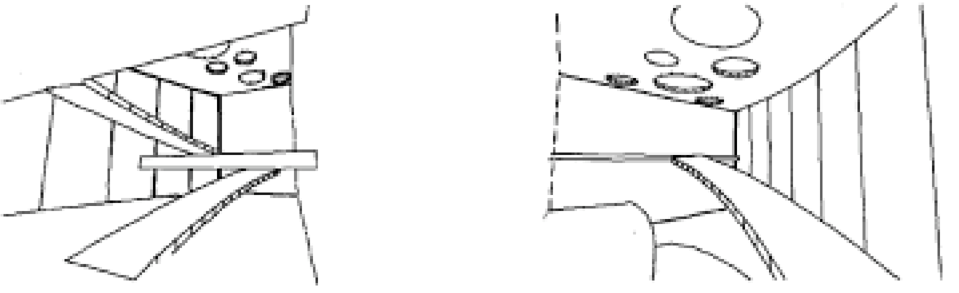

**Figure 19.** The relationship between the ramp and the openings in the ceiling that allow light to penetrate into the space.

The last stage of this proposed strategy was to look at the building from the outside (Figure 20). The exercise focused on how the existing systems were to be expressed on the outside of the building. In this student project, the pattern of openings cut into the ceiling slab reflect the stair-ramp below. Similarly, a portico was added on the exterior of the curvilinear wall and the tower was given some sculptural characteristics by adding of a balcony and stairs to its top.

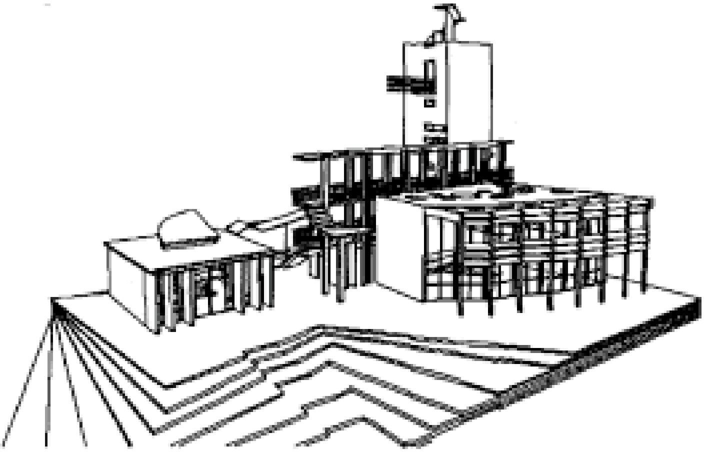

**Figure 20.** The design continues focusing on the exterior of the building.

Considering design as the interplay between systems gave the students an opportunity to better understand the design logic that was governing the design process. The students were aware of the properties of every system as well as the role of each system in the overall definition of the design.

When a new system was introduced to the design the critical issues included not only the issues specific to the new system, but also how to define the character of the interrelationships between the new and the existing systems, as well as those between all of the systems and the contextual conditions established by the students. As a result of the interaction between systems, hierarchies were established which helped to determine the role of every part within the whole.

By approaching design in this way, we were purposely breaking with some of the conventions of traditional design studios in order to offer students the opportunity to freely explore architectural issues in a context which is unique to computers. The students gained a solid background about some basic principles involving architectural design, which can then be extrapolated upon and used for more 'realistic' design problems.

## Conclusions

In order to set up an agenda for the education of design with computers it is necessary to put the current stage of development in this field into context. At the moment, there is little justification for the use of computers in design if we consider the capabilities of the current systems alone. On the other hand, it is precisely the absence of a clear role for computers in design that has become the driving force behind continuous research in the field. The ideas expressed in this paper are meant to contribute to that research.

In the context of a professional program in an architecture school, a main objective for educators involved with teaching design with computers is to break the barriers that cause the subject to be treated as a specialization, closed or even unrelated to other areas of the curriculum. The ultimate validity of ideas developed around the use of computers in design can only be tested when the issues involved become a part of the general architectural debate that occurs in schools of architecture. Along this line, our goal is to use computers as a platform from which a different understanding about architectural issues can emerge.

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