INTEGRATION OF ENERGY ANALYSES IN DESIGN THROUGH THE USE OF MICROCOMPUTERS

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Abstract

Social, economic, and professional forces are compelling architectural designers to evaluate the effects of design decisions upon environmental comfort and energy efficiency in buildings. Siting, massing, locations of functions, facade and fenestration design, and materials are all important determinants of the perceived thermal and luminous environment of a space. However, the combined complexities of the physical processes involved, and of new building types, programs, materials, mechanical systems, utility rates, etc., have made it difficult for designers to develop a "feel" for the impact of these decisions.

Consequently, there is a need for analytical tools for use in the design process, which provide the architect with not only an evaluation of comfort conditions or energy consumption, but more importantly an understanding of the interplay between built form and energy flows. In this thesis, some important considerations for the development of such analytical design tools are discussed, and a model proposed.

The design process is characterized as "wicked" problem-solving, with constantly changing criteria, conditions, and solutions. This places important requirements for the capabilities of analytical design tools; they must be flexible in use, determine complex interactions of energy flows, and represent these interactions to the designer in a meaningful way.

An environmental model is proposed as a framework for structuring a "family" of energy analyses. These analyses look at the transformations of heat and light energy by the built environment at various scales of site, building zone, and body. A designer can manipulate the model in a number of ways; one can look at any single or set of transformations, view the resulting comfort conditions, set constraints upon those conditions, and determine the auxiliary energy and power needed to maintain those constraints.

The implementation of this family of analyses is also presented as a group of linked microcomputer programs with emphasis on issues of appropriate interaction between the designer and machine (e.g. interactive graphics, data structures, and flexibility). Finally, one member of the family which has been encoded for the analysis of daylighting is described.

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Theses and Premises

In a world more humanely disposed, and more conscious of where the prime human responsibilities of architects lie, the chapters that follow would need no apology, and probably would never need to be written. It would have been apparent long ago that the art and business of creating buildings is not divisible into two intellectually separate parts—'structures', on the one hand, and on the other 'mechanical services'. Even if industrial habit and contract law appear to impose such a division, it remains false.(1)

Thus wrote Banham in 1969, about the conceptual separation of environmental systems in buildings, those that provide heating, cooling, ventilation, and lighting, from spatial and structural systems. The former is typically held to lie in the domain of the mechanical engineer, the latter in that of the architectural designer. And it is almost totally within this century, even within the last fifty years, that the split has occurred. Prior to that, the provision of visual and thermal comfort was the province of the designer. In fact, these were major design determinants, form-givers. How and why did architects relinquish these concerns?

Some of the reasons are rather obvious and frequently cited. This was the period when modern environmental systems such as electric lighting, powered ventilation and air distribution, air conditioning, furnaces, and boilers came into being. Because of their complexity, it certainly could not be expected of the architect to design and size these systems. Similar technological advances occurred during this time in structural systems and materials, yet designers developed rules of thumb and other tools for maintaining control over at least the conceptual design of
the support structure.

The key difference between attitudes toward mechanical and structural systems lie in their perceived relation to built form. The skeleton, or support system is form, especially given the precepts of the modern era. And technological advances in structural systems permitted, even inspired new forms. Of course it can be argued that the development of modern mechanical systems proved an even greater liberator of form; so great, though, that designers no longer had to worry about that most fundamental function of shelter, the moderation of climate. The analogous freedom from structural constraints would have been the abolition of gravity! Comfort in buildings had become a given, no longer a significant form-giver. Heating and cooling needs were only addressed as part of the specification of mechanical and electrical systems, and thermal properties of materials (such as insulation) only considered during detailing of wall sections.

This freedom has not come without a price. During this period, modern architecture lost an understanding of the interplay between climatic forces, built forms, and comfort, which were previously so important to the designer. Climate was taken out of the design "equation" altogether. And comfort has been reduced to a few constant, uniform variables, such as air temperature, relative humidity, and illumination. And of course, the sophisticated engineering solutions required vast amounts of non-renewable energy.

Since 1969, when Banham so eloquently analyzed this state of affairs, a combination of economic, social, and even professional pressures have prompted designers to begin again to assume some responsibility for the provision of comfort, through the manipulation of space and materials in response to climatic patterns. The most obvious of these pressures has come from the need to optimize the use (and
cost) of non-renewable energy (the term "optimize" is used here very deliberately, as opposed to "conserve" or "minimize"). Perhaps even more important, though less specific, are the forces currently changing the architectural profession as a whole, and their effects upon the tasks of the designer.

Optimization of Comfort and Energy Use

A major premise of this thesis is that the most significant determinants of the ultimate thermal and visual environment, as well as energy efficiency of most building types, are the result of decisions made very early in the design process. They include siting, configuration, locations of functions, choice of materials, fenestration, and facade design. Generally speaking, these decisions determine both what set of climatic forces the building envelope "sees", and how the envelope transforms and transmits these forces to the interior of the building. In addition, sitting and configuration have an important impact upon climatic forces seen (or not seen) by nearby buildings and open areas.

These types of decisions occur early in the design process, during what are commonly referred to as the predesign and schematic design stages. Considering only energy use, this premise is not a particularly original or risky assumption. In fact, the AIA claims that about 40 to 60 percent of the potential energy savings in a project are attainable during these early stages (unfortunately they don't say relative to what; savings are probably based upon "conventional" buildings).(2)

In the real world, optimization of energy use usually means reducing energy costs, which is not necessarily the same thing as minimizing energy use. The tradeoffs between
first costs and operating costs are old and familiar ones—important variables include who is paying what (speculator, owner, tenant), and how costs are evaluated (e.g. life-cycle costing, return on investment). Even if one chooses to minimize operating costs, reducing overall energy consumption is not necessarily the best strategy. Many utilities have adopted rates which vary according to demand (power), time of day, or seasonal use. So, the pattern of a building's energy use can be as important as its total in determining costs.

Usually in any discussion of issues and strategies for improving the energy efficiency of buildings, it is assumed that comfort is maintained. A description of comfort and its criteria appear in a later chapter, but it should be noted here that much more freedom and efficiency in design is afforded by viewing thermal and visual comfort parameters as dynamic forces to be manipulated rather than as static requirements.

Opportunities and Dilemmas

The second major premise follows from the first. If we can say that it is the decisions of the designer which have the most significant impact upon a building's comfort and energy use, then the needs of both clients and society shall require the designer to become more capable of producing efficient buildings. Pressure from clients (owners and/or occupants) will result primarily from concern about energy costs. It is probable that in the long run, the cost of non-renewable energy will continue to outstrip inflation, so this pressure should only increase.

Perhaps more important though, will be the growing concern of society (in this country and elsewhere) about the "external" costs of high energy consumption, and the cor-
responding social benefits from conservation. We have been aware of these externalities for a long time, but some are just now reaching crisis proportions (such as acid rain and CO₂ levels in the atmosphere). It has been estimated that about 30 to 40 percent of the national energy budget is consumed in the construction and operation of our building stock. The potential savings are tremendous. And they are being codified into standards and regulations to assure new construction will achieve those savings. These codes either prescribe minimum material and equipment specifications (prescriptive standards) or define maximum allowable energy budgets for different building types, and calculation methods to determine if a design can meet the budget (performance standards).

These new forces upon the built environment—economic pressures for optimum energy use, and social pressures for minimum energy use and basic comfort criteriapresent both an opportunity and a dilemma for designers. The opportunity is to reassert the role of built form together with mechanical systems, as determinants of a building's environment. Habraken notes "If one accepts the view of the building as a combination of a number of very different systems, each with their own elements and structure, forming configurations in space that join and separate, support or complement each other, and sometimes have quite different life spans and 'modes of existence,' then one accepts a sophisticated (and I would say intellectually interesting) model that poses very intriguing design questions."(3) This opportunity is only being very slowly seized by the design community.

The dilemma lies in the complexities involved in turning environmental requirements into building elements. The physical processes governing the flows of energy through buildings are like the processes of design itself—full of interactions, each seeming to require simultaneous con-
sideration. One cannot deal with the many aspects of comfort and energy use as unique phenomena, in a sub-optimization process which results in an overall "best" solution, any more than one can create the ideal house by designing optimum rooms and joining them. Designers need an almost intuitive understanding of the interrelationships among comfort, climate, and built form. One is tempted to say that this understanding must be "regained", and certainly there is much to learn from traditional form-making of different cultures. But given new building typologies, different and complex patterns of use, a huge variety of mechanical systems and controls, new materials, and of course, new pressures, the problems to be solved are quite different from those before the modern era.

Design Tools

This brings us to the central thesis of the work presented herein. Environmental designers currently need analytical tools to address issues of comfort and energy use in buildings. They need tools which reveal the physical processes and interactions at play, as opposed to design aids which obscure, and simply provide an "answer". What is commonly referred to as "energy-conscious design" shall not become a reality until an understanding of these processes truly becomes part of the consciousness of the designer rather than a separate consideration. Towards this end, we need tools which are educational, which impart this understanding, and in so doing, perhaps render themselves obsolete.

As important as what they convey, is how analytical design tools convey information. They must be complementary to the working methods of designers, to their ways of problem-solving. This calls for a great deal of flexibility, of slack, in the use of such tools.
It has been said that to be a "success", a design tool for the analysis of comfort and energy use must be "useful, usable, and used."(4) To be useful, the tool should impart an understanding of the interplay between energy and buildings. To be usable, a tool must be flexible and compatible with the design process, providing the appropriate type of feedback at various stages of the process. And to be used, the tool itself must be understandable, easy to use, and provide immediate feedback on design options and proposals.

The microcomputer appears to be the ideal vehicle for such design tools. The considerable computation power is obviously useful in performing the more tedious calculation tasks which are a central part of these analyses. Feedback can be provided with impressive speed. Microcomputers are relatively inexpensive, and rapidly becoming commonplace in schools and professional offices. They can be economically devoted to specific tasks, such as design analyses.

More interesting, though, is the emerging potential for sophisticated interaction between the designer and the machine. This is of crucial importance for the comprehensible representation of the complex relationships which exist in the analyses of comfort and built form. "Designer-friendly" programs can now make extensive use of interactive graphics and relational networks to provide an intuitively understandable exchange of information. They can "make a direct link between solution and performance, restoring to the architect his 'feel' for what he is doing."(5) This in fact is the "bottom line" for these types of design tools, supporting and restoring the "feel" for comfort and its sensitivity to built form.

In the chapters that follow, some of the important considerations in the development of design tools for energy analysis shall be examined. First, a brief overview is
presented of various attempts to characterize the nature of the architectural design process; this provides some understanding of the operations and vocabulary of design. The ramifications of these for the capabilities and modes of interaction required of design tools are then drawn out, with some discussion of the successes and shortcomings of selected energy analysis methods. Upon this basis, an environmental model is proposed and described, one which consists of a "family" of interactive analyses. The semantic and syntactic structure of the model and its hypothetical implementation as a series of microcomputer programs are discussed, in the context of "designer-machine conversations". Finally, we conclude with a short description and analysis of one member of the "family" which has been encoded, for the analysis of daylighting in a space.
On the Nature of Design

Architectural Morphology

It should be an obvious first step in the design of any analytical tool to understand the process which the tool is assisting. Unfortunately, the failure (as gauged by lack of acceptance) of many such tools intended for use by environmental designers is often due to insufficient understanding of the nature of how designers design.

Perhaps this should not be surprising, since architecture itself defies simple models or descriptions. We can break it down into categories, observe its evolution, and make judgements about its results; yet we find it difficult to rationally express how "architecture" comes into being (or even what it is).

In this respect, architectural design has been likened to language, both characterized as "artificial morphologies". (1) An artificial morphology can be assumed to result from cognitive behavior by people. The semantic and syntactic structure, the embodiment of meaning, in such a system, seems to be intuitively understood; meaning transferred within the system, without this process being externalisable. In language, this structure permits "rule-governed creativity", or the ability to derive and transmit meaning from unfamiliar experiences. For example, the meaning of an unfamiliar word can often be inferred from the context of the surrounding words, expressions, gestures, etc.

Hillier and Leaman have noted that both architecture and
language "either is or contains, a system of social signification. It is this, rather than the physical nature and form of the morphology that renders it opaque to present scientific understanding. In the case of architecture, the problem resides in how architecture 'works' in relation to society. How and why do different societies at different times construct and transform artificial space, and what is the effect of these transformations. How can the 'intelligibility' of artificial space be accounted for and reconstructed?" (2).

These observations point out an inability to "rationalize" architecture and the design process, because of the social and cultural meaning inherent in the morphology. This becomes an important consideration for the development of appropriate analytical tools for design. As will be discussed in a later chapter, any tool for the analysis of thermal and visual comfort in buildings is in fact a model of a natural morphology (e.g. thermodynamics). Meaning in these natural systems lies in algorithmic relationships contained in "models", and one can use these relationships in processes complementary to "rule-governed creativity".

The difficulty in modeling the architectural design process does not mean that models have not been proposed, or that we can say nothing about it. In fact, much can be learned from past attempts to do so. They have spurred introspection on the part of designers and others regarding what we can say. We can talk about the criteria of design problems, constraints, basic operations performed, when and why the process stops, how information is gathered, and so on. It is this understanding which is needed to successfully integrate energy analysis with conceptual design.
Design and Construction Overview

Before delving into the nature of the ethereal design process, let us consider the more mundane context of the entire building process, and define more precisely what is meant by the term "conceptual design".

The standard design and construction flowchart consists of six successive phases—programming and predesign, schematic design, design development, construction documents, construction management, and postconstruction. In theory, each of these phases are independent of the others—one begins upon the completion of the previous phase. However, the distinctions between the phases is never particularly clear; certainly there is a great deal of overlap even at this level.

Conceptual design in this schema encompasses the programming and predesign phase, the schematic design phase, and some small part of the design development phase. To be sure, these distinctions are somewhat arbitrary, but they span the steps from information-gathering to the complete spatial synthesis. They have also been called the briefing and sketch design phases.

Programming and predesign are primarily information-gathering and synthesis operations. Feasibility studies, space need projections, flow diagrams, facilities surveys, occupancy scheduling, and budgeting occur during this phase. Schematic design results in siting, massing, zoning, and major materials decisions. During the design development phase, detailed drawings and documents are prepared, mechanical, electrical, and structural services are specified, and costing is performed.

Such a general level of description does not provide much insight into how built form comes into being. However, it
does provide a familiar context for examining the much more complex processes that occur within primarily the predesign and schematic design phases. It bears repeating that it is here that the most significant impacts upon the energy use and comfort conditions in buildings can be made.

Design as Problem-Solving

Theorists and practitioners studying the architectural design process over the last two decades have regarded design as a special kind of problem-solving process. Models from the general theory of problem-solving have been used as a framework for these studies.

A problem arises from the existence of goals, and problem-solving is the cognitive behavior directed toward the attainment of these goals. Not all goal-directed behavior can be deemed as problem-solving, though. If the steps necessary to attain the goals are obvious, then there is no problem. If I am in a cold house, and see a thermostat on the wall, there is no problem. If I turn up the thermostat and nothing happens, I've got a problem. More formally, "we say a system has a problem when it has or has been given a description of something but does not yet have anything that satisfies the description".(3)

The general theory of problem-solving begins with a representation of the system under consideration. Problem-solving is the process of searching through alternative states of the representation, until a state is reached which meets certain criteria.

This framework seems intuitively appropriate for problems in the realms of the physical sciences and engineering. Their solution procedures arise from theories of natural morphologies, in the form of models driven by algorithmic
relationships. These types of problems are referred to as "well-defined" or "well-constructed" problems, because within the theory of the morphology, a proposed solution can be tested to determine if it is "true" (or correct). Furthermore, it is stipulated that the test must confirm or deny truth-hood in a finite number of steps; in other words, if a system can only determine the correctness of a proposed solution by generating known solutions until the proposal is generated, the proposal may never be proved and the system is not considered to be well-defined.

Now, in the good old days (i.e. the Newtonian era), it was firmly believed that most problems of the natural and physical sciences could be classified as well-defined. Within these formal systems, theorems could be tested, validated, and become part of the body of knowledge of the system upon which further explorations are based. However, the discoveries by Einstein and Bohr in physics, Godel in mathematics, and others have shown that formal systems (or representations) cannot test the truth-hood of the entire system, that it can never be self-describing. And more recently, philosophers of science such as Popper, Kuhn and Feyerabend have raised serious questions about search procedures and objectivity of criteria (i.e. methodology) in the physical and natural sciences. Perhaps the structure of science is also shaped by a rule-governed creativity similar to artificial morphologies. In any event, it can be said that the well-defined problems of the sciences are not without uncertainties regarding their models, search procedures, and evaluation criteria.

Early attempts at creating representations of the architectural design process, most notably by Alexander, tried to use the framework and techniques of well-defined problems. More recently, ideas from the sciences of the artificial have been applied to the study of environmental design problem-solving as an "ill-defined" process. (4)
Rittel terms this ill-defined process as one composed of "wicked" problems (as opposed to "tame" or "benign" problems which can be solved by straightforward systematic procedures).(5) The characteristics of wicked problems are crucial to gaining an understanding of the nature of design.

Wicked problems have no definitive formulation: a formulation of an environmental design problem is an entirely subjective process, coming as it does from a messy, tangled, information-rich context. Many criteria are implicitly held, and information is never complete. No definitive formulation is given at the outset of the design process, and as design progresses, the formulation does not remain stable; conditions and criteria may change.

Every formulation of a wicked problem corresponds to a formulation of the solution, and vice versa: this is analogous to characteristics of quantum mechanics, in which the act of observation is inseparable from what is observed, and the method of observation will have an effect upon the behavior of the observed (and vice versa). Problem formulation in design is filtered through a designer's network of modes of observation and conceptualization, and subjective responses. For example, how one perceives and defines space will play a large role in problem formulation, and the solution process. As mentioned earlier, the solution process can be considered a search through various states of the problem formulation, and the "search rules" (e.g. hierarchical, relational, heuristic) shape and are shaped by the formulation.

Every wicked problem is a symptom of another wicked problem: or which came first, the chicken or the egg (or the next chicken, or egg,...). Every problem should be considered as the symptom of a higher order problem, and the original problem is in fact the product of lower level symptoms. This is an important point, because it implies there is no obvious entry level for approaching a wicked problem. This belies the logic of top-down design.

Wicked problems have no stopping rule: a solution can always be improved upon. The process continues until the designer has run out of time, resources, or patience. Time and resources are typically equated; this has important ramifications for the usefulness of analytic design tools.
The solution to a wicked problem can never be true or false, it can only be good or bad; because the solution to wicked problems are not based solely upon the algorithmic relationships of natural morphologies. Instead, their validation is based upon other relationships, such as correspondence with historically derived solutions, past experience, etc. Wicked problem solutions are judged by values, and hence are good or bad, not true or false.

The solution to a wicked problem has no immediate or ultimate test: this characteristic is a direct result of the previous one. It states the main difference between well-defined and ill-defined problems, the issue of testability. Since many of the consequences of a design solution will only become apparent in the future, there is no way of testing for these in the present.

Wicked problems have an inexhaustible list of admissible operations: a culmination of some preceding characteristics, this simply means that since the process is unbounded, and the conditions and criteria unstable (and often contradictory), there is no fixed palette of search procedures for arriving at a solution. As Feyerabend wrote regarding scientific methodology, "anything goes."(6)

So what lessons are to be learned from this? These characteristics address design at a systems level, where there are initially unknown as well as known goals, subjective and objective criteria, and questions of values and standards. Definition of problems is as difficult and important as the solution (and in reality cannot be separated). And it is not amenable to optimization of solutions, but instead is more a process of "satisficing",(7) where there is no single right answer, but instead a range of solutions, some better than others.

As implied in the wicked problem characteristics, an environmental design problem is in fact a collection of problems at different levels- sub-problems, if you will. The sub-problems are integrally linked together, yet their solution processes (search procedures) will be very different, and solutions perhaps contradictory. This is a
familiar and frustrating experience for design students; it seems that one must work on many sub-problems simultaneously, yet independently, with no guarantee that the results will "work".

Undoubtedly, as we design, the bounds of sub-problems change. The "level" at which we deal with problems changes constantly. We deal with issues of value and function as part of form, and we deal with form as a purely physical manipulation. A sub-problem can be treated as both an "instance" and a "class". We view problems as instances, or manifestations, which are somewhat unique and definable, yet they can also serve as classes, or prototypes for the consideration of other problems.

The point to be understood is that the processes by which a designer comes to a solution, or proposal, operate on many levels, with "meaning" embodied in many ways. Consider that each sub-problem cycles through these levels in unique sequences, at different rates. One cannot even really consider these levels as discrete aspects in "sub-problem-solving". The processes are "so clearly interwoven that it is not operationally useful to separate them." Solutions emerge with problem definitions, different sub-problems interact and overlap with each other, and within a sub-problem, the levels of meaning interact and overlap.

It is interesting to step back at this point and note the progression of design process modelling over the past twenty years, as a way of visualizing this problem-solving maze. Hickling has categorized the evolution into five stages. These are shown in figures 2.1a-e. The first type are the linear processes in which one deals with one aspect of the design problem until a solution is reached and then moves on, never to return. The next type is the linear iterative process, wherein recycling and feedback mechanisms are introduced to shore up the obvious gaps in
the linear models. However, the very notion of linearity is limiting, even if iterative. Hence the subsequent stage is that of the cyclic iterative process. In such a model, the skipping back and forth permitted in linear iterations is not treated as temporary "setbacks" but considered as quite normal. This is also dubbed a "learning" process.

An even greater level of freedom is encouraged in the next logical type, the cyclic whirling process. This step attempts to encourage the act of "creative insight", modelled as jumps between stages of the solution process (as opposed to the iterative models which allowed these jumps, but still considered the norm to be cycling within a stage). The final step is one in which each of the problem-solving stages in the cyclic whirling process, which also embody decisions, is extended into its own cyclic whirling pattern. This extension of course, could go on indefinitely, and perhaps does in the real processes these patterns attempt to model. Note the emerging similarities displayed in figure 2.1e between the complex design process and conceptual models of sub-atomic particles.

Still, all this discussion seems to deal with only the trappings, or the cloud surrounding the act of design. What can we say about the creative moment when the idea takes form, quite literally? In terms of our five fundamental stages, this occurs in the proposal stage, the synthesis of information into a solution.

This is the part that arises from rule-governed creativity, that part of an artificial morphology that is so opaque to rational analysis or description, Darke describes "primary generators" as the agents of this rule-governed creativity.(11) The generators are axiomatic ideas such as intentions (achieving desirable views and privacy in living rooms) or historical allusions (as in post-modernism). Hillier and Leaman have hypothesized that the way in which
we construct artificial space, and how it is intelligible, is governed by an evolutionary code.\(^{(12)}\)

Habraken has listed six basic operations which describe the physical manipulations in which the designer engages to create a proposal.\(^{(13)}\) These operations are the physical manifestation of the act of design, they are the "words" of design.

\textit{Selection of elements}: selection of the physical vocabulary of the designer, the elemental built forms which embody meaning. The scale of the elemental forms is a characteristic of the individual designer; for example they can be volumes, or forms which create volumes (e.g. walls, partitions, windows, columns).

\textit{Determination of the relationships of elements"}:
their relative position in space, adjacencies, enclosures, etc.

\textit{Development of elemental variants}: variations in the use of materials, shapes, dimensions, etc. of elements.

\textit{Site description}: typology, topography, circulation patterns, etc. of the site and region.

\textit{Determination of the relationship of site to elements}: how elements are positioned upon the site.

\textit{Development of variants in the site}: variations of typologies, elements, and use patterns of the site.

Again it appears we can only see the shadow cast by the design process, and not the thing itself. This chapter has been merely an attempt to review what we know about the shadow, and repeat those questions other have asked about the obstruction. Even this cursory understanding of the characteristics and complexities of the design process, however, provides some important insights for the design of tools to be used in this process. The ramifications of these insights are discussed in the next chapter.
2.1a - Linear model

2.1b - Linear iterative model

2.1c - Cyclic iterative model
2.1d- Cyclic whirling model

2.1e- Extended whirling model
The Design of Design Tools

The analyses of thermal and visual comfort in building design can be regarded as well-defined subsets of an ill-defined process. They are based upon the algorithmic relationships of our models of natural morphologies, in this case, the propagation of electromagnetic energy through space.

The ideal analytical tool is one that provides the designer with the type and level of information appropriate to the problem under consideration. Compared to other design issues (e.g. formal and functional relationships), the feedback from these analyses is unique, "hard" data; what will the ambient illumination levels be under these conditions, what air temperature excursions can be expected under those conditions, and so on. Of course, the nature of the questions which can be asked, the analyses performed, and the usefulness of the responses, are dependent upon the models used to represent the physical processes; this is discussed below. The point here is that the analyses will provide unique and complete response for specific problem formulations, and given the assumptions of the model, the responses are "correct", and not open to debate.

What is very much open to debate is the manner in which the analyses and data are used by the designer. They certainly cannot provide solutions to wicked problems, or provide that "intellectual leap of faith" resulting in a proposed solution.(1) Analytical design tools produce elemental "nuggets" of information which are quite meaningless outside of their interpretation and integration into the whole of the problem. They are in fact, "primitives" of wicked
problem-solving, analogous to phonemes in spoken language, or lines in a drawing.

This is not to say that primitives are trivial or simple. On the contrary, energy analyses for example, quickly become very complex, dealing with many variables and interactions. And for many design sub-problem formulations, primitives will provide most of the insights leading towards proposed solutions. The distinction between primitives and techniques which generate wicked problem solutions is not always clear. "Expert systems" such as those currently performing medical diagnoses, are speculated for use in architectural design. These systems may perform many of the tasks associated with design, such as detailing design, space layouts, environmental systems design, structural design, and others. Are these sophisticated primitives or intelligent systems?

Given the primitive nature of analytical tools, the question of how they are best integrated into the problem-solving process is raised. Analyses are usually separated into two general types; those that lead to decisions and those that analyze those decisions. In terms of the fundamental stages of a design sub-problem, these correspond to the preparation and evaluation stages, respectively (note that the types of analyses therefore bracket the proposal stage).

Energy analysis techniques in the preparation stage are predictive; they are used to identify potential problems for a given program, and aid in the formulation of design strategies for dealing with these problems. A familiar example of this is the psychrometric chart (figure 3.1). Regional climatic variables (dry bulb temperature and relative humidity) can be plotted on the chart for each month, and the position of the resulting profiles in relation to the comfort zone identifies the type of climatic modifi-
cations that need be provided by the building and its sys-
tems. On top of this chart, one can overlay "strategies" for these modifications (figure 3.2), such as ventilation, radiative cooling, evaporative cooling, solar heating, etc. The bioclimatic chart, developed by Olgyay, is a ver-
sion of the psychrometric chart, specifically for archi-
tects. Recently it has been updated to accomodate new re-
search on comfort conditions.(2) Both of these tools ana-
lyze ambient climatic conditions relative to comfort, and suggest design strategies for improving uncomfortable situations.

A recently developed analysis tool called "Energy Graphics" addresses the issue of energy consumption in buildings in a fashion similar to how the psychrometric and bioclimatic chart deal with comfort.(3) In this technique, the de-
signer organizes programmatic requirements into "energy use groups", distinguished by schedules of use, internal heat generation, and allowable temperature ranges. Very gene-
ral, standard assumptions are then made about envelope di-
mensions and thermal properties for each of these groups, and the energy performance of each group is computed. The results of the calculations provide guidelines for deve-
loping design strategies for improved performance of each use group.

The second general type of analyses are evaluative; they are used to evaluate design decisions. For example, with Energy Graphics, refinements based upon the guidelines from the base case analysis, are in turn analyzed to evaluate the success of the design strategies. Energy Graphics is able to perform both predictive and evaluative functions by normalizing most building form variables for the first evaluation, thereby establishing a base case from which guidelines are drawn.

The key difference between the two types of analyses lies
in their relationship to the proposal stage. Predictive analyses are needed to provide one with strategies for turning environmental requirements into building elements. Evaluative analyses can only proceed after a solution has been proposed. Both functions need accommodation in a design tool; one that is solely evaluative will not tell a designer what sort of building elements will provide the desired environmental requirements, but rather what conditions will result from a set of building elements. Lawson calls this "backwards thinking" for the architect. (4)

Appropriate Analyses

To be truly useful, a design tool should impart to the designer an understanding of the physical processes being analyzed. This can be done by establishing a clear link between the solution and its performance. How is built form a manifestation of the strategies suggested by predictive analyses, and why does it behave as the evaluative analyses predict it shall? The tool should not appear as a "black box" to the designer, from which an answer magically appears.

Design tools are educational, and should make themselves obsolete after the designer has "internalized" the processes and relationships they analyze. This understanding of the first principles of energy and buildings must be internal to a designer's thinking, must become part of the "feel" of design. An architect's education, whether in school or in practice, is largely received in the context of environmental design problem-solving, so these first principles should also be learned in this context. Again, the tool should not just provide a "bottom-line" answer, but impart an understanding of physical processes.

Most energy tools for designers calculate loads, the amount
of energy consumed in a building under standard weather conditions for a specified interior temperature range. Typical lighting analyses will determine the raw illuminance levels across a space from windows and artificial sources. If a designer makes some change in the built form, the effects upon energy consumption and lighting are calculated. This type of analytical tool is purely evaluative; it also assumes that one or two types of feedback are sufficient to characterize the interactions between energy and built form. No direct link is established between design alternatives and their effects upon energy use and comfort, other than via consumption. If a designer lowers the location of windows in an office space, a corresponding shift in illumination towards the window wall will be seen, but the cause of the change will not. The effects upon other room surfaces (glare discomfort, visibility, etc.) are not addressed, and one is left to draw their own conclusions about the processes taking place. Unfortunately, many design aids, especially computerized ones, operate in this way, seemingly under the belief that providing the bottom line is the most important function.

Also, these types of tools contain the implicit assumption that comfort (thermal or visual) is provided, usually on the basis of one variable (room air temperature). This is almost ironic, since comfort is one of the primary functions of environmental design, one in which the interplay between building form and energy flows is all important.

The perception of comfort, both visual and thermal, is a psychological as well as physiological phenomenon. As such, it has proven difficult to establish rigorous quantitative indices which take into account all of the important parameters governing the perceptions. In the case of thermal comfort, over the years many controlled studies have been performed to develop correlations between physiological factors (respiration, perspiration, skin tem-
perature) and environmental factors (air temperature, humidity, radiant temperature, and air velocity).(5) "Comfort equations" have been produced, but the uncertainties inherent between controlled chamber experiments and the real world have caused many to question their usefulness. The same situation applies for issues of visual comfort and performance. Indices for the evaluation of glare discomfort, perceived brightness, and visibility exist, but are not universally accepted.

Given the current questions regarding the accuracy of comfort equations and indices, perhaps their real usefulness lies in their role as warning flags to the designer. They can indicate when one is bordering on unacceptable thermal or visual conditions. However, even in this limited role, the indices should not be used to obscure the variables they bring together. A designer should know the air temperature, humidity, radiant temperatures, etc. as well as the index value which they make up. One can then decide how much to depend upon an index, and how much upon experience and intuition.

In the preceding chapter, architectural design was described as rule-governed creativity; the ways in which we perceive and understand space are somehow codified, in a manner we cannot explicitly express. This code allows us to translate the meanings of space into new designs. The code is like an algorithm which we are quite unable to write down. Environmental analyses are also algorithmic codes, of a much more explicit nature. To the extent possible, these algorithms should be the first principles governing the flow of energy through buildings. Designers need tools which reveal first principles rather than obscure them in assumptions and artificial relationships. The first principles are the purest form-givers. They also describe the most intuitively understandable relationships and hence are most appropriate for use with the creative
algorithms of design.

Architectural decisions deal with siting, form, and physical use patterns of a building (and how these may change over time). Appropriate energy analyses must address these decisions in terms of environmental requirements (such as availability and access to sunlight, exposure to wind, ambient temperature and humidity patterns), and the transformations of all these by the building envelope, its form, materials, and their properties. These transformations result in interior sunlight patterns and solar gain, temperature and humidity excursions, infiltration and ventilation patterns; in short, the environmental parameters of thermal and visual comfort. Energy consumption and efficiency is almost a by-product of this process; if desired conditions cannot be provided by built form transformations of climatic energy patterns, then auxiliary energy must be added. This is a very different emphasis than is usually found in energy tools.

This also brings up another sense in which these analyses are primitives of the design process. Within the context of the natural systems being considered, we make a clear distinction between physical form and energy patterns. This permits not only an understanding of the relationships between them, but also emphasizes the manipulation of form as the variable directly controlled by the designer. Habraken writes "design as a exploration of a possible environment, and its potential for use and meaning, must begin with the autonomy of form to proceed towards its possible meanings and possible uses, given certain uses."(6) Issues such as function and values are introduced by the designer in the translation of the analyses, not the analyses themselves.

Energy in buildings should not be treated as a static quantity, but instead as a constantly flowing stream. Most
basic equations of heat transfer express energy as a rate (Btu/hr, or Watts). This, of course, is the definition of power. Even comfort is the result of continuous energy exchanges between the body and environment. The designer must know how these exchanges, and the energy required to maintain them, will vary over time. Recently, energy utilities have begun varying the price of energy on the basis of consumption patterns, or power profiles, as opposed to pricing based upon the amount of energy consumed. As a result, a designer must also be concerned with not only total energy use, but when and at what rates that consumption occurs.{(7)}

To condense and summarize these points, let us say that appropriate design analyses reveal the basic interplays between energy flows and building form, which result in the environmental conditions we perceive as comfort. This should be done through the use of fundamental algorithmic relationships (first principles) which can be manipulated by the designer in much the same way that one's "formal vocabulary" is manipulated, by intuition and rule-governed creativity. The design tool should encourage internalization of these principles.

As an illustration of these points, consider a tool for the analysis of the performance of passive solar residences, the Solar Savings Fraction (SSF) method developed at Los Alamos Scientific Laboratory.(8) SSF is defined as the fraction of the annual energy load of a base case house which can be saved through the use of passive solar heating techniques. The basic parameters of the base case house (glazing area to floor area ratios, thermal mass) are given. An acceptable interior temperature swing is also fixed, hence comfort is also "given". Cooling is not addressed, other than to say that venting is assumed to prevent overheating. The most interesting feature of the method is the manner in which the SSF is determined. The
designer calculates two ratios, one representing building parameters (heat loss coefficient of the envelope divided by the solar collector area) and the other representing climatic parameters (solar gain divided by degree days). The SSF is calculated as a function of these two ratios. The functional relationships were derived from statistical fits (correlations) to computer simulations of hundreds of houses covering a range of parameters. The computer model is a basic thermal network.

In this type of correlation method, the designer is far removed from the basic relationships of heat transfer which are buried in the computer model. Instead, energy performance is perceived as driven by some rather unfamiliar (and not particularly intuitive) parameters. There is not much obvious meaning in a quantity representing the ratio of heat loss to effective solar glazing area. Any understanding of the principles of heat transfer in buildings is only laboriously extracted.

Analyses for Wicked Problems

The last section examined what type of questions a designer needs to ask of an analytical tool. In this section, we look at the subject of how those questions are asked. More specifically, how must the use of a design tool accommodate the demands of wicked problems?

An important characteristic of wicked problems is the changing nature of the problem formulation. Typically, the goals and information available early in the design process are incomplete and general. They include implicit intentions and criteria. Lawson states, "in the natural process, the early stages of design tend to be more concerned with patterns and relationships. The scheme is seen in sketchy outline with an overall feel for the quality of..."
environment. The actual size and thickness of things is filled in later." (9)

This characteristic calls for flexibility in several ways. First, a design tool must be able to accommodate varying levels of information specificity and completeness. Incomplete or vague data can be filled in with reasonable assumptions (if amenable to the designer), perhaps based upon past responses. Also, frequent changes in the available information must be expected, as alternatives are compared, or more information becomes available.

Flexibility in the form of feedback to the designer is needed. Early in design, one wants to know about the overall patterns of emerging environmental conditions. Analyses should act as general warning flags, letting the designer know about serious potential problems in a strategy. As the problem formulation and proposed solution become more detailed, so should the level of analysis. For example, early daylighting analyses may provide data on general daylight availability and illuminance gradients at desktop height throughout a space. Later, as design decisions at a more detailed level are made (such as wall materials, window detailing, etc.), analyses are needed which address surface exitances, veiling reflections, and glare discomfort.

The hierarchy and interactions among sub-problems and their solutions also present some dilemmas for design tool use. It has already been noted that design is not the type of process where one can optimize sub-problem solutions, and combine these solutions into an overall optimum. This is because sub-problem criteria are often contradictory. What is a good strategy for one aspect of the design may interfere with a good strategy for another aspect.

A useful design tool should therefore have the capability
of analyzing sub-problem formulations in isolation, as well as the interactions among sub-problems. The interactions between daylighting and space conditioning loads provide an example. One can optimize a space to take advantage of daylight availability. This analysis will also indicate where and when artificial lighting is needed. However, these concerns need to be balanced with those of solar gains and their effects on air conditioning. At this point then, an analysis should be performed to determine the conditioning loads including the radiant gains from both daylight and artificial light. This may result in the modification of the fenestration design, room geometry, and so on. If a designer only has the tools to determine lighting levels, a balanced evaluation of the interactions of design alternatives cannot be made.

A design tool can include appropriate analyses, and include the functions necessary to be compatible with wicked problems, but this is no guarantee that the tool will be comprehensible to the designer. The capabilities and limitations of any analysis must be known to the user, or the tool may be used improperly and its results misinterpreted. These are issues of how the designer perceives the tool; how must a problem be formulated for the analysis, and how are the results presented. Here we shall briefly discuss some of these issues in general; specific implementation will be presented in the later chapters.

In principle, the problem formulation for a technical analysis should involve the operations and representations to which a designer is accustomed, both to facilitate the understanding of the tool, as well as to ease integration into the design process. The basic manipulations of physical elements described in the last chapter, selection of elements, relative positioning of elements, site description, and the relationships of elements to site, need to be clearly delineated as discrete functions. Several
computerized energy analyses currently available combine some of these operations in ways which make it difficult to make physical changes (such as moving the position of a window in a wall), or even to be sure what the program thinks the building looks like. As will be shown later, the organization of these operations becomes critical when spatial relationships are important.

The Computerized Instrumented Residential Analysis (CIRA) program is an example of one computerized tool in which the problem formulation is presented clearly to the user.(10) Though not intended to be a design tool, its organization is complementary to the process. The user creates components of walls, windows, floors and ceilings. To each component are ascribed dimensions, orientation, and thermal properties. These data are already part of a designer's vocabulary. In other methods (such as SSF), these same components are described in terms of heat loss coefficients, a "component" which is not part of the standard vocabulary.

The form of the feedback from the tool to the designer should also make use of this vocabulary. If appropriate analyses are those that clearly show the relationships between energy and form, then so must the representations of those relationships. Spatially or temporally varying data should be provided in a context that illustrates these variations. Feedback should show trends and patterns over space and time, rather than as static quantities. It is often remarked that architectural designers are visually-oriented, and graphic representations of the transformations of energy flows by building elements are extremely important for conveying an intuitive "feel" for processes at work. If one can actually "see" the radiant temperatures of room surfaces, or the luminous distribution within a field of view, much more meaning is conveyed than would be possible through tabular or numeric forms of
In this chapter, some desirable and necessary features of a useful conceptual design tool for energy analysis have been outlined. These include appropriate analyses, flexibility of use and meaning, and the use of a familiar vocabulary. In the following chapters, the model for such a tool shall be proposed based upon these observations.
3.1 Psychrometric chart
Definitions

Inherent in our understanding of any morphology, natural or artificial, are the notions of theory and model. The object of theory is the set of transformations or invariances which comprise the behavior of the morphology. A theory takes the form of a model, made of symbols which represent these transformations and invariances. The model and its symbols are the "code" by which we understand the space-time morphology. Operations on the symbols should reproduce observed transformations in the morphology. We then say that the theory and model have captured the behavior of the system in symbols, and can use these to predict the behavior under specified conditions. This basic definition applies to models as simple as calling the flip of a coin, or as complex as predicting hemispheric weather patterns.

In the context of buildings and energy use, we are concerned with environmental models. An environmental model can be defined as "some formal structure which relates a property of a built form to some physical quantity of heat, light or sound and some 'external' stimulus."(1)

There are three key parts to this definition, built form (elements and properties), energy flows (heat transfer, luminous flux, sound waves), and stimuli (temperature differentials, air pressure). Stimuli, more accurately termed "energy potentials", drive the flows of energy, which are "mediated" by built form. Somewhat analogous to the inextricably intertwined aspects of the design process, the mediations by built form elements can alter the flows of energy, which in turn
affect the potentials, and so on.

These relationships are evident in the basic equations which alone make up perhaps the simplest environmental models. For example, the equation for the steady-state conduction of heat through a building element is

\[ Q = UA \cdot dT \]

where the flow of energy (heat transfer, \( Q \)) is a function of properties of the built elements (area \( A \), conductance \( U \)) and energy potentials (temperature differential \( dT \)). A fundamental equation describing the behavior of light is the inverse square law of illuminance,

\[ E = \frac{I}{d^2} \]

where the flow of energy, in this case the illuminance incident upon a surface, is the result of properties of built form (\( d \), the distance between the light source and the receiving surface) and the driving potentials (\( I \), the intensity of the source). These three fundamental components are found in other models of radiant transfers, convective flows, acoustics, etc.

Simply stated, an environmental model provides a framework or context for understanding the interactions between physical elements, energy flows, and the potentials which drive them. And it can illustrate the sensitivities or relative importance of the different parts of the model. This is particularly important for those aspects under the control of the environmental designer, the properties, dimensions, and location in space of built form. In the conduction equation discussed above, for example, heat transfer is directly proportional to the area or conductance of the material considered. Illuminance is inversely proportional to the square of the distance between the source and surface (assuming a point light source).
Environmental models on the scale of the conductance and illuminance equations are not of much help to the architectural designer, however. Not only is an understanding of individual forms of energy potentials and flows needed, but more important are the interrelated, cumulative, and secondary effects of the passage of energy through the built environment, and their effect on thermal and luminous comfort. This calls for an environmental model based upon a "conceptual algorithm" at a larger scale than the fundamental equations of which it is comprised.

A more useful environmental model should consider regional climatic patterns as the initial potentials or stimuli driving energy flows through the built environment. The final potentials of interest are those which are perceived as "comfort" (or lack thereof) by the occupants of the environment, and the resources required to maintain those potentials. The mediation of energy flows by built and natural forms at physical scales of site, building envelope, zone, surface, and human, must all be considered. The variety of forms of energy which need to be included are determined by the potentials of interest. These include sensible temperature, vapor pressure, radiant temperature, luminous intensity, and air pressure.

In the remainder of this chapter, an environmental model containing the expanded capabilities just defined is proposed. Its components, organization, analyses, and use are described.

Model Description

Because designers tend to be "spatially-oriented", it seems natural to organize an environmental model around the concept of the flow of energy through space, and how it is transformed by the natural and built environment. Specifically, since these flows are driven by potentials, and since physio-
logically we sense energy potentials rather than energy flows (e.g. temperature as opposed to heat flow), it is more useful to consider the transformations of potentials, as they propel the flows of energy from climatic sources to the site, through the building skin and interior zones, ultimately to create the thermal and luminous environment experienced by the occupants. The environmental model proposed herein lets the designer follow the path of these flows, as they are filtered by the screens of built form.

To facilitate discussion, let us call this model "TRACERY". The Penguin Dictionary of Architecture defines "tracery" as "the ornamental intersecting upper part of a window, screen, or panel...". Research is continuing on the derivation of a suitable expression for which "TRACERY" is the acronym, but in the meantime, that it simply catches the spirit of the model is sufficient justification its adoption.

The primary conceptual components of TRACERY are explicit derivations of those described in the simpler environmental models discussed earlier. They are energy potentials, energy flows, and their transformations from interactions with built and natural forms. In addition, the notion of "constraints" on acceptable potentials is introduced. These components shall be defined, and their organizations and interactions at different scales in TRACERY described.

**Energy Potentials and Flows** The term "energy potential" has been used so far to describe the stimuli which drive energy flows. In the realm of physics, potential energy is the energy embodied in a system. Typically, this embodied energy represents that required to transform or move the system from a "higher" order state to a "lower" order one. Consider the "system" of a ball on a table on a floor. The potential energy in the system is embodied in the elevated, higher state of the ball, and there is pressure on the ball to come to rest on the floor (the lowest state of the system).
Inherent to the idea of potential energy, then, is a difference in energy states in a system, and pressure for energy to flow from the higher to lower state. If we define TRACERY as the system, the initial energy state or potential is climate and regionally induced. The final potential state is that perceived physically as thermal and luminous comfort. Potentials at intermediate stages include those encountered at building envelope and interior zone scales. Energy potentials included in the model can be categorized by type:

- sensible temperature differences, which represent perhaps the most familiar potentials. Air, ground, and material surface temperatures directly drive conductive heat transfers, and indirectly affect radiant and convective transfers.

- vapor pressure potentials, represented by absolute or relative humidity, control the transfer of latent heat energy.

- radiant temperature differences, which determine radiant transfers such as solar gain, and night radiant cooling. Mean radiant temperature is a product of net perceived radiant temperatures.

- luminous intensities, resulting in luminous flux and corresponding surface illuminances and exitances.

- air pressure differences across openings in building envelopes cause air exchange (and the associated heat and vapor transfer). Air pressures can be naturally induced by wind and temperature effects, resulting in infiltration and natural ventilation, or it can be induced by fan power (forced ventilation).

Transformations Energy potentials provide the "pressure" for energy to flow through some medium. The media of interest in architectural design are those of the built environment, landscape elements, building forms, interior zones, materials, etc. The nature of transformations depends, of course, upon the type of energy flow encountered by physical elements, but also upon the characteristics of the physical elements. As mentioned earlier, the specification of these characteristics are traditionally the domain of the designer, the material
properties (conductivity, heat capacity, reflectivity, etc.),
the dimensions of elements, the relative position in space of
elements, and their patterns of use. As pointed out by
Habraken in chapter 2, these are fundamental operations of
environmental design.

Often, built and natural forms are designed to change over
time in various ways, which can affect their mediation of
energy flows and potentials. Examples of this include movable
insulation, seasonal patterns of deciduous landscape, adjust-
able awnings, variable transmittance glass, and operable en-
velope openings for natural ventilation. The dynamic behavior
of physical elements in response to environmental conditions
or schedules is an important function included in TRACERY as a
transformation property.

There are three basic ways in which energy potentials and
flows are transformed by built form:

- material properties affect the rate of energy flows,
given constant potentials. For example, if surface
temperatures on either side of a material are held
constant, the rate of heat flow through the material
is determined by the conductivity and thickness of
the material. Air infiltration through a building
envelope is controlled by the size and patterns of
envelope openings. The transmittance of glazing in a
zone will mediate the flow of daylight into the space.

- if the potentials driving energy change in time, as
with climatic sources or building use schedules,
built form elements can alter the patterns of energy
flows by changing the amplitude of variation and the
timing of minima and maxima of periodic patterns.
The most familiar example of this is the effect of
thermal mass on temperature excursions in solar
buildings.

- materials can also change the form of energy flows.
Solar irradiance, predominantly visible radiation, is
absorbed by a material and emitted at longer, infra-
red wavelengths. Some of the heat is transferred to
air in contact with the surface, setting up con-
vective flows.
Constraints

Environmental models are primarily used to play "what if..." games, to test design ideas and alternatives. The necessary operations in these games are not only those of manipulating desired elements, but also of specifying desired behavior of energy potentials. In TRACERY, behavior is controlled by constraints.

Constraints upon potentials are used to set the magnitude or range of acceptable potentials at a given scale. Limits placed upon air temperature, humidity levels, illuminance levels, and ventilation rates are examples. It is the imposition of constraints on potentials in a building zone that creates the need for auxiliary energy to be added. If zone air temperature is constrained between 18 to 24 C (64 to 75 F), then auxiliary heating or cooling energy may be required to maintain this range. Other auxiliary loads can come from humidity control, artificial lighting, and fan power. In the absence of such constraints, one can examine the "floating" behavior of a building, which is quite useful. There are two modes of controlling constraints, conditional (e.g. thermostats, photocells) and scheduled (time of day, seasonal controls).

Model Organization

The main components of TRACERY have been defined, energy potentials and flows, transformations by built and natural forms, and constraints upon potentials. The components interact with each other at a succession of physical scales thusly; initial potentials are incident upon built forms at a given scale, and are transformed into resulting potentials "seen" by forms at the following scale. The process is analogous to water flowing through a series of filters. Each filter can alter the properties of the flow incident upon it (rate, pressure, pH, temperature, etc.); and the properties after passing through the filter are those seen by the next filter.
In TRACERY, there are three filters, or scales of transformation. First are transformations of the site. These result in potentials incident upon the building skin. The next transformations occur at the building zone scale, resulting in potentials seen by the occupant. The last transformations are those at the level of "comfort zone", the position and characteristics of the individual in an interior zone. An analysis of this last scale of transformations is one of the "comfort" of the space. We shall now walk through TRACERY, looking at incident energy potentials, transformations, and resulting potentials, at each of the scales. A graphical overview of TRACERY is presented in figure 4.1.

**Site/Building Form Scale** The initial potentials which drive energy flows incident upon a site are created by regional climatic patterns and human activity (industrialization, urban density, etc.). The potentials and flows seen by the site include air temperature, humidity, solar irradiance, solar illuminance, and wind patterns.

The transformations of the initial potentials occur through the media of site topography, natural landscape elements, and building forms. The resulting potentials comprise the microclimate "experienced" by the exterior envelope of the building under consideration.

**Building Zone Scale** A building zone is defined as an area within the building envelope throughout which the thermal and lighting requirements and inputs are similar. Examples of different zones within an office building might include north zones, south zones, interior zones, and buffer zones (like lobbies, atria, etc.). Residences are usually considered to act as single zones, though greenhouses, attics, and basements can be passive buffer zones.

Incident energy potentials incident upon zone surfaces are either directly from the microclimatic sources (for exterior
envelope surfaces), or indirectly from the microclimate, filtered through adjacent zones. Transformations at this scale are caused by the zone envelope, walls, ceilings, floors, partitions, glazing, and shading devices. The resulting potentials are emitted by zone interior surfaces and air (temperatures, air movement, luminous exitances, etc.). If these potentials are constrained, then auxiliary loads may also be seen.

**Comfort Zone Scale** Comfort zone transformations modify the potentials and energy flows emitted by the interior zone to those physically felt by the body. The comfort zone is determined by the location, orientation, and field of view of the individual in the zone. Also included are the tasks performed, and type of dress. The final potentials are those that comprise the thermal and luminous environment as perceived by the individual.

**Use of the Model**

It was stated earlier in this chapter that to be truly useful, an environmental model must provide a framework for understanding the interactions between built form, energy potentials, and flows. In TRACERY, this framework is organized spatially. Transformations occur along a succession of three spatial scales, from site to zone to body. The resulting energy potentials and flows from transformations at one scale are the incident potentials and flows upon elements at the following scale.

At each level of transformation, one can specify the initial incident energy potentials. These can be the results of previous "upstream" transformations, or else any desired set of design potentials. One also specifies the properties, dimensions, and location of built and natural forms for a given scale. This description can be related to forms described at
a larger scale (for example, locating a zone within a building) or in isolation (with little relation to site elements, other than orientation). These specifications are the "inputs" for the transformations, which produce the potentials seen downstream. Also, if constraints have been placed on potentials, then any auxiliary energy required to satisfy those constraints will result from the transformations.

The structure of TRACERY is designed to maximize both vertical and horizontal flexibility of use. Vertical flexibility allows one to analyze the flow of energy over all scales, from site to individual, or to isolate the transformations occurring at one scale. For example, early in the design process, one might wish to solely evaluate the effects of building position and orientation on the site, noting shadow patterns and resulting incident solar radiation on different elevations for different design alternatives. Later on, as siting and envelope details become known, the transformations occurring at the building zone scale are important, daylight availability, solar gain, etc. Finally, the total net transformations can be determined. Vertical flexibility, however, is not constrained to an order or hierarchy of transformations. Analyses do not have to proceed from site to building zone to personal zone scales.

Horizontal flexibility describes the flexibility available within a given transformation. A useful analysis tool must be able to proceed with the scant level of detailed information often available in the design process; however it must also be able to accept significantly detailed data when available. In the next chapter, the actual structures and processes used to describe potentials and built forms in TRACERY will be discussed, however it should be noted here that these processes have been designed to accommodate varying levels of specificity and easy manipulation, in a way appropriate for designers.
Another variable of horizontal flexibility is the number and type of transformations examined at a given scale. In defining the term "transformation" in TRACERY, it was stated that the nature of the transformation depends upon the type of energy flow encountered. At each scale, a number of types of energy flows are encountered and for each, TRACERY performs an analysis of that transformation. One can perform all the analyses available at a given scale, or only those of particular interest (e.g. lighting vs. thermal transfers).

As currently envisioned, the analyses which could be performed at each scale in TRACERY are

Site/Building Form: shadow patterns on site and building form, irradiation/illumination incident on building form, and site wind patterns;

Building Zone: interior zone surface sunlight patterns, zone lighting (daylighting and artificial), interior zone surface irradiance, air exchange, and zone thermal network;

Personal zone: visual comfort, thermal comfort.

In the next section, each of these analyses shall be described in detail; what feedback is desired, what are suitable algorithms, and what are the information requirements.

Site/Building Form Analyses

Site/Building Form Shadow Patterns The major source of energy striking a site is the sun. For many reasons, it is important to know what areas of a site, and what surfaces of a building form are in sunlight at a given time. This analysis displays shadows cast at a point in time by landscape elements, exterior obstructions (nearby buildings or other built forms), and by the building form under consideration, upon the site and building form.
The basic feedback from this analysis includes a graphic representation of these shadow patterns from different points of view, solar altitude and azimuth angles, the percentage of site and building surfaces in shade at a given time, and the "intensity" of the shadow cast upon a surface. The intensity is a measure of the opaqueness of the shading obstruction. Building form elevations are divided into a grid of subsurfaces, with percentages and intensities calculated for each subsurface.

The most interesting algorithm for use in this analysis comes from computer graphics. Hidden line algorithms can quickly calculate what part of a given surface the sun can "see", given obstructions, ground plane topography, etc. (2) Other required algorithms are standard, such as solar geometry, diffuse reflectance by surfaces, and transmittance factors.

The basic inputs needed are climatic potentials data, including time of year and day, and site description data including site topography, landscape elements, exterior obstructions, and building form.

The primary inputs and outputs for the analysis are shown in figure 4.2.

**Building Form Irradiance/Illuminance** (fig. 4.3) This analysis calculates the solar irradiance and illuminance incident upon the surfaces of a building, after being filtered and reflected by the atmosphere, ground plane, landscape, and exterior obstructions. The irradiance striking the skin of a building is of obvious interest because it is a major source of heat gain in buildings, through both opaque and transmitting materials. Whether one is attempting to minimize or maximize solar gains admitted into a building, it can be important to know how much control is available of the gain reaching the envelope, through siting and building form options. Such information can help a designer make trade-offs...
between these options and the design of the skin. This flexibility may be obscured if only the final heat gains through the envelope are provided.

Illuminance of exterior surfaces is of less direct importance; however it becomes more useful at a later stage in the evaluation of zone daylighting.

There are several options for algorithms to calculate the irradiance from diffuse and direct sources. The most common methods assume an isotropic sky, and calculate a direct and diffuse component of solar irradiance as a function of the ratio of total ambient horizontal irradiance to extraterrestrial irradiance at a given latitude for a given time of day and year. Another method which can be used for both irradiance and illuminance, is based upon standard, non-uniform clear or overcast sky distribution. The diffuse and direct components of irradiance or illuminance are determined from that part of the sky seen by the surface of interest. Data from the shadow analysis determine what fraction of the direct component is actually received by the surface.

Contributions from exterior surface reflections can be a large part of the total energy received. This component is a function of the irradiance and illuminance incident upon the exterior surface, the surface reflectance (lambertian surfaces assumed), and the shape factors involved. Simplifying assumptions regarding the initial incident radiation and shape factors are typically made (e.g. all surfaces are either parallel or perpendicular).

Inputs for this analysis include climatic potentials (atmospheric turbidity, sky distribution functions, ambient horizontal irradiance/illuminance), site description, and data from the site/building form shadow pattern analysis.

**Site Wind Patterns** Microclimatic wind patterns are
important factors in the comfort of outdoor spaces, dispersion of local pollutants (traffic and building exhaust), and the air pressure differentials across a building envelope. Designers need simple models for predicting the effects of site topography, landscape, and building forms on wind direction and speed. One such model has been developed for the translation of measured wind speeds from one site to another, as a function of relative terrain and shielding parameters. Useful for estimating site wind speeds from weather station data, this translation is included in TRACERY for the analysis of envelope air exchange patterns. Wind shear effects are included in the model.

Architectural aerodynamics are extremely complex. The most sophisticated algorithms currently in use cannot represent actual turbulent wind conditions, but instead assume two-dimensional flow patterns around idealized building forms (e.g. cylinders, rectangular sections, etc.).

Building Zone Analyses

Interior Zone Surface Sunlight Patterns (fig. 4.4) This analysis is similar to the site shadow pattern analysis, except here the surfaces of interest are those inside the zone, and areas in direct sunlight are highlighted, as opposed to those in shadow. These areas are determined by window locations and dimensions, shading devices (exterior and interior), and external obstructions. Direct sun transmitted through adjacent zones (e.g. greenhouses, atria) is also included.

For this and subsequent analyses, the interior surfaces are divided into grids of subsurfaces. Besides the sunlight patterns, the percentage of area in direct sun, and the intensity of shade are calculated. The algorithms are similar to those used in the site shadow pattern analysis.
The inputs include time of year and day for the analysis, the zone description (surface dimensions, properties, and location in space), shading description, and site description. If no analyses or descriptions at site scale have been specified, then no site shading or obstructions will be included.

Zone Lighting (fig. 4.5) For a given zone and external conditions, this analysis predicts the illuminances and exitances of surfaces in the zone, both envelope surfaces and other horizontal planes specified by the designer (e.g. work surfaces). If constraints upon illuminances are specified (minimum acceptable illuminance levels), then lighting energy requirements will be determined. Illuminance at a point is calculated as the sum of initial incident illuminance through zone glazing (diffuse sky, direct sun, and externally reflected components), initial illuminance from artificial light sources, and internally reflected illuminance. Exitances are simple functions of illuminances and surface reflectances, assuming perfectly diffuse surfaces.

Both daylight and artificial sources are included here. If only a daylight availability study is desired, one can simply not "install" any artificial sources. Similarly, daylighting can be excluded. Each of the components of lighting listed above can be examined to see the relative importance of diffuse vs. direct vs. internally reflected, and so on.

A number of algorithms have been developed for lighting calculations. However, since we are interested in both illuminances and exitances of different room surfaces, that number is drastically reduced. Algorithms are required to calculate three components of interior illuminance, diffuse sky component, artificial component, and internally reflected component. The direct solar component calculation is trivial when given data from the internal zone sunlight pattern analysis.

The diffuse sky component (often referred to as simply the sky
component) is the illuminance striking a point in the zone, from that portion of the sky seen by the point. A "simplified" method for calculating this has been developed which determines the solid angle of the sky vault seen by a point through a window, and numerically computes the integral of the sky luminance distribution function for that angle. Another approach uses finite Fourier series techniques to generate functions that describe a "generalized sky luminance" distribution. This includes exterior obstructions as well as standard sky luminance distribution functions. The sky component is easily calculated for any point in the zone from function.

Direct illuminance from artificial sources is calculated from photometric distribution data provided by lighting equipment manufacturers. For fixtures which can be considered as point sources, this calculation is relatively simple; for area sources, the procedure is similar to that for daylight sources.

The internally reflected component is calculated using either a finite difference technique, or a surface integral technique.

An index of illuminance which attempts to quantify visibility as a function of task illuminance, contrast, and background exitances is the Equivalent Spherical Illumination (ESI). ESI is defined as the diffuse illuminance (sphere illumination) that would be required to make the task as visible in the sphere as it is in the real environment. Although the concept of ESI does have some significant limitations, it is included here as the best current index for evaluating veiling reflections and body shadows from natural or artificial light sources.

Inputs for the zone lighting analysis include climatic potentials (sky luminance distribution and levels), zone surface...
descriptions (properties, dimensions, location in space), site
descriptions (exterior obstructions), artificial light source
descriptions (type, location), and illuminance constraints and
control strategies.

**Interior Zone Surface Irradiance** This analysis is very
similar to that of zone illuminance; it displays the total net
irradiance incident upon interior zone surfaces. The distri-
bution of radiant energy is useful in the design of direct and
indirect gain solar structures. The total is calculated as
the sum of irradiance from direct external sources, from
direct internal sources, and internally reflected from other
sources.

The components are also similar to those of illuminance. If
the surface integral method of calculating the internally
reflected component mentioned above is used, one can
explicitly see not only the incident irradiance levels on zone
surfaces, but also the "first bounce" effects, which are im-
portant in passive solar designs.

Internally generated radiant sources are included in this
analysis. Analogous to artificial lighting (in fact, includ-
ing the radiant heat gain from artificial lighting), these
sources come from equipment and people in the zone. Inputs
from these sources can be scheduled (e.g. corresponding to
occupancy) or conditionally controlled (as with photocell
controls, thermostatted radiant heaters, etc.). The energy
consumed by these sources is calculated during the analysis.

Climatic and zone data needed for this analysis are essen-
tially the same as for the lighting analysis. In fact, cor-
relations between sky luminance and radiance distribution may
allow these analyses to be combined. Additional zone use data
regarding equipment use and scheduling, and occupancy, if
necessary can be provided. Data from the zone sunlight pat-
tern analysis is used to determine if direct irradiance is
incident upon a point.

Zone Air Exchange (fig. 4.6) Air exchange between the inside and outside of a building, or between zones, is the result of air pressure differentials across openings in the envelope. The type and rate of air exchanges have a great effect upon zone comfort and energy use. The need for fresh air is obvious and rates are well-codified for various building uses. The important comfort parameters of humidity levels and air velocity are by and large determined by air exchange patterns.

In TRACERY, air exchange can take one of three forms. Air infiltration is that exchange which occurs through the leakage area (cracks and other unintentional openings) of the zone envelope. Natural ventilation occurs through larger, intentional openings such as windows or vents. For both infiltration and natural ventilation, pressure differentials across the openings are induced by wind and stack forces. The third form of exchange is forced ventilation, where the pressure difference is induced by fans.

The air exchange analysis calculates the total net air exchange between the zone interior and exterior. If forced ventilation is specified, then fan power consumption is determined. Fan controls can be scheduled (e.g. night ventilation) or conditional (as with economizer cycles, or in response to humidity constraints). Openings for natural ventilation can also scheduled in this manner.

Relative humidity is tracked, and if constraints have been placed upon acceptable humidity levels, then the energy required to adjust moisture content is included.

For single-zone structures, a good algorithm exists for the prediction of infiltration rates.(12) They are calculated as a function of envelope leakage area, ambient and interior
temperatures, and wind speeds (translated to the site as described earlier). Forced ventilation rates are simply specified as desired. As is the case with microclimatic wind pattern analysis, the author is not aware of any general models for accurately predicting natural ventilation exchange rates. Design guidelines abound, but these are not useful for quantifying air flows.

**Zone Thermal Network (fig. 4.7)** In the zone thermal network analysis, energy flows and potentials from most of the preceding analyses are the incident forces here. The net transformation of these inputs by the materials comprising the zone envelope result in zone air temperature, zone surface temperatures, and heat transfer through the envelope. If constraints are placed upon air temperature excursions, then heating and cooling loads will be determined.

The heart of this analysis is a simple nodal model. Envelope materials, zone and ambient air, interior furnishings, the ground, and other elements are defined as "nodes". Each node is ascribed a heat capacity, and links between nodes are given conductances. Energy flows and node temperatures within the network are calculated. In TRACERY, the nodes are properties of materials, and "invisible" to the designer.

A useful feature of thermal network analyses is that calculations can be performed at any desired time step. Hourly time intervals are needed to evaluate comfort over design days, and this is the time step employed in TRACERY. In the next chapter, the extension of hourly analyses to day and greater time spans will be discussed.

The incident potentials for the analysis come from climatic sources (air temperature patterns), transformed by site (incident exterior solar irradiance and wind speeds) and by envelope (incident interior irradiance and air exchange), and from zone sources (internal gains, heating and cooling power).
Comfort Zone Analyses

Visual Comfort  In chapter three, the problems and controversies surrounding the quantification of the psycho-physiological sensations of comfort were discussed. Visual comfort in particular, has been a difficult response to measure in the "real" world. However, several indices exist, and can provide a designer with "warning flags" for potential problems.

An interesting approach to the evaluation of the luminous environment is the "brightness contrast engineering" concept.(13) In this method, a perspective representation of surfaces within a desired field of view is created. The exitances of the surfaces, which have been previously calculated during the zone lighting analysis, are shown in contour form. These can be displayed as brightness values. Brightness is what the human eye sees, or the intensity of exitances as perceived by an observer. Marsden has developed an algorithm for the brightness-exittance relationship.(14)

So the perspectives represent what is actually seen from a given point of view. From this information, the designer can qualitatively evaluate the lighting in a zone by examining the surface exitances in the perspective. Or, brightness patterns and contrasts can be used as inputs for numeric indices of glare discomfort, such as the CIE glare index.

Research is currently underway to provide a direct link between this exitance and contrast data, and visual performance.(15) Visual performance stems from a combination of visual sciences and illuminating engineering. It is a measure of the sensitivity of some standard visual task (such as comparing lists of numbers) upon lighting conditions.
Thermal Comfort  Again, with all caveats regarding the quantification of comfort in mind, a final analysis of the transformations resulting in perceived thermal comfort are included in TRACERY. As is the case with the visual comfort analysis, the basic incident potentials come from building zone transformations. They are air temperature, relative humidity, radiant surface temperatures, and air velocity. The comfort zone description consists of location and orientation of occupant in the zone, activity levels, and clothing type.

Fanger's Comfort Equation is probably the most widely used index of thermal comfort.\(^{(16)}\) In TRACERY, the potentials and comfort zone description provide the inputs for the Comfort Equation, from which skin temperature and sweat secretion rate are calculated. Empirical studies by Fanger and others have produced ranges for these variables in which subjects expressed thermal comfort. These ranges differ for different activity levels.

Typically, comfort levels across a zone will be rather constant. Exceptions are high spaces with large thermal stratification gradients, localized areas of excessive air velocities, and areas of high irradiance (or sitting in direct sun!).

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4.1 Model overview
4.2 Site/building form shading analysis
4.3 Building form irradiance/illuminance analysis
4.4 Zone surface sunlight pattern analysis
4.5 Zone lighting analysis
4.6 Zone air exchange analysis
4.7 Zone thermal network analysis
Models and Languages

Many of the advantages of a microprocessor-based analytical design tool; speed, flexibility, ease of use, and graphics, allow for enhanced communication between the user and tool. Any well designed, interactive program requires quick responses to commands, intuitively understandable operations, "help" messages, default calculations, and appropriate forms of feedback. However, the considerations of "user-friendliness" and comprehensibility in an environmental design tool, handling spatially, temporally, iteratively changing streams of information, quickly become complex and crucial to the usefulness of the tool.

The use of computers involves a dialogue between the user and machine. With interactive programs, the constant exchange takes on the characteristics of a conversation involving two languages, that with which the user communicates with the computer, and another with which the computer talks back (sometimes literally). The former is invoked through actions applied to various interactive devices to send signals. These include typing on a keyboard, manipulating a "pick" (a joystick, stylus, mouse, or finger), and voice-activated signals. The machine-to-user signals take the forms of alphanumeric characters, lines, points, filled areas, color, and sound.

This is a rather low-level description of these languages. Analogous to natural languages, those between human and machine are much more than a collection of signals or words. Language is the bearer of meaning, through its use of symbols,
patterns, and context. This is an important consideration in the design of languages to be used for extracting meaning from natural processes as described by models. In the last chapter, "environmental model" was defined as the symbolic representation of a theory which attempts to reproduce or map observed transformations of energy flows by the built environment. Operations on the symbols of the model should produce transformations in the model similar to those in the natural morphology. Because we are dealing with a model which resides in a computer program, the languages of the designer-machine conversation determine how one "sees" the environmental model, and how one manipulates its symbols. In fact, these languages and the model are inseparable. One researcher of graphical interaction systems has written "...to design the user interface of a system is to design the user's model."(1)

We can think of the environmental model as a set of rules, or "code" for translating between a natural morphology (energy flow through the built environment) and an artificial one (designer-machine dialogue). The model becomes meaningless without the language.

The artificial morphology in such a case is regarded as a "signifying system" because transformations within the space-time morphology should be systematically related to transformations in the semantic morphology. Simply put, this is how meaning is transferred between the two systems. How they are systematically related is of great importance. Two systems can be related on the basis of a one-to-one mapping of symbols and transformations. This is like defining meaning in natural languages with a dictionary, looking up a word provides meaning. However, it usually provides several meanings, so an unambiguous definition is not likely on the level of the individual word. In fact, we derive meaning in language from groups of words (sentences), gestures, accents, etc.; this is context.
Of greater use for signifying systems than one-to-one mapping, the artificial morphology should be related algorithmically to the natural system. In chapter two, this was termed "rule-governed creativity", because it is capable of solving problems resulting from unfamiliar experiences. To support rule-governed creativity, each of the two morphologies related in the code must possess an internal structure such that translatability between them is at the level of parallel structural transformations. At the level where this parallel structure does not exist, meaning is lost.

The implications of these relations is that the design of the designer-machine languages, their symbols and operands, should follow the structure of the natural processes as translated by the environmental model. Whether explicitly or implicitly intended, the structure of language will determine how the designer perceives the model and its structure. The conceptual model will embody operations familiar to the designer, with a clear organization of functions and tasks; the vocabulary of the languages must allow the expression of that organization.

Computerized or not, analytical design tools frequently do not establish this relationship between the mode of interaction and the environmental model at its root. As a result, the tool can appear as a "black box" to the designer. Relationships between objects (as symbols) are not clear, and their manipulations seem unfamiliar. The tool feels awkward and not intuitively comprehensible, and probably goes unused. More importantly, if the desired "bottom line" is received, little understanding of the processes modelled is imparted. In a model as encompassing as TRACERY, clarity of the language and model is crucial.
TRACERY Conversations

Drawing further upon the analogy with natural languages, each of the languages of designer-machine conversations can be analyzed at four distinct levels: conceptual, semantic, syntactic, and lexical.(2)

Conceptual design of a language defines objects or classes of objects, relationships between the (classes of) objects, and operations performed on the (classes of) objects. For example, the description of site elements in TRACERY includes as objects ground planes, landscape elements, exterior obstructions, and building forms. Each of these objects can be created, positioned, and oriented on the site as needed.

Semantic design refers to the interconnections of symbols and operations used in a language. To defined postitional and cause-effect relationships, meanings are ascribed. The meaning of signals sent to the machine through the use of some interactive device, such as dragging a pick across a graphics tablet, is part of the semantic design. The meaning of a shaded area (such as a shadow pattern in a site plan) in the display seen by the user, is part of the semantic design of the machine-to-designer language.

Syntactic design defines the sequence of inputs and outputs, or the grammar of the language. The rules for combining words or tokens into well-formed expressions comprise the syntax. Words and tokens are the smallest units of meaning in the language; if they are further broken up then meaning is lost. For example, a representation of a wall section has meaning, while the individual lines of the section do not. The establishment of the appropriate level of resolution for words and tokens is a key concern in architectural systems.

Lexical design determines how input and output words and symbols are formed. Hardware primitives, or "lexemes" are used to perform these functions. In the input language, lexemes are the interactive devices and operations performed on them, such as pushing a button or dragging a pick. Output lexemes are the primitive shapes (alphanumeric characters, lines, points) and their attributes (such as color and font). Combinations of lexemes creates words and tokens.
In chapter 4, a conceptual design for the use of TRACERY at the most general level was provided. Restated, TRACERY consists of transformations at three physical scales, site, building zone, and comfort zone. At each scale, three interactions between the designer and machine occur. The initial conditions are described, by specifying the incident energy potentials and built forms. Also, the types of transformations desired are specified. Finally, the form of representation of the resulting transformed potentials is selected.

The discussion of languages in TRACERY shall begin with this general level outlined above. How the model as a whole is presented to the designer; the connectedness of the above interactions and the physical scales, is described in terms of the semantic, syntactic, and lexical aspects of languages. Then some of the major interactive functions of TRACERY shall be further broken down to get a more detailed look at the structure of the designer-machine conversation. This will include examination of the structure and specification of the climatic potentials, site description, and zone description.

Relational Menus

Figure 5.1 shows the video display through which the designer perceives the whole of TRACERY. Let us call this the "model screen". The model screen contains viewports for incident potentials, built form descriptions, and resulting potentials at each of the three physical scales. The connections between each of these is graphically shown by lines and arrows. Within each viewport is the name or identifier of that set of potential transformations or descriptive data currently under consideration.

Obviously, this display is a very direct representation of the components and structure that comprise TRACERY. Note the similarity between the model screen and the graphical overview.
of figure 4.1. The semantic languages at this level are straightforward derivations of the environmental model.

In this display, the program is informing the designer of three basic things. First, what interactive functions are available, such as the specification of the incident climatic potentials, or the description of the zone. Also, for each interactive function, the needed inputs from other components of the model are shown. For example, to perform any of the transformations at the comfort zone scale (to analyze visual and/or thermal comfort), incident zone potentials and a comfort zone description must be provided. Finally, the designer is told the set of potentials, descriptions, and transformations upon which the program is currently operating. In figure 5.1, the transformation specified at the zone scale is a lighting analysis. The zone to be analyzed has been named "Corner Office" by the designer, with incident site/building form potentials resulting from an earlier analysis of the building form "Headquarters" located on the site "Riverside".

The model screen can be considered to be a "relational menu" display, which also informs the designer of the current status of the tool. As with a typical menu display, the designer selects one of the operations (or lexically speaking, one of the viewports), whereupon the designer "descends" to the next level of the model, perhaps to modify an element of the site description, or to select the representation for viewing the results of an analysis. The important difference between the model screen and a typical menu display is that the relationships between the operations are explicitly shown. Menus usually present options as discrete and unconnected, in list form. Any hierarchical relations between operations, such as the fact that a zone must be physically described before it is analyzed, must be remembered. Menus represent the displayed operations as disassociated aggregates. The actual relationships embodied in the code (or model) must be derived by the
designer from effects which occur at deeper levels of the program. Very likely, this will either not occur, or the derived relationships will differ from those of the model.

To illustrate this point, let us suppose that operations corresponding to the seven viewports of the model screen are displayed in a linear aggregate menu. The designer wishes to perform a daylight availability analysis of a new zone, and therefore selects the option for "Zone Potentials". Another menu of zone transformations is displayed, from which "Lighting Analysis" is chosen. At this point, it must be determined what zone and incident conditions are to be included in the analysis (an existing set from computer memory or a new set). To do this, the program can either go back to the main menu, displaying a message to the effect that the designer must now specify the initial conditions, or automatically branch into the operations for describing either zone or potentials. In either case, the flow within the model appears forced and unconnected. After repeated use, the designer will learn that potentials and built forms must be specified before specifying the analysis; the menu display does not indicate this.

This point has been emphasized because the relational menu screen of connected viewports is used extensively in TRACERY, in all levels. Most of the operations described in the preceding example are also required in TRACERY; however, the model screen (and subsequent screens) place these operations in a context that is an isomorphism of the structure of the conceptual model. It shows what exists upstream from any transformations, and what exists downstream.

The syntactic and lexical designs of the model screen (and other relational menus) are based upon the assemblage of viewports and the process of selecting a viewport. A viewport is simply a box containing the name of the operation it represents, as well as the current status or element of that
operation. Each viewport represents a hierarchy of deeper levels resulting in the description and specification of that operation; the viewport can be thought of as a "window" at the highest level looking into the deeper levels. Selecting the viewport allows the designer to descend to the next level.

The selections can be performed in a number of ways, moving a cursor on the display into a viewport with keystrokes, light pen, or mouse; or each viewport can be labelled with a letter or number and selected with a single keystroke. Perhaps most appropriate (though also most expensive) would be the use of a touch-sensitive display (TSD), so that the designer could simply touch the viewport desired. Another selection function included in TRACERY is the ability to jump directly to any level of any operation from the model screen, and back again, without going through the intermediate levels.

The operations embodied in each of the seven viewports of the model screen shall now be briefly described. Successive sections shall deal with some of these in greater detail.

**Climatic Potentials** In the last chapter, these were defined as the incident potentials seen by a site. They are air temperatures, humidity, solar irradiance, solar illumination, and wind patterns. The designer selects this viewport to review, modify, or create climatic potentials comprised of each of these patterns. The potentials and length of time they span are selected for use in the subsequent transformations and displayed in the viewport. In figure 5.1 for example, the user has chosen one day for the analysis period, a weather-day named "Summer Peak". One can create different profiles of hourly, daily, weekly, or annual duration, and store these in the machine's memory, thereby creating a library of climatic profiles. This is explained in greater detail later in this chapter.

**Site/Building Form Potentials** There are three distinct
functions accessible through this viewport. If the designer wishes to analyze a site transformation (shadow patterns, irradiance/illuminance, or wind patterns), that operation is performed through the viewport. The form of the results (graphic, tabular, etc.) is also specified here. Thirdly, it is used to specify which potentials from previous site transformations (stored in memory) are to be used as incident potentials for transformations at the zone scale.

Zone Description The creation and modification of zones embody the most complex set of operations in TRACERY. Within this viewport, one can specify which zone is to be used in the transformations (the name of this zone is displayed in the viewport in the model screen, as well as the building in which the zone is located), create new zone descriptions, or modify existing zones. A zone is built up from a hierarchy of walls, planes, sub-plane assemblies, and materials. This hierarchy and its manipulations are discussed in greater detail later in this chapter.

Zone Potentials The functions included in this viewport are similar to those of the Site/Building Form Potentials viewport. The zone transformation options include sunlight patterns, zone lighting analysis, surface irradiance, air exchange, and a thermal network analysis. Selected zone potentials are also used as the incident potentials for comfort zone potential transformations.

Comfort Zone Description The location, orientation, tasks, and other characteristics of the occupant in relation to the zone, are specified in this viewport. This information determines what potentials emitted by the zone are perceived by the occupant.

Comfort Zone Potentials This final viewport, like the other potential viewports, is where the designer selects the transformations desired at this scale (visual or thermal
comfort), and how to view the resulting indices of these transformations.

These are the basic components of TRACERY, as displayed in the model screen. This screen serves as the template, or framework in which all the dialogue and manipulations at deeper levels of the program come together. Now we shall explore some of these deeper levels, starting with the specification of climatic potentials, then the site description, and finally the zone description.

**Climatic Potentials: Structure and Description**

The structure and flexibility of climatic variables is perhaps one of the most unique features of TRACERY. In most large environmental models, climatic potentials are limited as a function of location. Typically, weather patterns are derived from thirty to forty year averages. Occasionally, design days may be specified, or simply the most extreme days in the typical year are available.

The basic unit for climatic potentials in TRACERY is the "weather-day". A weather-day is composed of six "potential profiles", dry bulb temperature, wet bulb temperature, total horizontal irradiance, total horizontal illuminance, wind speed and direction. To provide a sufficient level of detail to evaluate comfort in a space, these potential profiles are created from twenty-four hourly values.

So a single hierarchical structure of weather data is established (figure 5.2). The weather-day is comprised of six potential profiles, each of which is created from hourly values. In terms of designer-machine languages, the unit of meaning in this structure is the potential profile. While the individual "word" may be an hourly value of, say, dry bulb temperature, it has little meaning outside of the profile.
Hourly values are only addressed in TRACERY in the larger context.

The user can manipulate hourly values of each of the six parameters to create or modify a library of profiles. This library will also include sets of standard profiles for a given location based upon long term weather averages. For example, for dry bulb, wet bulb, and wind, three standard sets of profiles in the library might be provided for average, high, and low values for each month. Solar irradiance and illumination standard profiles might represent average, overcast, and clear sky values for each month. In addition to these, a designer can add any other profiles of interest, for example, recreate profiles for specific days from measured data, or create extremes for testing performance bounds.

These potential profiles are created, manipulated, and combined graphically. As with the model screen, this is primarily to emphasize the relationships of the various potentials, over in time. One can note how dry bulb temperature peaks relate to solar irradiance peaks, perhaps to gain a feeling for how much solar storage or lag time might be needed in a passive solar design. Or compare wind and temperature profiles for an indication of the usability of outdoor spaces under those conditions, will windbreaks be needed, and so on.

And by considering the potential profile to be the basic unit of meaning (and hence manipulation), it becomes easier to express unusual or atypical combinations of climatic potentials, to test interactions of transformations, and second order effects. An important example of this can be seen in the analysis of energy use in commercial space during hot summer days. This is frequently a period of high demand rates for electricity. By combining an air temperature profile for a hot summer day with a clear sky illumination profile, one can test the availability of daylighting to offset peak loads. Substituting an overcast sky illumination profile will
provide some insight about performance under these (probably humid) conditions.

The highest (most general) level of the hierarchical structure of climatic potentials is that of time span. The length of time that is specified for the weather data determines the time span of the transformation analyses. In TRACERY, there are several time span options, based upon the weather-day. The first of these is the hourly span, or point in time. The designer selects a weather-day, and specifies a particular hour in that day for the analyses. This span is suited for point in time transformations such as the shadow and sunlight patterns, or perhaps lighting. The next time span could be called the "day-week", because it is composed of anywhere from one to seven consecutive weather-days. The designer selects the days and sequence (they can all be the same weather-day, repeated). With this time span, one can observe patterns of transformations over a day period (or longer), or see the effects of changing weather patterns (e.g. a sunny day followed by several overcast days).

The final and longest time span is the full year. The annual period does not actually consist of 365 consecutive weather-days, but is compressed in TRACERY to a total period of about seven weeks, which can be extrapolated to a full year. This algorithm, known as SELECT,(3) allows much faster calculations of annual totals and averages of energy loads, solar irradiance, net heat flow through the envelope, etc.

The specified time span often has the effect of defining the transformations and resulting potentials. For example, a daily profile of hourly lighting-energy use is essentially a power profile, illustrating peak demand as well as a daily total consumption. An annual analysis, on the other hand, provides total yearly energy use for lighting. Both analyses yield useful feedback, but feedback which is qualitatively different, and, as pointed out in chapter 3, feedback which is
probably needed at different stages of the design process

Site/Building Form: Structure and Description

The "site" can be considered as a hierarchical structure of objects and sub-objects occurring at site scale (figure 5.3). The objects are the ground surface, landscape, exterior obstructions, and building forms. Ground surfaces and building forms are created by combining sub-objects, and all the objects and sub-objects have associated properties (reflectance, transmittance, and variations of these over time).

The ground surface is simply that, the surface of the site, in relation to which the other objects are positioned. In a sophisticated syntax, the designer can define the edges of the site by drawing a site plan, and describe the topography of the site by drawing contour lines within the boundaries. Reflectance is ascribed to the ground surface, and sub-surfaces can be specified with different reflectances (e.g. parking lots, fields, etc.). Also, reflectances can be varied with time, such as a field covered with snow for part of the year.

Landscape consists of natural forms such as trees, if these are deemed important as shade or windbreaks. They are simply described as one of several basic polyhedra, spherical, cylindrical, or parallelepiped. Dimensions are provided by the designer, as well as location on the site, reflectance, and transmittance. Wind resistance is also a potential property of these objects. Exterior obstructions are similarly easily described, except that they are represented as two-dimensional polygons (probably limited to rectangles). These can represent elevations of nearby buildings, or other built forms on the site (fences, walls, etc.).

The building form is the overall form, or massing of the
building which contains the zone(s) of interest. In a single-zone building, the building form and the zone envelope are identical. At the site scale, the building form is a polyhedron created from building surfaces, which are polygons. The designer describes the building surfaces graphically and combines them to build the form. Each surface is given a reflectance. The building form can be positioned upon the site as desired.

As with the structure of climatic potentials, it is important that the hierarchical structure of the site and its objects be understood by the designer. The physical forms of the sub-objects and objects are polygons and polyhedra, which are the words and sentences, respectively, of the languages of site description (the lexemes are the lines, arcs, etc. which make up the symbols). A relational menu display similar to the model screen, is used to show the connections between the operations of describing the sub-objects (shape, dimensions, and properties), combining the sub-objects, and positioning the objects on the site.

**Zone: Structure and Description**

The structure of the zone description is similar to the site, except somewhat more complex. There are several more levels of sub-objects, sub-sub-objects, etc. This hierarchy is illustrated in figure 5.4.

At the top of this structure is not the zone itself, but rather the building form, which has been described as part of the site. The two are linked by specifying the location in the building form of the exterior walls of the zone (as opposed to those partition walls which separate adjacent zones). In the discussion of zones, the term "walls" shall include floors, ceilings, and sloped surfaces.
In the description of the building forms at site scale, the polygon, or plane, was the signifying "word". This is true for all scale and physical forms in TRACERY, because of the nature of the transformations being modeled. Recalling the analogy of water flowing through filters, the TRACERY filters reflect, transmit, and transform flows of energy. Energy emanates from sources in directional or diffuse patterns, through three dimensional space. This requires at least a planar form for meaningful interactions. If one were modeling structural forces, linear elements such as columns and beams would be the appropriate "words", since they are the media through which structural forces flow.

While the polygon may be the most logical physical unit for filtering flows of energy, there are certainly other possible forms which can be said to be the basis for "meaning" in the built environment. In fact, the built form "word" which a designer consciously or subconsciously uses as that unit which cannot be meaningfully subdivided, is an extremely important individual design determinant. Mitchell states, "In a very direct sense, the choice of elements begins to establish a language of architectural design."(4) At the risk of oversimplification, one might say that much of Wright's work is a study in the use of planes, while Aalto and Le Corbusier manipulated volumes; Mies Van der Rohe's buildings, on the other hand, often seem "inspired" by the nature of materials at a very small scale, as if designed by section. A designer's pattern of use of perspective sketches, plans, elevations, sections, etc. at different stages of the design process are good indications of how one visualizes the construction of built form.

So while it may be that the plane is the most appropriate "word" in an environmental model, this must be balanced with other methods of describing physical elements in space. In any event, the limits and ramifications of the semantic design of a zone description language must be realized.
The zone is a polyhedron, a volume bounded by planes. However it may not be convenient to consider each plane as a discrete component. Let us consider the task of designing a simple window wall for an office building. One can think of the dimensions of the glazed area as being a function of the wall dimensions; the height and vertical placement of the window are dependent upon the floor to ceiling height of the wall, and the length perhaps spans the wall (e.g. band window curtain walls). In such a situation, the glazed and opaque regions are not really thought of as separate, discrete components, but instead are totally interconnected. On the other hand, the designer can consider the window to be a discrete unit, with a pre-determined height and width, which is placed (perhaps repeatedly) in the wall.

The design of the descriptive language will determine which of these "perspectives" exists in a tool. Specifically, the semantic and syntactic designation of the unit of meaning is the crucial variable. In the former perspective, wherein the wall and window are mutually defining, the appropriate level of meaning is contained in vertical and horizontal wall sections. In the latter perspective, the window and the wall plane are separate, self-defined components. The units of meaning are their respective descriptions (syntactically created in plan and section views), and the window wall is created by linking the two in elevation.

Both perspectives are accommodated in TRACERY by allowing two-dimensional descriptions (unbounded vertical or horizontal sections) and three-dimensional descriptions (self-contained, from vertical and horizontal sections) to reside at equal levels of the hierarchical structure. In other words, specific sections frequently used by the designer can be stored in a library. A wall is then created as the combination of typical sections (by specifying the edge conditions and joints between sections). This simplifies the design of a
envelope when the same section is used throughout the building, but the sections are of different length in plan. In such a case, a separate wall plane sub-system component does not have to be created for each length variation.

Alternatively, a wall can be created as a collection of planes containing sub-plane assemblies (such as three-dimensional window-overhang components). If all the dimensions of the window and overhang are fixed, which is common with the use of standard components, then the window and overhang can be manipulated as a unit.

The lexical design of this construction process is obviously of importance. Where appropriate, the tools and techniques of the designer should be used. Interactive devices such as light pens, graphic tablets, or mice are most useful in drawing lines and other symbols. Objects and sub-objects are created and combined in the familiar representations of section, plan, and elevation.

At the lowest level of the zone hierarchical structure are the materials used in creating wall planes and sub-plane assemblies. Materials contain the physical properties needed for the analysis of heat flow and luminous flux. These include conductance, specific heat, volumetric density, transmittance, reflectance, absorbtance, and emittance. Materials can be combined to build a material section, such as a wood framed wall with sheathing and insulation. Designers could describe zones from a library of standard materials and material sections, or create custom materials and sections.

**Graphic Representation of Transformations**

An important aspect of machine-to-designer language which has not yet been addressed is that of output, or how results of the analyses are presented to the designer. TRACERY consists
of ten different analyses at three physical scales; assuming several optional output formats for each analysis, the number quickly becomes overwhelming. Let us consider here the basic types of formats needed, and the primary considerations in their design.

Purcell has pointed out, "that which distinguishes a designer's data base from most other professions is the scope and variety of the graphic analogues which the designer employs...". (5) In TRACERY, the transformations being analyzed involve interactions between very real, visible, built forms, and less tangible flows of energy. Whenever possible, the results of the transformations should be seen in the visual context of the built form, to facilitate the interpretation and understanding of the interactions.

Also, a designer does not usually need absolute data, but rather relative performance information which reveals the sensitivity of flows or potentials to design parameters. For example, the rate of change of illuminance levels across a zone with increasing window area is of more interest than the absolute levels from one alternative. With this knowledge, a designer can get a feel for how much "slack" is available in the sizing of the glazing (at least from the perspective of lighting issues). These trends, or parametric analyses, are best compared and interpreted graphically.

The format of a given analysis output is determined by two variables, space and time. Energy flows and potentials can vary in space (e.g. shadows upon a surface, illuminances across a zone) and over time (e.g. air temperatures over 24 hours, 12 month profile of energy consumption). Generally speaking, the time span of the analysis is the most significant of the two variables. This is because in a two-dimensional format such as a video display or a sheet of paper, there is a practical limitation to the transmission of three-dimensional variations in data. One cannot easily
represent temporal variances and three-dimensional physical space.

So we can simplify our discussion by dividing the graphics into "instantaneous" or temporally varying types. As mentioned earlier, the time span is specified as part of the climatic potentials description. There are three options, hourly (point-in-time), day-week, and annual spans. Hourly analyses are considered instantaneous, because the hour is the smallest time increment available. The day-week and annual spans can be considered either instantaneous (if only a total value for the period is desired) or temporally varying (to obtain an hourly profile for day-week, or a monthly profile for annual).

Most of the analyses have meaningful instantaneous representations. Shadow patterns, irradiance, illuminance, radiant temperatures, brightness and exitance patterns; all lend themselves to various instantaneous graphics because the important information to be imparted to the designer from these analyses is how they vary spatially. There are six basic types of these graphics.

**Site plan** (figure 5.5) Mainly used for the site/building form shadow analysis, this representation shows the location and orientation of the site objects (ground surfaces, landscape elements, exterior obstructions, and building forms). Shadows falling upon ground surfaces and building forms are shown.

**Building form axonometric** (figure 5.6) This view is useful for displaying shadow, incident irradiance, and illuminance patterns upon the building form.

**Zone plan** Shadow patterns upon the zone floor and irradiance and illuminance incident on horizontal surfaces can be shown in relation to walls and windows in this standard representation. Numeric values, such as illuminances, can be drawn as either contours or discrete values at points in the plan. See figure 6.4 in the next chapter for an example of this graphic.
Zone section (figure 6.5) The section can represent the same data as the plan, indicating the gradation of values across the zone. This provides a more qualitative feel for relative values in a space.

Zone axonometric (figures 6.7, 6.8) Unlike the section, the axonometric displays gradients over and entire zone. This can be used to display variances over all visible surfaces (shadows, exitances, incident irradiance, surface temperatures), or across a horizontal surface (workplane illuminance).

Zone perspective as discussed, this graphic can aid in the evaluation of lighting brightness and contrast patterns within a field of view, as well as a visual display of perceived radiant surface temperatures from the zone thermal network analysis.

As for temporally varying data, one interesting graphic which does employ a spatial context is the representation of heat flow through a section or plan (figure 5.7). This view was developed by Olgyay, and displays the effect of orientation (or tilt) upon heat transfer. A designer can evaluate the effects of insulation values, exterior surface color, shading, window area, etc. over time for different wall, ceiling, or floor sections.

Although not intended for inclusion in TRACERY at this time, a very promising "graphic" which is rapidly becoming practically feasible on microcomputers, is real time animation. This would allow the introduction of the fourth dimension of time into the spatial representations. For example, one could observe the changing lighting conditions during a day, or the movement of shadow patterns.

Videodisk technology, in conjunction with microcomputers, can also provide an added dimension for the designer. A graphic database of perspectives within a building are created and stored on the disk. These could then be recalled as desired to simulate a walk through the spaces, with the ability to control the field of view. The microcomputer can also be used to manipulate the images, perhaps to represent changing surface brightnesses or radiant temperatures.
5.1 Model screen
5.2 Climatic potential hierarchy
5.3 Site description hierarchy
5.4 Zone description hierarchy
5.5 Site/building form shadow pattern
5.6 Building form axonometric
5.7 Heat flow through walls
Microlite: A Case Study

Up to this point, the discussion of the proposed model, TRACERY, has been theoretical. As envisioned, TRACERY would be a "family" of simple, microcomputer programs linked together through shared data structures and a common format for user interaction. This type of organization has several advantages. If changes are made in one type of analysis, the others are unaffected. Also, the tool as a whole can be developed incrementally.

One member of the TRACERY family has been designed and coded for use on microcomputers. Known as "Microlite", the program calculates illumination levels from daylighting incident upon a horizontal plane in a zone.(1,2) Recalling the organization of analyses in TRACERY, Microlite provides the natural daylighting component of the zone lighting analysis (the other major component being illumination from artificial sources).

Although it may appear to be a case of putting the cart before the horse, much of Microlite was developed before TRACERY was. In fact, this sequence has brought to light many issues and potential problems which a solely theoretical investigation would have overlooked. It can truly be said that much of the intended form for TRACERY is a result of an evaluation of the strengths and shortcomings of Microlite as a working tool. In this chapter, these lessons are presented, and directions for future developments are discussed.

A daylighting analysis was chosen as the vehicle for this first step because it encompasses many of the important issues for analytical design tools in general. Of all the natural flows of energy, daylighting is perhaps the most familiar to
designers as a form-giver. The architecture of most cultures and climates reveals characteristic forms and techniques for transforming the light from the sky. Well-shaded windows with large, splayed reveals are common in warm climates with bright skies, such as the Mediterranean. Under the typically overcast skies of northern Europe, tall windows capture as much sky as possible. The vocabulary of daylighting transformations (windows, skylights, clerestories, overhangs, surface colors, etc.) is already a familiar one to designers. Some of the principles seem to have been lost in the short era of cheap electric lighting, especially in the context of new building types, but they are quickly being updated and relearned. The importance of daylighting is now recognized, not only as a source of energy savings, but more importantly as a way of reducing peak energy demands and dramatically improving the visual quality of a space.

A daylighting analysis must also deal with the more difficult issues confronting a design tool. The designer and program must exchange information on not only the dimensions and properties (reflectance, transmittance, etc.) of the physical elements, but also the relative positions in space of the elements to each other and the site. All of the objects, sub-objects, and assemblies of the zone description must be included in this analysis. And the variation in the resulting transformations, both spatially and temporally, must be presented to the designer. So a daylighting analysis has proven to be a useful isomorphism for many of the tools in TRACERY.

Program Description

There are presently two versions or "editions" of Microlite. The earliest version was written for the Apple II Plus microcomputer, and the later one for the IBM PC. The differences between the two are not primarily due to machine differences,
but rather are the result of perceived limitations in the first version, and the need for expanded capabilities. The two versions should be viewed as stages in an evolution which is still continuing. In this section, the later version shall be described, with subsequent discussion of the differences between the two.

As mentioned, Microlite calculates the illumination incident upon a horizontal plane in a zone. Usually, the designated plane is at working surface height, and the calculations are performed for a grid of points on that plane. The illumination at a point is determined as the sum of two components, light from that part of the sky visible through the window (sky component, or SC), and light reflected from exterior and interior surfaces (reflected component, or RC). The total for these two components is given as either the daylight factor (the ratio of illumination at the reference point to the illumination on an unobstructed horizontal surface) or illumination in footcandles. Direct sunlight is not presently included.

The algorithm used for these calculations was developed at Lawrence Berkeley Laboratory for analysis of parallelepiped zones, with vertical window walls, under standard CIE overcast and clear sky luminance distribution functions. The SC is calculated by integrating these distribution functions over the solid angle subtended by the visible sky dome through the window at a point on the grid. That part of the RC received from interior surfaces, the internally reflected component, is currently calculated using the split flux method. The light entering the room is divided into two parts, light received directly from the sky, and that received directly from the ground. The two components are modified by the area-weighted surface reflectances below and above the mid-height of the window, respectively. This produces one average illuminance for all points in a room.
The semantic structure of Microlite resembles a simplified version of TRACERY, with some differences in terms. To perform an analysis, the designer creates a "zone" from a combination of room, site, and window components. Rooms, sites, and windows are created and stored in independent libraries. To each component are ascribed properties and dimensions; they are positioned relative to each other in the zone description. The illumination data resulting from each analysis is also stored in an output library, so the user can view the results at any time, or compare them with other analyses. The data can be displayed in plan, section, axonometric, or tabular representations.

To use the program, the designer selects a desired operation from the main menu (figure 6.1). There are six options; one each for editing room, window, site, and zone components, one to perform an analysis, and one to view the results. Notice that the main menu used in Microlite is a typical linear menu, as opposed to the relational viewports discussed in chapter five. Even though the number of basic operation options required in Microlite are much fewer than in TRACERY, their relationships have still proven to be confusing to subjects who have played with the program. It was these considerations that led to the invention of the relational menu.

The room description consists of the width, depth, and height of the room, surface reflectances, and height of the horizontal grid of points for the calculation. The window description includes the window type, dimensions, transmittance, and reflectance. The site description includes the sky type, data for calculating the solar angles, direct and diffuse solar luminances, and the ground surface reflectance. Within the zone description, one room and site are combined and oriented, and windows are selected and located in the room walls.

One difficulty with this structure occurs in the relationship
between the windows and the room walls. The dimensions of each are assigned independently, and brought together in the zone by positioning the lower left corner of the window relative to the lower left corner of the wall (as viewed from the interior). There is no provision for dimensioning the width and height of the window as a function of a wall, so the designer must know this relationship before describing the window. Also, this positioning is not performed graphically in the current version of Microlite, so mistakes are easy to make.

In the first version of the program, this structure is even more convoluted. There is much less separation between the components. Windows are described only as a function of a particular room wall, so using the same window several times in a room is impossible. Both windows and sites are combined within a room description; there is no zone component. The two different object hierarchies are somewhat complementary, because they are suited to different ways of designing a window wall. The older hierarchy supports the design of an integrated window wall (although somewhat clumsily), such as a curtain wall, in which the dimensions of the window vary with the wall. The more recent hierarchy contains the window as a pre-defined, dimensioned object, which is then positioned in a wall. The zone object hierarchy described earlier for TRACERY includes improved versions of both structures.

Returning our attention to the later version, when the designer opts to perform an analysis upon a described zone, program control switches to the illuminance calculation routines. As the program loops through the grid of points, the calculated values are displayed, as is the time remaining until the completion of the analysis (figure 6.2).

The separate values of the SC and RC are stored in data files, which are used to construct the various data representations (plans, sections, tables, etc.). By storing these data, the
designer can retrieve them at any time to compare them with other data for different design alternatives.

The last operation option in the main menu is for viewing the data resulting from the analyses. To do this, the designer first selects which set of data is to be viewed, and then the format of the representation. There are four graphic representations, plan, section, elevation oblique, and plan oblique. Also, a data table similar to that in figure 6.2 is available.

The zone plan (figure 6.3) displays the illumination values of the points in the horizontal plane. The values can be in units of daylight factor or footcandles, as the total illumination (SC + RC) or either of the components alone. This is basically just a table of data, except the data are presented in their position in the zone, with respect to windows, walls, and orientation. The plan is drawn to scale (with a scale and north arrow included), with the location of the windows shown on plan. So from this representation, the designer can obtain a quantitative evaluation of raw illuminance throughout the zone.

The zone section representation provides a different view of the information (figure 6.4). The section displays the illumination gradient along one "slice" of the horizontal measurement plane. This provides both a quantitative and a qualitative feel for the variations of illumination. One can quickly assess the ratio of high to low levels through the section, and determine the likely "daylight" zone (that area adjacent to a window wall where artificial lighting is not needed).

As with the plan, the designer can specify in which units the illuminances are to be displayed (daylight factor or footcandles), as well as which component to view (SC, RC, or the total). In addition, the section to be drawn must be speci-
fied. To make this selection, a plan view of the zone is
drawn, with a pair of conventional section arrows on the peri-
meter (figure 6.5). The designer moves these arrows with
keystrokes to indicate the desired axis of the slice
(north/south or east/west), the position along the axis, and
the direction of the view. This is an example of using tech-
niques familiar to the designer to simplify a potentially
confusing task.

The elevation and plan oblique representation provide perhaps
the best overall qualitative feel for the illuminance through-
out the entire space (figures 6.6 and 6.7). A three dimen-
sional "contour" of the lighting levels is drawn, clearly
showing the peaks and valleys in the space, and indicating
relative gradients. These drawings carry no explicit data in
their present form.

On a more general, syntactic level, Microlite contains several
features which are becoming standard for good software, but
are particularly useful for computerized design tools. An
architect will not be constantly performing energy analyses
during the design process; in fact it is hoped that one's
reliance upon a computerized tool will diminish over time. At
best, designers will be infrequent users of a program, so
certain "user-friendly" features are important inclusions. A
good example of their use can be seen in CIRA, which provided
the inspiration for their inclusion in Microlite.

At any point in Microlite, where the designer can make selec-
tions or provide information, a variety of special functions
are available. By typing "?", a list of these functions and
their mnemonics is displayed. Some of these are for simple
screen manipulations such as jumping to different parts of the
program, or "scrolling" long displays up or down. More
interesting, however, are the help, list, and default
functions.
Whenever input of any type is expected, one can ask for help, and receive a message explaining what information is required from the designer. For example, if upon entering the transmittance for a window component, the user asks for help, the definition of transmittance (as that for visible light, normal to the window), will be displayed.

The list function can be invoked whenever data is requested from the designer. If the requested data is numeric, the upper and lower acceptable bounds are given (e.g. 0 to 100% for transmittance). If the required data is a selection of "type" (e.g. type of window glazing: single, double, clear, etc.), then a list of types and their mnemonics is provided.

The default function is particularly useful for a design tool. One of the quirky aspects of wicked problems is the uncertainty and changing nature of the problem formulation. "Smart" defaults provide some of the flexibility needed to accommodate this, as well as greatly simplifying the use of the program.

If specific information regarding component properties, site conditions, solar geometry, sky luminances, etc. are either unknown or unimportant at a certain point in the design, the designer can allow the program to provide default information. These defaults can be based upon previously entered information where applicable. Consider the determination of the solar altitude and azimuth angles required for the analysis. These can be entered directly, or defaulted as the result of previously entered latitude, longitude, and time of day and year data.

Default responses can also be tailored to the individual "vocabulary" of the designer. Frequently used materials (and properties), dimensions, etc. can be built into the default data files of Microlite, allowing the designer to concentrate upon higher level problems with some security in the lower
level assumptions.

In fact, this notion of "tailoring" the program to the forms, components, materials, and needs of the individual designer is a major "design determinant" of Microlite. The use of libraries for storing room, site, and window configurations, data sets, and even default assumptions is a key to this tailoring ability.

Enhancements

As mentioned earlier, Microlite is still evolving. Over the long run, it is hoped that the artificial lighting analysis routines can be added, at which point the program will complete the zone lighting analysis transformation in TRACERY. Microlite obviously represents the first steps in a rather long process. However, in the short run, some enhancements to the program capabilities are planned, both to the algorithms and the user interaction system.

Perhaps the weakest feature in the current version of Microlite is the use of the split flux method for the calculation of the internally reflected component of illumination. This component obviously is not uniform across a zone, and in large spaces will overestimate the lighting levels towards the rear, away from the window. A more rigorous calculation of this component using the finite difference technique shall be used to replace the split flux method.

A more rigorous determination of the internally reflected component requires calculating the exitances of the interior zone surfaces. These exitances are by themselves of great interest to the designer, as discussed in chapter 4. They allow the evaluation of more qualitative aspects of lighting comfort and performance, such as brightness ratios, glare, and visibility.
Currently, Microlite can only explicitly analyze unshaded, vertical windows. Skylights, lightshelves, overhangs, and fins can be accommodated by the algorithm, but only by modifying the source code. Since these are now standard pieces in a designer's repertoire, both the object hierarchy and input routines need to be changed to allow their description and storage. This is also planned.

Graphic conversations with Microlite are currently limited to the specification and feedback of analysis results. Because the room and window geometries are limited to rectangular shapes, this has not been a significant drawback, but with the inclusion of more complex window assemblies (overhangs, lightshelves, fins), graphic description and verification is a requirement. Site descriptions of the zone relative to external obstructions would also be greatly facilitated with this capability. Eventually, peripherals such as light pens and graphic tablets shall be used.

The most interesting graphic representations now available in Microlite are the three dimensional views. However, these contain no quantitative information. The use of true, three dimensional contours, color coded with hidden line removal, will provide the illumination data while maintaining the qualitative feel for the lighting distribution. As another major addition to the graphic data representations, we hope to explore the development of the "synthetic camera" perspective view of surface exitances discussed in chapter 5. The improved internally reflected component calculation will provide the data for this.
6.1 Main menu

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<tr>
<th>Main Menu</th>
<th>Building Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>Review, Modify, or Create ROOM Component</td>
</tr>
<tr>
<td>[2]</td>
<td>Review, Modify, or Create SITE Component</td>
</tr>
<tr>
<td>[3]</td>
<td>Review, Modify, or Create WINDOW Component</td>
</tr>
<tr>
<td>[4]</td>
<td>Review, Modify, or Create ZONE Component</td>
</tr>
<tr>
<td>[5]</td>
<td>Perform Daylighting Analysis</td>
</tr>
<tr>
<td>[7]</td>
<td>Quit Program</td>
</tr>
</tbody>
</table>

Select one:

6.2 Data table

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<th>Overcast</th>
<th>Illumination Data</th>
<th>office</th>
</tr>
</thead>
<tbody>
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<td>To West Wall</td>
<td>To South Wall</td>
<td>Daylight Factor (x)</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------</td>
<td>-------------------</td>
</tr>
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</table>

Calculation time remaining: 2:56
6.3 Zone plan

6.4 Zone section
6.5 Zone section setup

6.6 Elevation oblique
6.7 Plan oblique
Chapter Notes

Theses and Premises


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1.


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