PART I: PRINCIPLES
Design Objectives: Sunlighting for Economy and Delight

Sunlighting—designing with instead of defending against the sun’s light—is economical. The economies of sunlighting are twofold: more comfortable and productive interior environments for the occupants and lower energy costs for the building.

Sunlighting—the design of spaces that satisfy our needs for biologically important information for orientation and security—is delightful. These needs are fundamental but are often neglected in modern architecture: sunlighting seeks to restore delight to its centrality as a design objective.

The economy of sunlighting fulfills Vitruvius’ trinity of commodity, firmness, and delight:

*Commodity.* Artificial lighting is the major energy user in many of today’s buildings, accounting for about 50 percent of the energy consumed in a typical office building. As such, lighting—and its attendant cooling load—represents a large portion of the building’s operating budget. Designing with the sun can reduce the total amount of energy used as well as the peak usage. In this age of rising energy costs, sunlighting is therefore a good investment.

*Firmness.* Sunlighting is not a faddish aesthetic following a trendy concept but the intelligent application of the natural environment to the achievement of programmatic needs. Thus, sunlighting results in buildings whose beauty is not transient or skin deep but firm and enduring. Sunlighting has produced buildings of classic beauty and lasting value the world over.

*Delight.* Few would deny that the sun can provide especially delightful illumination. More than that, sunlight gives reassuring orientation to place, time, and weather. When applied with consideration to psychological and physiological needs, sunlighting produces interior environments that are comfortable, delightful, and productive.

**DESIGN OBJECTIVES**

While Vitruvius’ trinity provides a nice set of ideals to strive for, design is never so simple in practice. The purposes, programs, building technologies, and processes of modern design and construction require the collaboration of specialists, the balancing of multiple and interrelated ob-
Balancing the five design objectives creates beautiful architecture.

Architecture suffers when one objective is overemphasized.

The following five categories of design objectives are better suited to the present day:

1. providing user comfort and delight in the interior environment;
2. satisfying the programmatic needs of the users;
3. minimizing the building energy cost;
4. optimizing the public architectural image; and
5. minimizing the initial building construction cost (fig. 1-1).

In practice, these objectives can be difficult to integrate and balance. The evaluation of architecture according to these categories reveals their synergistic integrations, the trade-offs between them, and the importance attached to each-by intention or by default-during the design process. Many modern buildings reflect almost total adherence to only one or two of these objectives, while ignoring all the others. For example, a building whose goal is solely to create a public image may be expensive to build, waste energy, and be an unpleasant space in which to work. Similarly, a building whose goal is reduced energy use may be ugly within and without (fig. 1-2).

In the struggle to attain these multiple goals, the first category-user comfort and delight-has too often been virtually ignored. In my opinion, user comfort should be the central category to which the other priorities must respond. Although comfort is not the only result desired, it is critical to begin with it as a priority. While the criteria for comfort can easily be integrated with the other concerns, starting with other priorities will often eliminate or severely compromise the potential for achieving interior environmental comfort and delight.

Good design using sunlighting can have an impact on all five goals. Using sunlight in buildings is most important to me because it can improve the quality of life. Building sunlit buildings may entail some increased initial (construction) cost; however, reduced energy consumption during the building’s operation can offset this. While it is difficult to quantify with accuracy, a delightful environment can also have a positive economic impact.

Providing User Comfort and Delight

A person’s comfort within a built environment has many aspects, including thermal, visual, aural, and psychological comfort. While comfort is not easily quantifiable as a set amount of heat, illumination, window view, and so on, its qualitative parameters can be described. The perceptual processes that underlie comfort are universal, though what individuals find "comfortable" varies according to their expectations and activities. What visual comfort is and how it can be achieved is the focus of this book, although the sun’s thermal implications are also discussed.

A comfortable visual environment is one in which the apparent sources of light are surfaces one wants to look at, consciously or unconsciously. It is delightful when the qualitative characteristics of these sights are what one enjoys as appropriate to the moment and activity. To design delightful visual environments, one must first understand vision (how
we see), perception (what we see), and what we want to see in various spaces and for various activities (the nature of a delightful luminous environment). These subjects are discussed in detail in chapter 2. A good luminous environment makes it possible to perform necessary tasks—such as typing or conferring—comfortably. It also helps us on a subconscious level to feel secure in our environment by providing orientation information. The presentation of all the information we need creates a delightful environment.

The inability to create delightful environments can result in direct, measurable economic consequences, such as an inability to draw in customers or lack of improvement in office workers' productivity. These consequences can outweigh the building's initial construction cost. According to studies conducted by the GSA in the 1960s, and more recently by IBM, the total costs of owning and operating an office building over a period of forty years are: 2 percent for the capital costs of site, building, and equipment; 6 percent for operation, maintenance, and reconfiguration of space; and 92 percent (by far the largest) for the salaries of personnel (fig. 1-3). Thus, even a modest productivity increase of 5 percent would have a dollar value equal to twice the initial cost of the building; for an increase of 10 percent the factor would go up to four.

There are a number of studies that show that such a productivity increase may be obtained by improvements in the interior environment. A study by the Buffalo Organization for Social and Technological Innovation (BOSTI) is perhaps the most representative. The BOSTI investigation examined such environmental concerns as: amount of personal space, furniture type and layout, temperature/air quality, lighting, windows, privacy (both speech and visual), and ease of support and communication. With regard to illumination, BOSTI pointed to the importance of intensity, distribution, and control (like control of temperature, control of illumination affects both environmental satisfaction and job satisfaction). BOSTI found that those workers with the most demanding tasks were least satisfied with their lighting, while managers and supervisors were most satisfied. While the predictable effects on "outcome" (output) to which environmental factors contribute may seem small, their leverage

![Pie chart showing total owning and operating costs over 10 and 40 years](1-3. Typical building operating costs. (Courtesy of Leo Daly))
over the life cycle of a building can be significant. Clearly, the capital costs of the environmental factors inherent in the building’s design (and operation) are the least-cost component of the total owning and operating cost.

How Bright Is Best?

It should be noted that "improvement" of lighting does not denote or imply a simple increase in illumination level. Brighter is not necessarily better and can be worse: excessive, not insufficient, light can result in permanent eye damage. The allegation that "more is better" is not substantiated by research. Studies such as that by Butler and Rusmore in 1969 detected "no difference in performance ... associated with illumination levels above 3.5 footcandles." Further, a 1975 study by the Federal Energy Administration of simulated office tasks concluded:

For reading comprehension and speed of comprehension, there were no large or important differences in performance as a function of illumination level over the range of 1 to 450 footcandles. This is true for two age groups, one of about 20 years of age and the other ranging from 45 to 62 years. There is a difference in performance between reading good contrast or poor contrast material, and a difference in performance between the age groups; but neither of these differences is related to changes in illumination.

It is my contention that improvements in the morale or sense of well-being on the part of the worker (i.e., how comfortable, pleasant, and delightful an environment is) will inevitably have a greater effect on performance than simple increases in illumination levels.

Satisfying Programmatic Needs

A building does more than provide comfort for humans, and the requirements of what takes place within a building often determine its form. The organization and nature of the client’s business often dictate to the designer the building’s form and the sunlighting strategies that may be employed. Objects within the building may even have a specific influence on illumination—for example, the preservation requirements for artwork in a museum. Sunlighting must respond to a building’s programmatic requirements.

Minimizing Building Energy Cost

Designing without considering energy costs is akin to farming without considering water supply. The issue of using the earth’s finite supply of stored energy has been raised above simple economics to become a moral issue. It is almost criminal to waste our energy resources selfishly. We have the means to devise greater efficiencies; we should not wait until the market forces us to practice what we are capable of accomplishing.

Energy costs represent a major portion of a building’s operating costs.

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Lighting in turn accounts for a significant portion of the energy used (fig. 1-4). In a typical office building, lighting accounts for 24 percent of the BTUs used annually. Because lighting uses electricity, which is the most expensive form of energy, it accounts for 63 percent of the dollar cost of energy. Excessive artificial lighting or inadequate shading of the sun also result in increased demand for air conditioning. Sunlighting can reduce the amount of electricity used.

Sunlighting is a particularly advantageous way to save energy because its potential coincides with the peak electrical demand period—hot, sunny summer days (fig. 1-5). This has increasingly greater economic significance as utilities change their rate structures to reflect more accurately the true costs of generating power. The cost of power reflects the cost of fuel and the cost of generating capacity. Reducing the peak load requirements reduces the need for new power plants. Because the cost of new power plants has risen, utilities are becoming more interested in conservation as an alternative and are moving to penalize peak-time electrical use by means of "ratchet clauses" and higher rates. (A ratchet clause requires that a percentage—often at levels as high as 80 percent—of the year's maximum demand be extended as a fixed demand charge throughout the remaining eleven billing periods. Thus, a building owner must pay an enormous penalty for just one fifteen-minute surge in demand (fig. 1-6).

The built-in cost of peak demand makes it much easier to calculate the dollar benefits of sunlighting. It is also much easier to evaluate a number of buildings along one parameter—for instance, the energy demands (use) of various designs at peak demand time, than it is to calculate a given building's energy savings in many different situations throughout the year. While taking advantage of current energy price structures may sometimes cause its potential coincides with the peak electrical demand period—hot, sunny summer days (fig. 1-5). This has increasingly greater economic significance as utilities change their rate structures to reflect more accurately the true costs of generating power. The cost of power reflects the cost of fuel and the cost of generating capacity. Reducing the peak load requirements reduces the need for new power plants. Because the cost of new power plants has risen, utilities are becoming more interested in conservation as an alternative and are moving to penalize peak-time electrical use by means of "ratchet clauses" and higher rates. (A ratchet clause requires that a percentage—often at levels as high as 80 percent—of the year's maximum demand be extended as a fixed demand charge throughout the remaining eleven billing periods. Thus, a building owner must pay an enormous penalty for just one fifteen-minute surge in demand (fig. 1-6).

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**Optimizing Public Architectural Image**

Nobody wants an ugly building. Corporate image is often considered to be strongly reflected in the presence and facade of a building, that is "different," This superficial "identity" is effective only as long as a building remains alone in its style and place. When similar buildings compete for attention, the result is often rather boring.

Architectural corporate images based on skin-deep styles are apt to be as changeable as styles in clothing fashions, but the nature of the medium consigns them to permanence. A contextual solution based on beauty beyond the facade and universal, everlasting human needs will remain beautiful in its surroundings regardless of its neighbors. Refining our objectives will result in buildings whose identities result from their use, internal organization, and environment, as well as their skins. Such beauty remains even when surrounded by competitors that rival the external presence.

Unfortunately, however, the general public (those who have not lived in the building) and the architectural press seem to recognize only a building’s exterior. While the exterior is undoubtedly important, problems occur when this is the designer’s dominant concern. A comfortable,
delightful building concept clothed beautifully will endure, but a building based on a beautiful skin concept is unlikely to be as delightful for the occupants within or retain its external uniqueness over time.

**Minimizing Building Cost**

A building is most valuable when it provides the maximum satisfaction of the aforementioned concerns at a minimum cost. The initial, short-term costs of construction can be minimized by well-integrated building systems and the use of appropriate materials and methods for a given location. Long-term costs include the operation and maintenance of the building, the cost of money (interest payments), personnel productivity, and the cost of replacing the building. While some of these costs are intrinsic to the building’s program, most can be minimized by clever design.

Ideally, these are not conflicting concerns, but synergistic influences that affect each other beneficially. The achievement of this synergism, however, requires the collaboration of specialists-architectural, structural, mechanical, lighting, etc.-for the evolution of concepts and detailed designs. The team design process often proves effective and is detailed below.

**CONCLUSION**

While I am interested in the use of sunlighting for energy conservation and operating-cost benefits, the greatest challenge in my consulting career is to create buildings that are also delightful environments for working and living.

A windowless office building (or an effectively windowless building in terms of lighting), built of mirror glass to defend against the sun, may be economical to build and operate at today’s energy prices. It may also have a conspicuous presence as a unique and beautiful urban sculpture. However, these buildings are often far from delightful environments in which to work.

The best use of sunlighting is not only to save energy and guard against rising energy prices but, more important, to create more pleasant, delightful luminous environments for the occupants. To achieve these objectives, sunlighting must be given the highest priority. To achieve these objectives economically and with elegance in the design of both interior spaces and exterior architectural images requires design teams of the most competent professionals working in a multidisciplinary team process, as described in chapter 10 (and employed in most of the case studies in this book).

To achieve delightful sunlighting more easily, all members of the design team-owners and user’s representatives as well as design professionals-should understand the principles of perception and appreciate the subtleties of what makes a comfortable, delightful visual environment. The following chapter should aid that understanding.
Most architects and lighting technicians have very little understanding of the relationships between the amount of light and visibility and the perception of brightness. Often they do not know the difference between illumination (measured in footcandles or lux) and luminance (measured in footlamberts or candelas)—the basic units in lighting design. They are therefore unable to discern whether a space is insufficiently illuminated or whether it merely appears dark because of dark colors on unlit walls. The wrong design process and poor solutions result from accepting single-number footcandle criteria promulgated by the light and power industries (created to sell power).

As a result, lighting is generally designed to produce an exact, measured quantity of illumination at desk level rather than to provide for human perceptual needs. An illuminating engineer can visit a given space and estimate the amount of artificial light by counting the number of fixtures and mentally calculating the number of footcandles present. If that same “expert” was asked to estimate the amount of light in a daylit space with his eyes, he would probably be totally confused (having always depended on a light meter) and estimate incorrectly by a factor of ten to one hundred (fig. 2-1). Because it is difficult to judge the quantity of light, lighting design must be based on what one is able to perceive and what one wants to look at—the quality of the luminous environment.

Designers must learn to design with concepts that can be judged with their brains and eyes rather than with instruments. This realization is fundamental to taking advantage of the freedom and creative opportunities available in the design of the luminous environment. Other factors that should be considered are the effects of sunlight on the biological health of people and plants and on thermal comfort.

**VISIBILITY**

As pointed out in chapter 1, humans see well over a wide range of illumination levels. We can see in moonlight as well as in sunlight. An object in direct sunlight may be as much as a million times brighter than the same object illuminated by moonlight, but the human eye can perceive both. The law of diminishing returns operates above very minimum light levels, thereby making additional amounts of illumination increasingly
Light levels (illuminance) may vary tremendously over small distances with very little perceived difference. Differences are even harder to judge if the surfaces illuminated are of various forms and colors. Differences are even harder to judge if the surfaces illuminated are of various forms and colors. When assessing how illumination will be perceived in a space, graphing data on a logarithmic scale will most accurately represent the perceived reality, since perception of light is logarithmic in nature: each doubling of the luminance is perceived as a barely noticeable difference (fig. 2-2). The only reason to use a linear scale is to graph the effects of illumination levels on cost rather than on people (fig. 2-3). In fact, increases in light levels often accentuate latent visibility problems such as glare. If the illumination level is relatively unimportant for visibility, one might ask, "Why is it important to redistribute sunlight to the inherently darker portions of a room?" The reason: to make those areas of the room appear more cheerful.

The quality and geometry of the illumination in relationship to the viewer are much more important than the quantity for most tasks. For example, we have all had the experience of tilting a fever thermometer to the "perfect" angle in order to read it or of rearranging ourselves or the television set to eliminate bothersome reflections. Similarly, light coming from the wrong direction can reduce the contrast between ink and paper because of veiling reflections. Look at a magazine while facing a window or unshielded light source; compare its visibility when turned away from the light source.

To optimize visibility, the amount of light coming from the trouble-
COMMONLY EXPERIENCED BRIGHTNESS LEVELS

- Lawn or dark road, sunny day—1600FL
- Lawn or dark road, overcast day—220-400FL
- Sidewalk, moonlight—0.15FL
- Streetlight—0.03FL
- Book, one candle—0.3FL
- Incandescent lamps—over 10,000FL
- Luminous ceiling—50FL
- Concrete pavement, overcast day—550FL
- Concrete pavement, sunny day—4400FL
- Snow, overcast day—850FL
- Snow—6800FL
- Sky—700-1500FL

2-2. Commonly experienced brightness levels are best graphed on a logarithmic scale.
(Reprinted, by permission, from Lam, Perception and Lighting as Formgivers for Architecture)
some direction (the mirror angle) should be minimized relative to that coming from other directions. To know which angles are least desirable, place a mirror at the task location. Since the angle of incidence is equal to the angle of reflectance, the light source, if seen in the mirror, would also be seen as a competing (veiling) reflection on a glossy page. The effect is more subtle on a matte page with glossy ink or pencil writing, where the effect is a reduction in contrast between the dark figures and the light background.

The ideal control over the direction and intensity of light is possible if each task can be provided with its own "task lighting." This is most practical when the activities, furnishings, and equipment can be fixed in location (for example, nurses’ stations, hotel registration desks, museum displays). More typically, however, we should provide a general level of illumination suitable for most activities and only provide task lighting to assist with the most demanding tasks, such as drafting. When designing general illumination, the viewing angle and direction cannot be controlled. When desks face in all directions and there are many tasks, the light source should be spread out as much as possible so that only a small portion of the illumination on any task will come from a "troublesome" direction. Examples of "spread-out" sources include the surfaces of light-colored rooms indirectly illuminated by sunlight or electric light sources.

Incidentally, the strategy of providing pleasant general lighting combined with task lighting is far more economical than trying to increase the general level of illumination to that demanded by the most critical task. The comfort of the occupants who are not doing critical tasks will be greater if they are not subjected to excessive levels of light and glaring light sources. Fortunately, the tide is turning against these power-company-inspired "heat-by-light" buildings of the 60s and early 70s.

**PERCEPTION**

The information sought—what we want to see—should be our focus. Anything that interferes with this is considered visual noise. Therefore, we should illuminate what we want to see, be it a task or a pleasant visual rest area. Conversely, we should not create or accent visual noise!

**Brightness**

As mentioned above, our perception of brightness is very flat and related more to a logarithmic than a linear scale. We are not aware of large variations of illumination levels within a space or over time. It is difficult to perceive quantitatively the distribution of light in a space (see fig. 2-1). It is easier to perceive a variation in the rate of change in light gradients than the amount of change. It is by such changes of rate that we perceive edges and form.

Since expectation is a large factor in perception, it results in our perceiving wide fluctuations in daylight levels as natural, and thus unnoticeable. The same fluctuations from normally constant artificial light sources would be noticeable and disturbing, or perceived as relevant information—a lamp burning out, or the end of intermission at the theater, for example.
Relative Nature of Brightness

The dominating feature of human vision is adaptation. Everything we see is referred to a reference level, whether of lightness, darkness, or color, and we make our interpretation in terms of this reference level. All visual experience has some basis in past or present knowledge. Brightness, as well as color, is affected by simultaneous contrast, a situation whereby some objects seem brighter than others of equal luminance in a uniformly illuminated space.

In our daily experience, many factors come into play as the eye adapts to each luminous scene. Context, experience, and expectation are all taken into consideration when perceiving whether an object is dark, light, too bright, or dull. For instance, an interior space at night may seem "brighter" than a daylight scene even though the exterior luminance is 1,000 times greater. Consider these perceptions in your own experiences:

- your living room at night versus a dark overcast day outdoors;
- a bright cafeteria versus a bright cocktail lounge;
- sunlight on a windowsill versus light fixtures of equal luminance;
- a bright mural versus a dirty dish cart.

When your mental observations are compared with light-meter readings the results may be surprising!

Aperture Contrast

Similarly, the view out a window may be several hundred times brighter than the interior; however, this difference in brightness will only be disturbing if there is a sharp contrast between the two (worst case: a small opening in the middle of a dark wall). Illuminating the wall area near the window will create a transitional area that will lessen the aperture contrast.

Glare and Sparkle

The lighting industry and electrical engineers try to define glare in terms of luminance and luminance ratios. Webster's dictionary defines glare as an "interference with visual perception caused by an uncomfortably bright light source or reflection," and sparkle as "an attractive brilliance." A sunlit surface of interest is likely to be perceived as pleasant and as "sparkle," whereas a lighting fixture of equal brightness would be considered "glare." While a window view might be momentarily perceived as "glare" (e.g., when viewing a face in silhouette to it), it would not be perceived as such if one was looking out the window. To understand what glare is, we must recognize that glare is a perception, and perceptions are interpretations of information, not sensations.

Overcast Sky and Sunlight

One perceives a clear sky as pleasant and a nonuniform, overcast, or partly cloudy sky as interesting, whereas a solid overcast sky is perceived as "dull." Because it is uninteresting, the uniformly overcast sky
is likely to be perceived as glaring and "too bright" even when its measured luminance is far less than the sunlit landscape or blue sky.

An object can be regarded as sparkling instead of glaring if it is the desired object of perception, such as a chandelier, a view, or an interesting patch of sunlight. Context—the relevance or irrelevance of a scene—rather than brightness ratios, determines "glare."

**Gloom**

Gloom is experienced in the following situations:

1. Conditions for performing an activity are suboptimal: not enough light; focal object obscured by shadows; focal object silhouetted rather than highlighted.
2. Desired biological facts are:
   1. difficult to obtain because observer is excluded from view, sunshine, or feeling of daytime;
   2. unclear due to upsetting of constancies such as size, shape, color, or brightness; lack of focal points, visual rest centers, sparkle, or interest; or
   3. dominated by unwanted facts: dominance by overly bright ceilings or bright overcast sky; dominance by objects outside the immediate area where privacy is desired.

The view through a bronze or gray heat-reducing glass window usually is not disturbing because the viewer does not "compare" the view with anything. However, the color of the glass will be noticed and will be disturbing if an open or clear window is also in the viewer's field of vision (fig. 2-4). When there is a basis for comparison, the view through such glass appears tinted and gloomy.

**Darkness**

On an overcast day we will find the ground objects dark in comparison with the overcast sky. (Also, the overcast scene may seem dark, even though luminance levels may be hundreds of times greater than a "bright" interior space.) On a sunny day, when shadows define and emphasize their three-dimensional aspects, these ground objects will appear brighter than the sky. At night, we consider a street "brightly illuminated" when the ground elements are bright, although the sky is always dark and the illumination level may be a thousand times brighter than that on a "dark" overcast day.

**Dullness**

An object of great interest is seldom described as dull. Conversely, something inherently dull visually cannot be made less dull by greater luminance. It must be changed and given interest by the addition of colors (such as paint in a parking garage), shadows, or the dramatic upsetting of constancies (such as pools of light along paths of circulation). A scene may appear dull because the intended object of attention is dominated
by something dull. Intentional upsetting of constancies can create drama, excitement, or tension. If this upsetting of constancies does not appear to be intentional, the same effects can be gloomy and disturbing. For example, the highlighting of a floor show may make one less conscious of a dining room's features, to positive advantage. Equal highlighting of the kitchen scene viewed through a service door would be unpleasant and make the dining room appear dull.

**SUMMARY-VISIBILITY AND PERCEPTION**

The quantity of light is only one of many factors that determine how well we see and the overall quality of a luminous space. Each viewer and each space have specific information needs, and each object and task have specific characteristics. Above very minimum illumination levels, relevant lighting geometry, rather than quantity, is the most effective way to meet these needs and delineate these characteristics. Visibility is also relative to focus, distraction, and context. To increase visibility by brute strength (footcandles) rather than skill (geometry) is wasteful and likely to produce bad side effects in the form of glare.

An understanding of the process of and the components of perception helps to explain why a room interior may appear "too bright" at night but "too dark" during the day (due to the viewer's knowledge of simultaneous exterior conditions). This effect would be increased if there were a black window at night and even a crack of daylight during the day for reference (e.g., around the edge of drawn blackout shades).

Our judgment is altered by what we expect to be bright in a given environment under given conditions for a particular activity. An unlit mural, located as an obvious focal point in a room, would appear dark because we expect it was meant to be featured. A chandelier in a theater always appears too bright if even barely lit during the performance, though not too bright at full intensity during the intermission. Highlight-
ing an empty fireplace or an ugly floor would create a scene described as "too bright" except to the janitor as he was cleaning up. Thus, to produce a predictable, comfortable, brightness perception level, those involved in design must determine what should be perceived, as well as the dimensions of the stimuli (luminance). This most important first step requires that the designer predict the information needs, conscious and unconscious, of the probable users.

THE LUMINOUS ENVIRONMENT

A "good" visual environment is one that satisfies the visual information needs of the occupants. Surfaces of interest are highlighted, surfaces lacking interest are deemphasized. There is a maximum of "signal" (wanted useful visual information) and minimum of "noise" (unwanted, irrelevant visual information). What is lit and how is more important than how much illumination is provided. The best visual environments are those in which the apparent sources of light are those surfaces one enjoys looking at: room surfaces, people, interesting views of nature-information that is subconsciously needed for our activities or for orientation for survival (biological information needs).

Poor, or "noisy" visual environments are dominated by visual information that is irrelevant to the interests or needs of the occupants, is ambiguous or unpleasant, or distracts from desired perceptions. Examples of visual noise indoors include informationless surfaces such as translucent fluorescent light fixtures and luminous ceilings or translucent walls, whose brightness unpleasantly dominates our attention (fig. 2-5).

A typical outdoor example of a poor luminous environment is a totally overcast day. On such a day one's focus is dominated by the bright but uniform, uninteresting sky when one really wants to look at the landscape, buildings, and people to get information relevant to one's activity, interest, or survival. Sunny days are more comfortable because the ground-related objects of interest are relatively bright and most are easy to see.

2-5. Translucent walls are of little interest and compete with both the view outside and objects of interest within the room.
ACTIVITY NEEDS FOR VISUAL INFORMATION

The relationship between what people will be expected to do in a building and where and what kind of light is needed for the various activities imparts the design of any luminous environment. It is important to list and analyze activities that will take place, ranking these actions in terms of priority and frequency.¹

A look at a programmatic approach to designing space shows that these considerations can be roughly broken down into:

- Activities, which have
- Subactivities, which have
- Visual subactivities, which have
- Various information needs from objects of varying characteristics.

In this process, the designer becomes aware of conflicting demands for optimum performance (fig. 2-6). The following paradigm offers an example:

**SPACE:** lecture classroom

**ACTIVITIES:** lecture, discussion, demonstration, audio-visual

**SUBACTIVITIES:** listening to speaker, music or meaningful nonverbal sounds; taking notes, movement, relaxation

**VISUAL SUBACTIVITIES:** looking at faces, gestures, clothing, notes, projected images

**INFORMATION NEEDS:** same as visual subactivities

In order to determine the appropriate characteristics of systems to be employed, each activity must be located in the space and its requirements analyzed along the following parameters:

- Is the object of the activity vertical or horizontal?
- Is the object local or found throughout the space?
- Is the object seen by variation in reflectance, color, texture, shape, or a combination?
- Is the object two- or three-dimensional? Glossy or matte? Light or dark?
- Is there use of CRTs or other special lighting needs?
- Is the activity of long or short duration, or intermittent?
- Are the various activities simultaneous or sequential?

Various types of information needs, object characteristics, and relevant lighting characteristics for activities and subactivities should be sum-

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2-6. Competing demands for optimum performance.

18 The Delightful, Healthful, Luminous Environment
### SPACE PROGRAM CHART

#### BIOTHERMAL AND ACTIVITY NEEDS

**Movement**
- Circulation information
- Orientation in space
- Leisure
- Relaxation
- Restful visual activity
- Balance
- Non-activity

**Lighting Budget**
- Type:
  - Biological and activity needs
  - Information needs
  - Hardware system

#### INFORMATION NEEDS

<table>
<thead>
<tr>
<th>Movement</th>
<th>Visual Sub-Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circulation information</td>
<td>Route, signs, layout of objects and building elements</td>
</tr>
<tr>
<td>Orientation in space</td>
<td>Levels, edges, obstacles, people, and other moving objects</td>
</tr>
<tr>
<td>Leisure</td>
<td>Shape of space; relation to exterior</td>
</tr>
<tr>
<td>Restful visual activity</td>
<td>Nature of enclosing structure</td>
</tr>
<tr>
<td>Balance</td>
<td>Daylight reference</td>
</tr>
<tr>
<td>Non-activity</td>
<td>View of sky, winds, rain, sunlight, artwork, and other people</td>
</tr>
<tr>
<td>No distraction by high signal noise ratio</td>
<td>Isolation when desired</td>
</tr>
</tbody>
</table>

#### CHARACTERISTICS OF VISUAL ENVIRONMENT

- Positive, clear articulation of paths, nodes, and areas by building elements and graphics
- Adequate illumination, shadows, gradients; minimum disability glare, irrelevant disturbing pattern
- Spatial and structural articulation
- Clear windows, skylights
- No glaring light fixtures; relevant order of focus for activity and characteristics of space
- No mixed color sources on similar surfaces in similar circumstances
- Illuminated wall and ceiling surfaces during the day to balance window brightness and to relate to exterior daytime conditions

#### NUMERICAL CRITERIA

- **Use of Materials**
- **Footnotes**

2-7. Space Program Chart. (Reprinted, by permission, from State University Construction Fund, *An Approach to the Design of the Luminous Environment*)
Visual information is continuously monitored in many activities. The child shown here must pay attention to the ground surfaces to avoid tripping or falling into the water and to the movement of other people to avoid collision.

Disorientation at the T.W.A. terminal of Kennedy airport. The sloping floors, nonvertical walls, and lack of windows give one no points of reference.

Gallery of the Guggenheim Museum (Frank Lloyd Wright, Architect). This space is disorienting for similar reasons as the T.W.A. terminal. Here, however, the pictures, which are hung on a true horizontal, do give one a reference level to substitute for a level horizon. (Photograph courtesy of John Lam)

BIOLOGICAL INFORMATION NEEDS

Survival, protection, and sustenance affect the need to perceive and feel comfortable with the environment. Lighting that provides well for biological needs in most spaces simultaneously takes care of most activity needs.

Inaccurate or inadequate visual information can be distracting and even dangerous. Dissatisfaction or gloom results from any lack deemed unreasonable (i.e., not by choice or in exchange for another advantage). Even during sleep, perception of changes in location, movement, and state is necessary at all times for the protection of the body.

Every activity requires visual contact in order to obtain necessary information. Some examples of activities and their concomitant information needs are:

ACTIVE ACTIVITIES: walking, running, jumping (perception of level, ground surfaces, obstructions, and direction as shown in fig. 2-8), and working (perception of object of focus)

INACTIVE ACTIVITIES: protection from physical attack (from animals, people, machines, weather, fire, and intense sound) and protection of organs (particularly sensory and reproductive) from physical damage

More subtle instances of the need for visual contact can be shown in the need to maintain a sense of equilibrium (fig. 2-9). On a foggy day at the beach, for example, we are uncomfortable because the biological need for a defined horizon is unfulfilled.

Likewise, the effect is uncomfortable in the Guggenheim Museum in New York City (fig. 2-10) where the floors slope but the pictures are hung on a true horizontal.

While these more subtle effects influence perception, there are clear information needs that we monitor continuously and unconsciously in sharply defined areas. These include:

- Location, with regard to water, heat, food, sunlight, escape routes, destination, and so on;
- Time and other environmental conditions that relate to our external schedules as well as to our innate biological clocks;
- Weather, as it relates to the need for clothing and heating or cooling, the need for shelter, opportunities to bask in the beneficial rays of the sun, and so on;

\[\text{2Dietz, Lam, and Hallenbeck, An Approach to the Design of the Luminous Environment, p. 75.}\]
\[\text{3Lam, Perception and Lighting as Formgivers for Architecture, p. 30.}\]
D Enclosure, the safety of the structure, the location and nature of environmental controls, protection from cold, heat, rain, and other elements;

D The presence of other living things—plants, animals, and people—particularly those perceived as dangerous;

D Territory, its boundaries and the means available within a given environment for the personalization of space;

D Opportunities for relaxation and stimulation of the mind, body, and senses;

D Places of refuge, shelter in time of perceived danger.  

Once we are aware of this information, we evaluate and reach a qualitative decision. We feel uneasy if information is ambiguous, tense if the facts are bad, disappointing, or signal danger, relaxed if the facts indicate everything is under control, and pleased if control is achieved.

Because of time orientation, during the day we subconsciously expect it to be brighter outside buildings than inside. At night we expect it to be darker outside buildings than inside. We tend to feel "gloomy" when the situation is ambiguous, such as on dark overcast days. The length of the "ambiguous" period is extended by the use of low-transmission glass. It is unexpected, and therefore depressing, to see our reflection when looking out a window at midday when we expect to see the far brighter scene outdoors. Recent studies have indicated that many people suffer from a "short-day syndrome" and are depressed in the winter months. For similar reasons, many, including the author, are less tired flying westward with the day extended than flying eastward with the length of the day sharply reduced.

Because we desire security from a surrounding enclosure, a clear understanding of a building’s structure satisfies biological needs (as does a view of sunlight or exterior landscape) and is perceived positively. The ambiguous nature of luminous ceilings or rows of luminous fixtures is likely to be found unpleasant. Although uneven gradients positively defining the shape of solid surfaces seem pleasant and natural, uneven gradients on a uniform flat material seem unnatural and distracting.

For some activities, such as relaxing at poolside, sunlight may be completely positive (fig. 2-11). But, while we all enjoy seeing signs of its presence, being in the sunlight may have definite negative consequences if the light or heat interferes with what we want to see or do (fig. 2-12).

We can, however, welcome feeling and seeing sunlight inside a building, as long as it does not interfere with our activities. Direct sunlight on our desk or work area can be very bothersome—but only if we are unable to move away from it or control it and are exposed to it for a long period of time. In cold climates, we may seek and delight in the radiant warmth of direct sunlight within as well as outside of buildings.

Visual environments are generally most pleasing when the surfaces of interest are the principal apparent sources of light, and the actual sources are concealed from normal view. This is accomplished in indirect lighting of walls and ceilings combined with well-baffled direct lighting of work surfaces.

Lam, Perception and Lighting as Formgivers for Architecture, p. 21.
Sunlight on the walls is welcomed information, not "glare," as would be produced by translucent lighting fixtures of equal luminance. The backlighting produced by the translucent panels in figure 2-5 is not seen as natural sunlight but as informationless unnatural distraction—more frustrating than pleasurable, and therefore "glare."

When we are inside a room at night, looking at a dark window bright with reflections of the room, we perceive the window as "darker" than an interior wall of lower luminance. The wall is nonthreatening, but the window is a source of possible danger since we can be seen through it but cannot see outside. Mirrored or low-transmission glass compounds (the difficulty of seeing out at night.

The people on the walkway in figure 2-13 are doubtless very much aware of the water's edge on one side and the wall on the other. Several points are illustrated:

D Inherent biological needs—Attention is drawn to the edge as a possible source of danger; there is also an awareness of the location of water.

D Object clarity—The edge is emphasized by a change in materials (especially important when illumination is or must be minimal because of conflicting demands, such as experienced in a theater) or where sloping shadows add positive information, supporting one's awareness of stair risers.

Figure 2-14 is a master table of biological needs. It summarizes the visual environment and hardware systems associated with various biological needs. Also included in the table are descriptions of the critical time/situation of each need and the relevant visual information.5

Good design must satisfy needs for information and qualitative conditions, rather than only quantitative criteria.

A room that one instinctively finds attractive and appropriate for its purpose is not an aesthetic frill; rather, it is likely to be a more comfortable and productive space. The characteristics of such a space have value, measurable by surveys if not by light meters.

LIGHT AND BIOLOGICAL HEALTH

A variety of physiological mechanisms in man respond either directly or indirectly to the spectral characteristics of sunlight and its artificial equivalents. Most of these responses are indirect, relying on the transmission of light by the photoreceptors in the retina to neural signals, which in turn affect various bodily functions. Although a number of these effects have been identified in animals, for the most part it has yet to be determined to what extent they pertain to and are significant for man.

Most common and perhaps least significant here are the reactions of skin to ultraviolet radiation. While tanning or burning from sustained exposure is now becoming recognized as a source of cancer, the degree of exposure in buildings is of such limited medical importance that it will not be discussed further.

By far the most beneficial function of sunlight to man that we have identified is the production of vitamin D by the absorption of ultraviolet radiation. Vitamin D in turn plays a significant role in the body’s absorption of calcium, a deficiency of which can result in rickets in children and osteoporosis in adults. Artificial illumination that simulates the solar spectrum can also induce this metabolic response in humans, but the quantities of ultraviolet radiation available from artificial sources are so low that eight hours of exposure to 100 footcandles is the approximate equivalent of three minutes spent outdoors on a sunny day.

For the aged, institutionalized, or otherwise confined-adults who are getting insufficient vitamin D to meet their biological needs—it may be found desirable or in some cases necessary to provide increased means for ultraviolet exposure. This could have important implications for policy makers, administrators, and building designers. High-level artificial lighting installations could be beneficial, but it is much easier to optimize natural light when possible. Solaria that take maximum advantage of the available sunlight could be required in certain facilities; balconies could be required in homes for the aged; and even normal populations could be encouraged to spend more time outdoors at midday. The Soviet Union is already making significant use of "photaria" (artificially illuminated solaria), particularly for persons living in polar regions or those working underground or in windowless buildings. Whenever sunlight is available at a site, however, solaria would be much more effective and pleasant, by providing several thousand footcandles for those who are unable to get sunlight for much or most of the year. Of course, it would be much easier if one could get a few minutes of sunlight rather than hours of artificial illumination of lower intensities.

LIGHT AND THE EYE

Exposure to light can damage the eye in varying degrees, according to the nature and intensity of the source and the length of exposure. The extent of impairment may range from permanent physiological damage to what is commonly termed "eyestrain." It is certainly clear from a review of the literature that overexposure to light is far more damaging to the eyes than underexposure and that both the ultraviolet and visible
When danger is expected from people or animals

Location of potential threats; the nature of the surrounding enclosure

Eliminate unlit areas and sources of glare which might conceal danger; clarify the nature of the surrounding enclosure — structure, possible exits, etc.

Avoid flimsy structural forms such as the typical luminous ceiling; avoid suspended structural elements with unshielded light sources; avoid using sources inconsistently different sources to light identical surfaces.

When danger is expected from structural failure

Comprehensible structure with clear continuity and visual logic

Use forms consistent with the expectations of the viewer; use light gradients consistent with the form of the structure which they illuminate.

Avoid unevenly illuminated EXIT signs, EXIT signs which do not dominate their surroundings sufficiently to be clearly visible; eliminate other signs in the vicinity of EXIT signs which would compete for the visual attention; avoid overly bright EXIT signs, on the other hand, in dark environments such as theaters.

When danger is expected from fire

Location of control and prevention equipment; escape routes clearly visible

Use lighting to articulate circulation paths and exits; use color coded fire extinguishers and clear EXIT signs.

Use proper glare shields or other control devices on luminaires so that sources do not achieve an undesired prominence or create disability glare conditions while providing required illumination for tasks or biological needs.

When danger may be caused by intense light or glare

Maximum evidence of high sanitation standards

Emphasize clean work area in kitchens, labs, etc.

Avoid highlighting areas such as dirty dish conveyors or garbage collection areas.

When danger might be anticipated due to unsanitary conditions

Orientations

All times; maximum when moving

Level horizontal reference clues

Use material joints (e.g. in masonry), moldings, expansion joints, millwork, etc. to establish clear horizontal orientation.

Avoid inclined floors without clear visual information defining the nature of the incline; spaces defined by irregular or curvilinear enclosing surface without clear horizon clues.

Definition of ground surface contours, enclosing boundaries, obstructions, level changes

Define level changes and edges with highlighting, consistent shadows, changes in material (color, surface, or reflectance)

Avoid distracting elements in the visual field at level changes; avoid confusing elements such as inconsistent shadows or carpet patterns which tend to obscure rather than emphasize level changes.

Location relative to destinations and exits

Articulate the building layout and circulation system by a clear differentiation of circulation nodes and destinations with distinctive patterns of decorative light sources or by selective highlighting of elements such as elevator cores, etc. corridors should be differentiated from walk spaces, and different types of corridors should be treated differently; good graphics should be used, particularly at decision points such as corridors and intersections.

Avoid undifferentiated lighting schemes which apply the same design to functionally disparate spaces, providing no visual guidance information.

Avoid backlit signs with opaque lettering, in which the shape of the background typically dominates the intended message.
Chief of Ophthalmology at the Massachusetts Eye and Ear Infirmary in Boston, and Professor of Ophthalmology, Harvard Medical School, has been particularly vehement on this subject for many years.

As a by-product of satisfying the user's needs for biologically important information, extensive plantings have been introduced in buildings to make up for their unnaturally large scale and to provide the users with needed contact with nature. In many spaces, particularly atrium spaces, the most stringent lighting is often required for plant material too large for the most stringent lighting is often required for plant material too large for

| Light for Plant Growth | 2-14. Master table of biological needs. (Reprinted, by permission, from Lam, Perception and Lighting as Formgivers for Architecture) |
to rotate (with greenhouse specimens) and too expensive to replace if unhealthy.

Because the high illumination levels required by some plants used indoors (100-500 footcandles) are many times more than those needed for human activities, plants should be places where sunlight penetration is maximum. In addition, supplementary lighting should be directed specifically to the trees rather than to the overall space (see case studies G1, G2).

Simplistic quantitative criteria for tree lighting are usually incorrect. Horizontal illumination levels measured at the top of a tree do not adequately describe the photons received by the leaves throughout the tree, which are needed for photosynthesis. For example, if four floodlights located directly overhead to illuminate the top of a tree were spread out and directed to illuminate the tree from all sides, the horizontal illumination at the top would be decreased, but the tree would receive an equal amount of illumination with a different distribution. This arrangement of lights would promote a more favorable (rounded, rather than vertical and spiky) tree growth configuration, in the manner of individual trees in open fields rather than trees in the woods.

Criteria

The proper measure of light for tree growth should be the total light (footcandles × hours) received by the tree from all directions, not only on the horizontal plane. Seventy-five footcandles from all directions is generally better than 200 footcandles from a single source. Trees also benefit more from the ultraviolet than the visible spectrum. A few minutes of direct sunlight (approximately 8,000 footcandles) is equivalent to many hours of diffused daylight or artificial light at building interior levels. For example:

8,000 footcandles × .25 hours
800 footcandles × 2.5 hours
80 footcandles × 25 hours.

SUNLIGHT AND THERMAL COMFORT

The relation between sunlight and thermal comfort in homes is somewhat different than that in offices and other types of buildings that most benefit from sunlining. In residences, the major effort in solar design is to store heat for use when sunlight is not present. The instantaneous effect of sunlight is less important because homes are generally less occupied during the day than are office buildings. Furthermore, they do not need as much light, and people are free to move about to the most comfortable spots. Residential solar design is primarily that of solar-thermal-economics.

The concerns are somewhat different in the sunlining of offices, where the need for illumination and thermal comfort is simultaneous, and the occupants are less free to move. Here, there should be more concern as to the instantaneous effects of solar radiation on comfort, as well as on energy conservation from good passive solar design.
Redirection of sunlight to illuminate a space more uniformly also has a corresponding effect of redistributing heat, because the indirect light is eventually absorbed by darker colored walls, floors, and furniture surfaces. This slow heat storage minimizes local overheating and reduces heating and cooling energy requirements. As in homes, this contribution has more of an effect on energy cost than on thermal comfort, which can be produced by the HVAC system in any case.

In buildings with sunlighting, the more stringent concern is with solar radiation as it affects comfort. Here people are not free to move at will. A thermostat setting for the room in general will not ensure comfort for those more exposed to the direct rays of the sun. Direct sunlight on the body or clothing may be welcomed when the thermostat is on the low end of the temperature comfort zone (in winter). It will not be wanted when the thermostat is on the high end of the comfort zone (in summer).

Another important radiation effect is that of heat loss or gain to large nearby surfaces that are much colder or warmer than body temperature. This can be a problem with large areas of glass.

I have visited offices on cold days when the curtains or blinds were closed (and desirable light and view shut out) to baffle the radiant heat from hot, heat-absorbing glass. If the thermostat had been lowered, others deeper in the room would have been too cold. Such discomfort would not have occurred if the sunlight had been allowed to pass through clear glass onto the much more massive room surfaces (floors and walls), which would have had little temperature change.

Similarly, if exposed to the cold glass of single-glazed windows, occupants will draw the blinds. This happens when double glazing is not considered to be cost-effective in conserving energy and insufficient value is given to the radiation effects on thermal comfort (see case study C1).
Reducing the importance of high light levels and exact quantities of light as criteria for evaluation requires that designers understand some basic physics of light and its control. This will enable them to best utilize energy to achieve the desired balance of qualitative and quantitative objectives. This chapter will discuss those physical principles most relevant to designers.

**LIGHT**

In sunlighting, we are concerned with the entire spectrum of solar radiation, including wavelengths of light outside the range of human vision. These include the shorter wavelengths (ultraviolet) that can damage sensitive materials such as those in museums, and the longer wavelengths (infrared) that produce heat (see chart of radiant energy spectrum in chapter 4). While all of the wavelengths in the visible spectrum generally produce similar effects, sunlighting design can, to a degree, modify the balance of the invisible constituent wavelengths (UV and IR) to suit programmatic needs.

**Speed of Light**

All forms of radiation are transmitted at the same extremely high rate of speed (approximately 186,300 miles per second) and behave alike in many ways. This phenomenon is very important in design. For example, it allows light to be modeled directly at any scale without the need for a scale factor. The modeling of sound is infinitely more complex because, with a speed of 1,100 feet per second, the difference between 1 foot and 100 feet is significant.

There is no loss of light passing through outer space, which appears black because there are no particles to intercept light. Although the level of sunlight is reduced about 30 percent (from 14,000 footcandles to 10,000 footcandles) from the edge of the earth’s atmosphere to sea level by the molecular particles of clear air and water vapor, the mass of clear air at building scale absorbs virtually no light.

Light travels in straight lines in a constant medium. When encountering a medium at an angle with a different index of refraction, light will
slow down and hence be refracted (fig. 3-1). The speed of light through glass is 30 percent less than it is through air, the phenomenon around which lenses are designed.

**TYPES OF LIGHT SOURCES**

For designers, the most important considerations about a light source are its size, shape, intensity from various directions, and its location in space.

Depending on its size (relative to its distance from the surface being illuminated), a light source may be a point source, a line source, or an area source. In photometric testing, the measuring distance is more than ten times the maximum dimension of the light source. Thus, a soft white lamp will produce soft shadows and behave like an area source to surfaces a few inches away but act like a point source when at ceiling height. Similarly, a 4’ x 4’ skylight will act like a point source when more than 40 feet away (fig. 3-2).

**Point Sources**

Illumination from a point source varies inversely with the square of the distance (fig. 3-3). There is no loss of light, only an increase in the area illuminated in each cone of light from a point source. On earth, illuminance from direct sunlight is constant at any height, because the rays are parallel when the light source is an infinite distance away (and changes in distance are insignificant).

Point sources produce sharp shadows.

**Line Sources**

When a light source is a point source on one axis and an extended source on the other, illumination from it varies inversely with distance. Thus, the measured intensity of illumination on a horizontal surface from a continuous narrow skylight or light fixture will be cut in half if the roof is doubled in height (fig. 3-4).

Line sources produce shadows along one axis.

**Area Sources**

When the light source is extended in both directions, the effect of distance from the light source (ceiling height) is much less. In the case of area sources, the illumination received at any point will vary with the
3-5. Top: the sun as a directional point source produces equal illumination on the ground of an alley and a highway. Bottom: the area source of the overcast sky illuminates the highway much more than the alley because it "sees" more sky.

3-6. The ceiling of a small room must have a much higher luminance than that of a large room with wider proportions to produce equal illumination.

3-7. Nondirectional sources can be made effectively directional.

Light and Its Control

Nondirectional and Directional Sources

Light is almost always nondirectional when generated. Light sources become directional depending on where they are placed relative to other surfaces and the nature of those surfaces. Light from an incandescent bulb hanging in the center of a room is nondirectional. The distribution of this light can be made directional by being blocked off in most directions (placing the bulb in a black can, for instance) or, more efficiently, by being redistributed to a single direction using reflectors or lenses (fig. 3-7).
The distance of the sun from the earth makes sunlight highly directional with virtually parallel rays. This makes diagramming its path in buildings very easy.

**CONTROL OF LIGHT**

Because of its very high intensity and constant movement, sunlight is difficult to use directly and should be used in a diffused form, ideally as indirect light.

Light can be controlled by taking advantage of a number of phenomena: reflection, refraction, polarization, interference, diffraction, diffusion, absorption, and baffling.

For sunlighting design, control of **reflection** is the most important principle. **Refraction** may be useful for distributing light, and **baffling** can be used to reduce glare when more positive redirection is not possible. The other phenomena listed may be used in developing special materials, but are not of primary significance here.

**Reflection and Reflectance**

Reflection may be specular, spread, diffuse, or compound depending on the direction of the light reflected. The **amount** of light reflected- **reflectance** - is independent of specularity. The reflectance of a material is the total percentage of light reflected, both diffuse and specular.

**Specular Reflection**

Specular (mirror) reflections are produced by polished surfaces. The angle of incidence is equal to the angle of reflection and should be diagrammed in that manner (fig. 3-8).

Specular reflectors may reflect very efficiently (mirror glass or special processed aluminum) or inefficiently (polished black marble, black structural glass, or the front surface of clear glass). Do not confuse specularity with efficiency (fig. 3-9). Polished stainless steel reflects light much less efficiently than matte white paint (55-65 percent versus 75-90 percent).

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance (or Transmittance)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specular</td>
<td></td>
<td>Provide directional control of light and brightness at specific viewing angles. Effective as efficient reflectors and for special decorative lighting effects.</td>
</tr>
<tr>
<td>Mirrored and optical coated glass</td>
<td>80 to 99</td>
<td></td>
</tr>
<tr>
<td>Metallized and optical coated plastic</td>
<td>75 to 97</td>
<td></td>
</tr>
<tr>
<td>Processed anodized and optical coated aluminum</td>
<td>75 to 95</td>
<td></td>
</tr>
<tr>
<td>Polished aluminum</td>
<td>60 to 70</td>
<td></td>
</tr>
<tr>
<td>Chromium</td>
<td>60 to 65</td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>55 to 65</td>
<td></td>
</tr>
<tr>
<td>Black structural glass</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Spread</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processed aluminum (diffuse)</td>
<td>70 to 80</td>
<td>General diffuse reflection with a high specular surface reflection of from 5 to 10 per cent of the light.</td>
</tr>
<tr>
<td>Etched aluminum</td>
<td>70 to 85</td>
<td></td>
</tr>
<tr>
<td>Satin chromium</td>
<td>50 to 55</td>
<td></td>
</tr>
<tr>
<td>Brushed aluminum</td>
<td>55 to 58</td>
<td></td>
</tr>
<tr>
<td>Aluminum paint</td>
<td>65 to 70</td>
<td></td>
</tr>
<tr>
<td>Diffuse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>White plaster</td>
<td>90 to 92</td>
<td>Diffuse reflection results in uniform surface brightness at all viewing angles. Materials of this type are good reflecting backgrounds for coves and luminous forms.</td>
</tr>
<tr>
<td>White paint</td>
<td>75 to 90</td>
<td></td>
</tr>
<tr>
<td>Porcelain anagel •</td>
<td>65 to 90</td>
<td></td>
</tr>
<tr>
<td>White terra-cotta •</td>
<td>65 to 80</td>
<td></td>
</tr>
<tr>
<td>White structural glass</td>
<td>75 to 80</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>35 to 65</td>
<td></td>
</tr>
</tbody>
</table>

3-8. Specular reflections: the angle of incidence is equal to the angle of reflection.

3-9. Specularity does not imply efficiency (the total amount of light reflected).

(Reprinted by permission, from *IES Lighting Handbook*, 1981 Volume)
When all reflections are perfectly specular, a light source is seen from only one angle. That is why you see your face in the bathroom mirror and not the light overhead (fig. 3-10).

Specular reflections can be useful when perfectly controlled and very detrimental when not controlled. They help control light in well-designed low-brightness fixtures as long as the proper lamp is used, but will produce glare with the wrong lamp or when wall washers are incorrectly aimed. Using specular reflections in sunlighting is even more difficult. With a moving source of light (the sun), specular reflectors must track for maximum effectiveness or settle on a reasonable compromise, such as to optimize one particular condition (fig. 3-11). Care must be taken to ensure that the undiffused sunlight reflects to a building surface and not to eye-level positions.

If the desired reflector geometry of a light fixture or sunlight reflector is not physically possible, it is better to use spread or diffused reflectors than specular ones. In this way, some of the light (rather than none) will go where wanted. Conversely, the light reflected in unwanted directions will be less objectionable. Spread and diffuse reflectors will occur accidentally if mirrors are not kept polished.

Mirrors reflecting direct sunlight must be very flat and free from distortion ("oilcanning"). Otherwise, the patterns of reflected sunlight can be unattractive.

Specular reflectors are used most efficiently when they cause a major redirection of light. In such cases, they intercept the light quite directly and produce a beam of light almost as wide as their surface area. Specular reflectors are less efficient when making small changes of direction, when the light is very oblique to the reflecting surface and requires a proportionately larger surface area (fig. 3-12). For applications of mirror reflectors, refer to chapter 6 (figures 6-72, 6-73), and case studies B7, Fl, F2, Gl, and G2).

**Spread reflections**

Spread reflections are softened reflections at the mirror angle created by slight irregularities in the surface due to corrugating, etching, hammering, and so forth. They should be diagrammed accordingly (fig. 3-13).

Spread reflections should be used when a properly controlled direction is possible but a softened image desirable. Some people prefer to see sunlight reflected in that form, but I prefer the sharp edges of untampered sunlight and perfect brightness control at the reflector. However, the softened images from slightly unpolished spread reflectors do have the advantage of hiding imperfect light-receiving surfaces and the distracting images of distorted or dirty reflectors (or filament images in light fixtures).

**Diffuse reflections**

Matte finishes produce diffuse reflections with no directional control. Regardless of the angle of the light source, matte finishes reflect equally in all directions. In schematic design diagrams, diffuse reflections from matte white ceilings should be diagrammed as nondirectional reflections, not specular (fig. 3-14).
While the luminance (brightness) of a specular reflector will be irregular (different from different directions) and mirror that of the source at one angle, the luminance of a diffuse reflector will depend on the illumination component normal to the surface and the reflectance of the surface (fig. 3-15).

Reflectance of matte materials is dependent on their color and hue. White and yellow have high reflectance; red, blue, and green have low reflectance. Paint charts usually list their respective reflectance values. The reflectances of some common building materials are listed in figure 3-16.

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance (per cent)</th>
<th>Material</th>
<th>Reflectance (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluestone, sandstone</td>
<td>18</td>
<td>Asphalt (free from dirt)</td>
<td>7</td>
</tr>
<tr>
<td>Brick</td>
<td>48</td>
<td>Earth (moist cultivated)</td>
<td>7</td>
</tr>
<tr>
<td>light buff</td>
<td>40</td>
<td>Granolite pavement</td>
<td>17</td>
</tr>
<tr>
<td>dark buff</td>
<td>30</td>
<td>Grass (dark green)</td>
<td>6</td>
</tr>
<tr>
<td>dark red glazed</td>
<td>30</td>
<td>Gravel</td>
<td>13</td>
</tr>
<tr>
<td>Cement</td>
<td>27</td>
<td>Slate (dark clay)</td>
<td>8</td>
</tr>
<tr>
<td>Concrete</td>
<td>40</td>
<td>Snow</td>
<td>7</td>
</tr>
<tr>
<td>Marble (white)</td>
<td>45</td>
<td>Snow</td>
<td>7</td>
</tr>
<tr>
<td>Paint (white)</td>
<td>75</td>
<td>Snow</td>
<td>7</td>
</tr>
<tr>
<td>new</td>
<td>75</td>
<td>new</td>
<td>74</td>
</tr>
<tr>
<td>old</td>
<td>55</td>
<td>old</td>
<td>64</td>
</tr>
<tr>
<td>Glass</td>
<td>7</td>
<td>Vegetation (mean)</td>
<td>25</td>
</tr>
<tr>
<td>clear reflective</td>
<td>20-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tinted</td>
<td>7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diffuse reflectors reflect light from small particles oriented in all directions. The effective reflectance of a surface is less if that surface is highly configured. For example, if a ceiling is coffered, the illumination it receives will be distributed over a greater surface area, and will be proportionately less efficient in its reflectivity than a flat ceiling of the same material (fig. 3-17). The design implications of ceiling configuration are more important in large rooms than in small rooms, where wall reflect-
Combined matte and spread reflections are more important because they constitute a higher proportion of the room surfaces.

**Compound and Semispecular Reflectors**

Most materials are compound reflectors. They produce diffuse reflections from the colored base material and some sheen from a shiny transparent surface (fig. 3-18). High-gloss paint and polished white marble give a combination of matte and specular reflections. The effect is quite similar to that of spread reflectors. Shiny fabrics may combine the characteristics of matte and spread reflectors.

As with spread reflections, proper application of compound reflections can be useful. For instance, if a bad geometric relationship between light sources and a polished marble floor or counter is unavoidable, the annoying reflections will be much less noticeable if the marble used is light in color rather than black.

**Selective Reflections**

**Ultraviolet**

The color (spectrum) of light reflected will be affected by the color of the reflector. A reflector that reflects all parts of the light spectrum equally is rare, if not nonexistent. Colored reflectors reflect some colors and absorb others. Other reflectors may reflect all visible colors equally but none of those beyond the visible range. Such selective reflectors can be very useful in changing the ratio of visible to ultraviolet light admitted—a phenomenon that is particularly valuable in museums. A zinc-based white paint will reflect only 4 percent of the UV component while reflecting 90 percent of the visible light (fig. 3-19). With multiple reflections the proportion can be improved still further as an alternative to using special UV-filtering plastic glazing.

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>40-60</td>
</tr>
<tr>
<td>Untreated surface</td>
<td>60-89</td>
</tr>
<tr>
<td>Treated surface</td>
<td>75-85</td>
</tr>
<tr>
<td>Sputtered on glass</td>
<td>55-75</td>
</tr>
<tr>
<td>Paints</td>
<td>25-30</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>75-88</td>
</tr>
<tr>
<td>Tin plate</td>
<td>70-80</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>55-60</td>
</tr>
<tr>
<td>Calcium carbonate</td>
<td>5-10</td>
</tr>
<tr>
<td>New plaster</td>
<td>10-35</td>
</tr>
<tr>
<td>White baked enamels</td>
<td>4-5</td>
</tr>
<tr>
<td>White oil paints</td>
<td></td>
</tr>
<tr>
<td>White water paints</td>
<td></td>
</tr>
<tr>
<td>Zinc oxide paints</td>
<td></td>
</tr>
</tbody>
</table>
Near \( \text{Visible Infrared Far Infrared} \) Wavelengths Wavelengths Wavelengths

\[
\begin{array}{cccccccc}
400 & 500 & 600 & 1000 & 2000 & 4000 & 7000 & 10,000 & 12,000 & 15,000 \\
\text{nm} & \text{nm} & \text{nm} & \text{nm} & \text{nm} & \text{nm} & \text{nm} & \text{nm} & \text{nm} & \text{nm} \\
\hline
\text{Material} & R & R & R & R & R & R & R & R & R \\
\text{Specular aluminum} & 87 & 82 & 86 & 97 & 94 & 88 & 84 & 27 & 16 & 14 \\
\text{Diffuse aluminum} & 79 & 75 & 84 & 86 & 95 & 88 & 81 & 68 & 49 & 44 \\
\text{White synthetic enamel} & 48 & 85 & 84 & 90 & 45 & 8 & 4 & 4 & 2 & 9 \\
\text{White porcelain enamel} & 56 & 84 & 83 & 76 & 38 & 4 & 2 & 22 & 8 & 9 \\
\end{array}
\]

---

Infrared

Infrared radiation is also reflected in different proportions than is visible light, depending on reflector material and color. For example, polished and diffuse aluminum reflectors reflect much more infrared in proportion to visible light than do white enamel reflectors (fig. 3-20). Aluminum reflectors can be used to direct both heat and light into a space or to reject them when they are not wanted through the use of blinds.

Reflecting sunlight into the building from white painted surfaces removes more IR than heat-absorbing glass will, with the additional benefit that the heat-absorbing (and reradiating) surface is located outside of the space. These materials are helpful in increasing the efficacy of sunlight and should be used to get light with a minimum of heat.

Research is needed to determine the IR reflectance of other common materials—such as other types of paint, sand, snow, grass, and concrete—that may be used for sunlight control in buildings.

Refraction of Light

Light is refracted when it passes through materials with different indices of refraction (general densities). It is much more difficult to make major changes in direction by refraction than by reflection; to do so, the light would have to be bent in several stages. The amount of redirection of light necessary in sunlighting is thus best achieved by other means.

At times, a small change in the direction of light is useful. In such cases, prismatic glass blocks or panels can be used effectively (fig. 3-21).
Unfortunately, a by-product of such refraction is distortion of all views. Therefore, views should be separated from the refracting device, either by providing an additional "view window" or by integrating the device into a reflecting surface (fig. 3-22). Prismatic glass block was used quite extensively in American schools and hospitals in the 40s and 50s, usually in combination with view windows. I always found them most unattractive; perhaps the practice did not continue because others did, too. In recent times there has been some use of clear glass block for interior partitions. It is generally used to borrow light and to provide physical, acoustic, and thermal separation and for decoration, however—not for controlled distribution of light.

This limitation may not be important for some applications, such as when permanent privacy is wanted, or when the glazed area is out of normal view. One such application is in glass-block pavements to illuminate spaces below. This was done by John Portman at the Emory University Athletic Center over the gym, pool, and concourses and also at his Marina Center, Singapore, to get light from the plaza to the concourse.

When the scene outside a window is unattractive, a distorted view that presents colors without details may justify the use of refraction for redirecting light to the ceiling. This may be far preferable to the use of a nondirectional diffusing material that is void of inherent interest and appears equally bright from all angles.

**Piped Sunlight**

Some designers have proposed "piping" sunlight with lenses and tubes, via acrylic rod, or by use of fiber optics, from rooftop to lower level rooms, where the light would then be introduced via light fixtures (fig. 3-23). The cost of such materials on the scale needed and for provision of building volume to be used exclusively for such purposes will always be disproportionate to the possible value in saving energy or providing delight. Why spend so much effort and money to end up with an ordinary light fixture?

This is quite different from using fairly simple devices, such as large one-way tracking mirrors located in multifunctional atria, to redistribute light. This type of device retains the identifying qualities of sunlight and must be integrated into the architecture of a building. Crisp sunlight patterns create views, where delight of the space and associated activities as well as energy savings can be enjoyed.

**Transmission and Glazing Materials**

Glazing materials vary in their light- and heat-transmitting characteristics. Glazing can transmit, reflect, or absorb solar energy (fig. 3-24). Tinted glazings work by absorbing specific frequencies of light. Low-E glass (e.g., Guardian’s Low-E or South Wall’s Heat Mirror 88) is coated with a material that makes it reflect infrared light without altering its transmission of visible light substantially. Heat-absorbing reflective glazings absorb and reflect across the spectrum (fig. 3-25). Remember that the heat is reradiated equally to interior and exterior—hence, it can be very warm near the glazing. The fact that less light is transmitted by reflective glazings often can make interior spaces feel gloomy.

<table>
<thead>
<tr>
<th>Glazing</th>
<th>Solar %</th>
<th>Visible %</th>
<th>&quot;R&quot; factor for winter night</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Clear</td>
<td>89</td>
<td>80</td>
<td>.87</td>
</tr>
<tr>
<td>Double Clear</td>
<td>80</td>
<td>65</td>
<td>2.04</td>
</tr>
<tr>
<td>Coated/Tinted Clear Low E</td>
<td>52</td>
<td>74</td>
<td>3.13</td>
</tr>
<tr>
<td>Green &quot;Solex&quot;</td>
<td>41</td>
<td>68</td>
<td>2.04</td>
</tr>
<tr>
<td>Bronze-tinted</td>
<td>41</td>
<td>48</td>
<td>2.04</td>
</tr>
<tr>
<td>Reflective Grey</td>
<td>6</td>
<td>8</td>
<td>2.27</td>
</tr>
<tr>
<td>Gold</td>
<td>9</td>
<td>18</td>
<td>2.94</td>
</tr>
<tr>
<td>Silver-Grey</td>
<td>23</td>
<td>29</td>
<td>2.17</td>
</tr>
<tr>
<td>Silver-Blue</td>
<td>12</td>
<td>18</td>
<td>2.27</td>
</tr>
<tr>
<td>Triple Clear</td>
<td>62</td>
<td>75</td>
<td>2.56</td>
</tr>
<tr>
<td>Clear Low E</td>
<td>48</td>
<td>70</td>
<td>3.13</td>
</tr>
</tbody>
</table>

3-25. Transmission- and insulation-valued glazings. (Note the R value of Low E glazing.)
For the purposes of sunlighting, it is preferable to use a glazing that admits the maximum amount of visible light, while admitting less of the ultraviolet and infrared portions of the spectrum. Green-tinted (Soflex T) glass has an advantage in this regard (fig. 3-26). Clear double glazing is usually the most cost-effective in temperate climates. Low-E glazing has its advantages but at the present time is at too much of a premium.

The transmittance of glass is affected by the angle from which the light is received. The transmittance from direct sunlight remains fairly steady from normal angle until 50° but diminishes rapidly after 60°. At very oblique angles (80+ degrees), the transmission approaches zero because the light is reflected instead of transmitted.
Data for single glazing with 0.90 transmittance at normal incidence and double glazing with 0.81 are as follows:

<table>
<thead>
<tr>
<th>angle of incidence</th>
<th>single-glazed window</th>
<th>double-glazed window</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>0.90</td>
<td>0.81</td>
</tr>
<tr>
<td>20°</td>
<td>0.90</td>
<td>0.81</td>
</tr>
<tr>
<td>40°</td>
<td>0.89</td>
<td>0.80</td>
</tr>
<tr>
<td>50°</td>
<td>-0.87</td>
<td>0.77</td>
</tr>
<tr>
<td>60°</td>
<td>0.82</td>
<td>0.71</td>
</tr>
<tr>
<td>70°</td>
<td>0.77</td>
<td>0.59</td>
</tr>
<tr>
<td>80°</td>
<td>0.44</td>
<td>0.29</td>
</tr>
<tr>
<td>90°</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

For diffuse radiation, the transmittance for single glazing is 0.82; for double glazing, 0.72.

**CONCLUSION**

Sunlighting design consists primarily of planning the geometric relationships of architectural elements to the light available in order to direct light where it is wanted. Understanding the nature of light and its control by reflection, refraction, and transmission is necessary to conceive, diagram, and design the architectural forms and details of sunlighting.
4

Sunlight: Source of Light and Heat for Buildings

Very detailed information about sun and sky has been presented in several sources, including Hopkinson's *Daylighting*. Those interested primarily in calculations and the theoretical basis for calculations should consult these sources (See Bibliography). This chapter will only present those facts about the sun as a source of light that have helped create the architectural forms of sunlighting.

The light of the sun is available on earth in two forms-direct and diffuse. When the sky is clear, buildings receive direct sunlight and sunlight reflected off surrounding surfaces (fig. 4-1). When the sky is overcast, the sun's light is diffused by clouds, and the sky is the apparent source of light (fig. 4-2). Sunlight design applies when sunlight rather than sky light is the predominant condition. Much of the early work applying natural lighting in buildings "scientifically" occurred in northern Europe (especially England) where sky light is the predominant condition. This has sometimes misled designers in other parts of the world, where sunlight is the usual condition. This book is about the sunlighting forms that can be created using natural light.

**EXTRATERRESTRIAL SUNLIGHT**

In space, just outside earth's atmosphere, sunlight arrives as a pure beam of virtually parallel rays of identical spectral quality. All sunlight falling on a space capsule is received *directly* from the sun. Since there is no substance to intercept the light, the surrounding space is black.

**DISTANCE OF THE SUN**

Because of the great distance of the sun as a light source (93 million miles), the rays of sunlight falling on the earth are virtually parallel. This fact is very significant. The parallel rays of sunlight have the following effects:

D No inverse-square law need be applied to sunlight calculations. With artificial light sources the light rays are divergent and illumination intensity decreases as an inverse square of the distance (see chapter 3). There is no significant diminishing of the sun's
illumination with the increases in distance possible within the earth's atmosphere. The light received on the top of a tree is no more intense than that at the bottom, thus generating a uniform growth rate. Similarly, an area of direct sunlight admitted at the top of a fifty-story atrium retains its shape and intensity at the floor.

D Simple optical control: the parallel rays of sunlight allow a flat mirror to reflect the exact shape and size of the light beam received.

**APPARENT MOVEMENT OF THE SUN**

The earth as a whole receives the same amount of sunlight every day and every year. The apparent movement of the sun around the earth is relative and due to the earth's rotation and orbit. The seasonal differences in the daily path of the sun are due to the tilt of the earth's axis (fig. 4-3). At any given moment in time, each portion of the earth receives the sun-

![Image](image-url)

4-3. The tilt of the earth creates the seasons and the altitude of the sun. (After Mazria)
light at a different angle that changes on a daily and annual basis. At any point, the sun is highest at solar noon of each day. The elevation of the noon sun is dependent on the distance from the equator. During equinox noon the solar altitude is equal to 90 degrees minus the latitude. At midsummer noon the altitude is 23.5 degrees higher than the equinox noon, and at midwinter it is 23.5 degrees lower.

Since the sun travels 360 degrees laterally in twenty-four hours, it moves 15 degrees per hour. The design of sundials is based on this fact, as is navigation during sunlight hours. The location of the sun in the sky can thus be described as having two components: its daily movement around the horizon is its bearing angle relative to south. Its height above the horizon, which varies seasonally, is its altitude (fig. 4-4). Sunlighting strategies for various latitudes should be based on the predictable seasonal differences in the sun’s altitude as well as other factors such as climate, altitude, proximity of water, vegetation, and buildings (fig. 4-5).

4-5. Designs should be based on the predictable difference in sun angles. The amount of time the sun’s altitude angle is below 22.5° and 45° for various latitudes during office hours (8:30 A.M.-5:30 P.M.) suggests where fixed horizontal shading can be most effective.
POWER OF THE SUN

The sun radiates its energy in all directions. The minute fraction of the sun's energy received by the earth has provided the basis of all life—both the incoming energy used to keep warm and sustain life and the retained fossil energy in the form of coal, petroleum, and other types of fuel. Evolving mankind has become increasingly dependent on using our stored energy reserves to provide the light and heat which in the past were provided exclusively by the sun and renewable energy sources. We have extended the hours of work and play and the level of thermal comfort, independent of geography and climate. However, we have now learned that the supply of nonrenewable energy is not infinite. We have also become aware of the costs in pollution and other negative side effects that can result from the conversion of excessive amounts of energy. We must therefore examine the amount of "free" incoming solar energy we can use to meet our current needs for light and heat and to allow us to extend the use of stored energy for future generations.

At the edge of the earth's atmosphere (normal to the sun), the level of solar illumination is approximately 14,000 footcandles. Even after passing through the atmosphere of a clear sky to sea level, the level can exceed 10,000 footcandles. As a comparison, a brightly lit office might have an average of 30-100 footcandles of electric lighting.

The instantaneous energy of one square foot of sunlight (on a horizontal surface at equinox noon, sea level, 40 degrees north latitude) is equivalent to the visible light of 3.3 40-watt fluorescent lamps, or 6 100-watt incandescent lamps. As heat, this solar energy is equivalent to 88 watts from an electric heater. Even if used inefficiently, there is obviously an abundant amount of radiant energy available from the sun.

ILLUMINATION FROM SUNLIGHT-VECTORS AND SURFACES

Were there no atmosphere surrounding the earth, the intensity of sunlight received at any point (normal to the sun) on the sunny side of the earth would be constant and equal to that at any other point.

Of course, the intensity of light normal to any particular planar surface is dependent on its angular relationship to the direction of the sunlight (fig. 4-6). When the sun is low (and horizontal relative to a point on the earth’s surface) the sunlight is received more directly on vertical...
Some designers think of "natural light" as the light from the sky and discount direct sunlight because it is difficult to calculate and control. Proper design of sunlighting requires recognition of the total light from the sun after its filtering by sky and clouds and its reflection by ground-level natural and man-made elements (even if difficult to quantify precisely). The composition and the color temperature of sunlight change slightly after it passes through the atmosphere. Figure 4-8 shows the spectral composition of sunlight before and after it passes through the atmosphere.

The relative amounts of light received by a building from sky and ground will vary depending on the position of the sun, sky conditions, and the shapes and reflectances of ground surfaces and objects on the ground.

4-7. Sunlight is most concentrated when the receiving surface is normal to the incident angle of sunlight.

4-8. Spectral distribution of energy in sunlight above the atmosphere and after passage through one air mass (zenith) containing 20 mm precipitable water vapor. (Reprinted, with permission, from Meinel, Applied Solar Energy)
FILTERING BY THE CLEAR SKY

When sunlight passes through the air mass surrounding the earth, some of the light is absorbed and some is scattered by molecules and dust particles. This scattering is more pronounced at the shorter or "bluer" wavelengths. Thus, the blackness of space becomes dark blue at the edge of the atmosphere, deep blue in the clear dry air of our highest mountains, light blue at sea level, and almost white when the haze of water vapor and dust is encountered. The sky has a high color temperature, meaning it is "hotter" or "bluer" than the direct rays of the sun (fig. 4-9).

On a clear day most of the illumination comes directly from the sun, which thus casts sharp shadows. The intensity of illumination from direct sunlight on a clear day varies with the thickness of the air mass it passes through. It is therefore almost entirely dependent on the sun’s altitude (fig. 4-10). It is less intense at sunrise and sunset at any latitude; and at noon it is less intense at high latitudes because the sun is lower. Because
4-11. Summary of variations in solar illumination perpendicular to sun's rays for sunny and less sunny climates. (From Hopkinson, Daylighting; reprinted by permission of William Heineman Ltd.)

<table>
<thead>
<tr>
<th>Solar altitude (h)</th>
<th>Air mass (m)</th>
<th>Sunny climates (i)</th>
<th>Less sunny climates (particular clear skies)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>10.4</td>
<td>1,200</td>
<td>840</td>
</tr>
<tr>
<td>10°</td>
<td>5.6</td>
<td>3,560</td>
<td>2,490</td>
</tr>
<tr>
<td>15°</td>
<td>3.8</td>
<td>5,280</td>
<td>3,950</td>
</tr>
<tr>
<td>20°</td>
<td>2.9</td>
<td>6,520</td>
<td>4,560</td>
</tr>
<tr>
<td>30°</td>
<td>2.0</td>
<td>8,000</td>
<td>5,600</td>
</tr>
<tr>
<td>40°</td>
<td>1.55</td>
<td>8,850</td>
<td>6,190</td>
</tr>
<tr>
<td>50°</td>
<td>1.3</td>
<td>9,360</td>
<td>6,560</td>
</tr>
<tr>
<td>60°</td>
<td>1.15</td>
<td>9,670</td>
<td>6,770</td>
</tr>
<tr>
<td>70°</td>
<td>1.05</td>
<td>9,870</td>
<td>6,910</td>
</tr>
<tr>
<td>80°</td>
<td>1.02</td>
<td>9,960</td>
<td>6,980</td>
</tr>
<tr>
<td>90°</td>
<td>1.0</td>
<td>10,000</td>
<td>7,000</td>
</tr>
</tbody>
</table>

the air mass through which the sunlight passes varies little, the sun's intensity (normal to it) changes little from directly overhead until it is below 15 degrees, at which time it is 50 percent of maximum. In figure 4-11, these changes are summarized for totally clear skies and for average clear skies in less sunny climates, such as England. The 30 percent reduction in England implies the presence of haze.

Sunlight intercepted by the clear sky vault becomes a nonuniform luminous source producing about 10 percent of the total clear-day illumination, most of it coming from the brightest area of sky immediately surrounding the sun. While not immediately obvious, this nonuniform distribution can easily be observed by the naked eye if one masks the view of the sun itself.

Note that the darkest part of the blue sky, approximately 90 degrees from the sun, is likely to be quite dim (about 300 footlamberts—equal to clouds on a dark, overcast day). Under hazy conditions, these variations are reduced; the brightest areas become less bright, the darkest less dark (figs. 4-12, 4-13).

The brightness distribution of clear skies suggests that a building design that controls the glare of the direct sun and redistributes direct sunlight effectively will also control the glare and best distribute the light...
from the clear sky because the brightest part of the clear sky is the area immediately surrounding the sun. Except in the area near the sun, the blue sky is less bright than most cloudy or overcast skies.

**DIFFUSION AND REFLECTION BY THE CLOUDY SKY**

Unlike clear days and totally overcast days, the illumination on cloudy days changes constantly (from 2,000 to 10,000 footcandles) with moments of full sunlight and other moments when the sun is intercepted by clouds. Even when diffused by clouds, there is usually a sufficient concentration of light to cast soft shadows, due to thin areas in the cloud cover (wherever the total illumination is more than 2,000-3,000 footcandles). While the brightest part of the clouds is usually nearest the sun, bright patches may appear opposite the sun when the sunlight reflected off the edges of clouds is visible from the ground below, as it is from an airplane (fig. 4-14).

Because of the rapid and constant fluctuation from direct sunlight to diffused sunlight that occurs on cloudy days, sun-control devices, if they are to control glare completely, should be set in the same way as for clear days at that time (fig. 4-15). Since the brightest clouds are usually near the sun, designing for direct sunlight best controls the glare and redistributes the light from cloudy skies as well.

4-14. Clouds are always brighter than the blue sky when seen from above or from the sunlit side. Thin clouds are brighter from below as well. (Photograph courtesy of Tom Lam)

4-15. Continuous recording of exterior horizontal illumination for a clear day (left) shows a smooth curve beginning at dusk and peaking at noon, when the sun is highest. On a cloudy day (right), the jagged lines indicate that illumination fluctuates constantly from clear to cloudy levels. (Courtesy of SERI)
DIFFUSION BY TOTAL CLOUD COVER: OVERCAST SKY

Typical overcast skies reduce the sunlight by more than 90 percent. When the cloud cover is so dense that all evidence of the sun is obscured, the luminance distribution is independent of the altitude of the sun. This is the so-called "C.I.E. standard overcast sky," commonly modeled in artificial sky laboratories. In nature, this "totally overcast sky" is rare. The average luminance of the sky is maximum at zenith and decreases to about one-third of maximum value at the horizon (figs. 4-16, 4-17).

In climates that are predominately overcast, it may be important to analyze the luminance distribution more precisely. When designing for sunlighting (where controlling the sun is the most important determinant), knowing the variations in the luminance distribution of overcast skies is irrelevant to the design, as supplemental artificial lighting would be used to balance or raise the illumination level, add highlight and sparkle, and improve (lower) the color temperature. The illumination from an overcast sky varies with the density of cloud cover and the altitude of the sun. When the sun is at 45 degrees, the average illumination should be about 900 footcandles. On a drizzly day, the average illumination is likely to be about 300 footcandles.

SUNLIGHT REFLECTED BY NATURAL AND MAN-MADE SURFACES

Because of the generally low brightness of the clear sky in sunny climates, the light reflected from the ground and buildings is often more important than that received directly from the sky. The presence of adjacent build-
ings may well increase rather than reduce the available light. Even black surfaces in full sunlight can achieve a luminance greater than that of the darkest portions of a blue sky. In designing for sunlighting, one should be aware of potential reflected light from natural and man-made surfaces or better yet plan to shape those elements to take advantage of them when other constraints allow.

**Sunny Side (South in the Northern Hemisphere)**

In an open space, ground-reflected light is of the greatest potential benefit on the sunny side if the immediate foreground is never in shadow (figs. 4-18, 4-19). However, adjacent buildings and trees on the sunny side may place the immediate foreground in shadow, and their shady sides are likely to be the darkest exterior surfaces seen. Keeping adjacent buildings and trees distant will maximize the lighting on the sunny side. Ground-reflected light is greatest when the sun is highest: during summer and at low latitudes. The high solar altitude, together with the reduced degree of foreground and shading required, make ground-reflected light more commonly available near the equator.

---

![Ground-reflected light is most available on the sunny side of buildings.](4-18)

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflectance</th>
<th>Overcast</th>
<th>Sunny (Solar Altitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1500 Fl</td>
<td>25° 45° 80° 100°</td>
</tr>
<tr>
<td>Green grass</td>
<td>6%</td>
<td>90</td>
<td>238 454 568</td>
</tr>
<tr>
<td>Water</td>
<td>7%</td>
<td>105</td>
<td>278 524 663</td>
</tr>
<tr>
<td>Asphalt</td>
<td>7%</td>
<td>105</td>
<td>278 524 663</td>
</tr>
<tr>
<td>Moist earth</td>
<td>7%</td>
<td>105</td>
<td>278 524 663</td>
</tr>
<tr>
<td>Slate (dark clay)</td>
<td>8%</td>
<td>120</td>
<td>318 605 758</td>
</tr>
<tr>
<td>Gravel</td>
<td>13%</td>
<td>195</td>
<td>516 983 1,231</td>
</tr>
<tr>
<td>Grandolite pavement</td>
<td>17%</td>
<td>255</td>
<td>675 1,285 1,610</td>
</tr>
<tr>
<td>Bluestone, Sandstone</td>
<td>18%</td>
<td>270</td>
<td>715 1,360 1,705</td>
</tr>
<tr>
<td>Macadam</td>
<td>18%</td>
<td>270</td>
<td>715 1,360 1,705</td>
</tr>
<tr>
<td>Vegetation (mean)</td>
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<td>- dark buff</td>
<td>40%</td>
<td>600</td>
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<td>- light buff</td>
<td>48%</td>
<td>720</td>
<td>1,906 3,629 4,546</td>
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<td>Concrete</td>
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<td>600</td>
<td>1,588 3,024 3,788</td>
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<td>2,977 5,670 7,102</td>
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<td>74%</td>
<td>1,110</td>
<td>2,938 5,594 7,008</td>
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**Shady Side (North in the Northern Hemisphere)**

On the shady side, the quantity of light reflected off adjacent walls and buildings can be very significant. Generally, the benefits of adjacent buildings increase with their height and proximity, unless the reflecting surfaces are excessively shaded (fig. 4-20).

The light reflected onto a building's shady side by sunlit vertical surfaces is maximized when the sun is lowest: during winter and at high latitudes. Thus the view of adjacent buildings from a north-facing win-
dow in Boston is likely to be brighter than that of similar buildings in Singapore or Saudi Arabia. As noted in chapter 2, it can be difficult to realize how bright the view from a north window can be, because the visual interest of an adjacent building will make it appear less glaring than a light fixture or an overcast sky of equal luminance. An unpainted concrete building reflecting 4,000 footlamberts and a brick building reflecting 1,500 footlamberts may not be perceived as being as bright as a 1,000-footlambert overcast sky. This is an important characteristic that makes natural lighting delightful. Since sunlit objects are enjoyable to look at, they will be perceived as pleasurable "signals" rather than visual noise or "glare."

**SPECTRAL COMPOSITION OF REFLECTED AND TRANSMITTED LIGHT**

Building surfaces and forms affect sunlight in the same way as the natural environment. As light is transmitted, reflected, or scattered, certain wavelengths may be absorbed or redirected more than others, affecting the color and/or efficacy of the light. The luminous efficacy of a light source is defined as the ratio of the total luminous flux (lumens) to the total radiant power (watts). The effect of atmospheric scattering and absorption on the efficacy of sunlight is to increase the ratio from approximately 94 lumens/watt in space to approximately 118 lumens/watt at sea level (at one air mass). The efficacy of sunlight also varies with solar altitude (fig. 4-21).

![Graph: Luminous efficacy of solar radiation as a function of solar altitude.](image)
This phenomenon may be applied to architecture when choosing the materials and locations for transmitting and reflecting surfaces. In a building in which the cooling load is greater than the heating demand, a greater luminous efficacy is more desirable than in a building with a substantial heating demand.

**AVAILABLE WEATHER DATA AND INTERPRETATION**

Weather data for determining the sunlight conditions in a given area are available in many forms, none of which is ideal for sunlighting purposes. The National Climatic Center in Asheville, North Carolina, has data from locations throughout the United States, including the National Oceanic and Atmospheric Administration stations. The published monthly summary of local climatological data is also available through local NOAA stations (fig. 4-22).

Perhaps the most commonly used description of available sunlight is known as the "sky cover," which measures tenths of cloudiness, 0 being absolutely clear and 10 being totally overcast. Unfortunately, this measurement is based entirely on visual estimation and is not consistently accurate.

Measurements of total solar radiation in langleys are available in a variety of time intervals, ranging from hourly to annually. Measurements are made using pyrheliometers and/or pyranometers, which are sensitive to a large range of solar flux. Although accurate, these measures are not entirely appropriate for our purposes because the translation from langleys to footcandles of visible illumination is a lengthy task of questionable accuracy. This is, however, the ideal measure for estimating solar gain and sizing HVAC systems.

A third type of data is the "amount of available sunshine." This is recorded in minutes of sunshine and translated into a percentage of possible sunshine. Traditionally (and in some locations currently), a Campbell-Stokes recorder is used. This device employs a lens that burns a piece of paper when direct sunlight is present. Inspection of the paper indicates the duration and intensity of the sunshine.

More accurate measurements are made with a sunshine recorder that uses two detectors, one of which measures global flux and one of which measures scattered flux. When the difference between measurements recorded by the two sensors is greater than a set threshold, the presence of direct sunshine is indicated.

This measurement is interesting because it is a relative comparison between direct sunlight and total light. It is not a reasonable indication of the intensity of the direct sun. Rather, it is a measure of whether shadows are cast and when glare from direct sunlight needs to be controlled. At present, solar radiation data are more useful for calculating HVAC loads than for the design of sunlighting (which is more dependent on when and how often glare from direct sunlight needs to be controlled). Combining the data from several methods is best.
## LOCAL CLIMATOLOGICAL DATA
### Monthly Summary

**Location:** BOSTON, MASSACHUSETTS  
**ISSN:** 0198-2427

### Data Table

<table>
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<th>Date</th>
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<tr>
<td></td>
<td>Pressure</td>
<td>Speed</td>
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</table>

### Notes
- Extreme values of the month are based on 7 or more observations at 3-hour intervals. The highest gust is the vector sum of wind speeds and directions multiplied by the number of observations. One of three wind speeds is given, the second under the fastest mile; the highest gust is recorded for each gust wind station direction in compass points. Fastest observed one-minute wind speed = 10 m/s. 
- Gust = Greatest in 24 hours and dates.
- I certify that this is an official publication of the National Oceanic and Atmospheric Administration, and is compiled from records on file at the National Climatic Center, Asheville, North Carolina, 28801.

### Bibliography
- Sunlight: Source of Light and Heat for Buildings

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**Source:** National Oceanic and Atmospheric Administration (NOAA), National Climatic Center. (1982). Monthly summary of local climatological data as supplied by the National Oceanic and Atmospheric Administration (NOAA). (Courtesy of the National Climatic Center)
SUNLIGHT IN THE UNITED STATES

In the United States, sunshine is plentiful (fig. 4-23). Most areas receive over 50 percent of the possible available sunshine on an annual basis. This does not mean that half the days are 100 percent clear and the other half 100 percent overcast. Actually, there will be substantially more days on which sunshine is present than not. In an area that receives 50 percent of the mean percentage of possible sunshine, it is common that during at least 75 percent of the days, buildings will be subjected to, and require control of, direct solar radiation.

Because the design criteria for clear and partly cloudy days are identical, they should be considered together in contrast to the overcast condition. This is only relevant when using the inferior "sky cover" data since this distinction is inherent in the amount of sunshine data by the method of measurement.

4-23. Top: mean percentage of possible sunshine in the United States (annual); Bottom: total heating degree days.
Inspecting the monthly climatological data summary for Boston, Massachusetts, we can see that during July of 1982 the sun shone 72 percent of the time but on 90.3 percent of the days (fig. 4-24). This breaks down to six absolutely clear days, five days receiving less than 50 percent of the possible sunshine, and twenty days of partly sunny weather. In this month of 72 percent of possible sunshine weather; 35 percent of the days were less than 72 percent sunny, and 65 percent were 72 percent sunny or better. All days except for three required control of direct solar radiation.

In the December 1982 monthly summary, 39 percent of the total possible sunshine was recorded. More importantly, for eighteen days during that month there was enough direct solar radiation to require control of glare (58 percent of the days were sunny at least 10 percent of the time). Compiling data to reflect these less obvious trends is necessary for design and presentation purposes.

It is also interesting to note that on July 29, 92 percent of possible sunshine was recorded with an observed two-tenths of sky cover. On the following day, July 30, 94 percent of possible sunshine was recorded with an estimated eight-tenths of sky cover. Tenths of sky cover and percentage of possible sunshine are evidently incompatible measurements.

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4-24. NOAA monthly climatological data for July, 1982 and December, 1982. (Courtesy of the National Climatic Center)

54 Sunlight: Source of Light and Heat for Buildings
SUNLIGHT IN THE WORLD

As shown by the global isoflux maps in figure 4-25, most of the world receives abundant solar radiation, more than 5 megajoules per square meter per day. In the northern hemisphere, the quantity of solar flux is generally substantially greater in June than in December, and in the southern hemisphere the reverse is true. Only northern Europe and the less populated areas of North America receive less sunlight than the United States. This climatic difference (of one isoline) represents an increase (in the amount of solar flux) of approximately 25 percent in June, and of approximately 100 percent in December, the time at which it is most desirable.

With sunlight being such a widespread and abundant resource, it is foolish to ignore it in favor of the overcast sky condition on which "daylighting" is based. The glare and heat accompanying sunlight must be controlled regardless, and when sunlight is present the vast majority of the time, it is wise to turn these design problems into assets.
Planning for Sunlighting-Concepts

The complexity of satisfying both institutional objectives and human needs makes the development and description of sunlighting concepts difficult.

If the goals were simple, the process might also be simple. If our aim was simply to achieve maximum lighting, or even maximum lighting with minimum energy use, the results could be measured quantitatively and the concepts stated concisely, with procedures and calculations expressed in a linear manner. The success or failure of such straightforward goals could be measured with instruments alone (light meters, watt meters, and the annual power bill). Judging the lowest-cost sunlighting solution would be easy, although considerably more difficult than judging the costs of a windowless building using only artificial lighting.

In the spectrum of design influences, the attempt to fulfill human needs is the complicating factor. People have very real needs and values that are often felt and derived unconsciously and difficult to define precisely.

The multiple design goals discussed in chapter 1 and summarized below suggest a holistic design process. Each strategy and technique must be evaluated by many criteria.

The conventional design of artificial lighting in commercial and institutional buildings has produced disastrous results: unpleasant, uninteresting, and sometimes unbearable visual environments. This can be attributed directly to incorrectly defined goals, resulting in simplistic quantitative criteria and a grossly inadequate design process. The type of multidisciplinary processes required to design electric lighting with humanistic rather than technical goals are applicable to the process of sunlighting design. However, the increase in the number of variables makes the sunlighting design process much more difficult. In artificial lighting design, one generally starts with a building of a particular shape, plan, and structure. Sunlighting design ideally begins much earlier, with the site planning of streets and buildings and the geometry and form of the buildings. To these variables, add a constantly changing light source with as many potential problems as opportunities, and you can begin to appreciate the complexities.
But everything worthwhile in life is complex. It can seem impossibly difficult to get exact answers to such simple, everyday decisions such as what chair to buy, or what to eat. Should we limit the choices only to those that fit within easily defined criteria?

Edward DeBono, in his books on the thought process, makes a distinction between linear and lateral thinking (fig. 5-1). He describes linear thinking as the sequential consideration of factors (typical of Western scientific methods) and lateral thinking as the simultaneous and unstructured consideration of multiple factors (characteristic of Eastern civilizations). He contends that lateral thinking is needed to solve complex problems, particularly in the setting of values and objectives.

This lateral approach is certainly valuable in design, as design objectives are almost never singular and quantitative, but rather overlapping and conflicting, qualitative and quantitative. The process used must therefore be lateral, circular, reiterative. It would be particularly difficult to consider adequately the many simultaneous problems and interactive solutions inherent to sunlighting design without lateral thinking. (The lateral thinking process is reinforced by the use of team design processes recommended in chapter 10.) Concepts must be fully explored, their implications by various criteria weighed, and the results reintegrated into the whole. As DeBono points out, linear thinking is valuable at the end of the process, to carry out the clearly technical objectives and criteria previously defined and put into context by lateral thinking.

**SUNLIGHTING GOALS: VALUE-IDENTIFICATION PROCESS**

The priorities involved in formulating sunlighting design concepts were thoroughly discussed in chapter 1; they are briefly reiterated here to set the tone and context for decision evaluation:

1. **User Comfort and Delight in the Interior Environment**
   The primary sunlighting goal, user comfort, includes both thermal and visual comfort as well as other biological and programmatic needs.

2. **Satisfaction of Other Programmatic Needs**
   Satisfaction of structural requirements, circulation, and the like is a necessary factor in the design of functional buildings.

3. **Minimum Building Energy Cost**
   Energy decisions should reflect the influences of site and program.

4. **Optimum Public Architectural Image**
   Elegance in the execution of the building is the criterion by which architecture is most often judged.

5. **Minimum Building Cost**
   If the design is not affordable, it will not get built.
SCALES OF RESPONSE

The ability to achieve the goals of sunlighting listed above is affected by decisions made at six distinct scales. Making the appropriate decision at the larger scale can simplify the detail decisions, or conversely, make sunlighting design very difficult or impossible. To achieve maximum comfort and energy utilization at minimum cost, one should proceed from the largest to the smallest scale. This chapter will discuss the largest two scales in detail: chapters 6, 7, and 8 will discuss the remaining scales in the context of the building form.

1. Urban Design/Master Planning: This is the golden opportunity to make sunlight available throughout the site or development.

2. Site Planning/Building Massing: Carefully shape and locate the building form to get sunlight onto buildings where and when wanted. The form chosen is highly dependent on the site and building program and must be discussed in those terms.

3. Architectural Scale: The configuration of the building’s exterior forms and surfaces should arise from the needs and activities of the occupants. This includes locating, shaping, and sizing apertures at the interface of the building’s interior and exterior. Shading and redirecting devices are incorporated at this scale to control the quality, direction, and amount of direct reflected sunlight reaching the glazed openings.

4. Hardware: Glazing materials and small-scale supplementary shading, redirecting, and/or blocking devices must be selected to complete the control of the amount and direction of the various components of radiant energy (visible, infrared, and ultraviolet light) entering a given space.

5. Interior Forms and Surfaces: To best utilize the light admitted for both visual and thermal comfort, shape the rooms’ interior proportions and surface geometries. Locate surface reflectances to retain and distribute light as desired.

6. Space Use and Furnishings: This includes space planning to best fit the use with the building condition, arrangement of furnishings for visual comfort, selection of materials for their reflectivity or transparency, and user education as to operation of the building.

THE UNIVERSAL DESIGN INFLUENCES: LATITUDE, ORIENTATION, AND CLIMATE.

Each scale has its specific dominating influences, but all reflect the primary influences of latitude, orientation, and climate. The latitude of a site, and the orientation thereof, determine the sun angles relative to a building in the various seasons. Sun angles, in turn, shape the geometric relationships between a building and its environment. Climate influences the degree and manner in which sunlight is used within a building. Cli-
mate also determines the relative cost-effectiveness of alternative strategies and devices and the ways in which they may be refined for a specific program. Acknowledging these influences will allow you to take advantage of relationship to the sun at any scale.

**URBAN DESIGN/MASTER PLANNING SCALE**

**Goals**

The goal at the urban design scale is to provide access to sunlight throughout the built and natural environment according to the seasonally varying needs for light, heat, and view.

**Influences: Scale Specific**

In addition to latitude, orientation, and climate, urban design influences include the local topography, microclimate and circulation requirements, and the mix of building uses and required building densities.

**Strategies**

To maximize the available sunlight, don't block it! Roadway layouts and building uses and heights should be planned and zoned to prevent excessive shading. Major landscaping should be arranged to allow sunlight to reach the various building types according to their need for sunlight, to encourage optimum orientations, and to simplify the achievement of comfortable environments and energy conservation. Ensure maximum sun in winter when the sun is lowest, and expect local control in summer to reduce HVAC load. At this scale expect the building facade to do its own shading, so that it can benefit by redirecting sunlight into the building as desired, and reflecting the remainder onto the shady side of adjacent buildings. Preserve solar access with zoning codes and laws.

**Forms**

Begin by taking advantage of the topography of the area to create the ideal microclimate. Buildings that step up hillside sites facing the equator receive maximum access to potential winter sunlight. In their book *Site Planning* (M.I.T. Press), Kevin Lynch and Gary Hack state:

A 10 percent slope to the south receives as much direct radiation (and to that extent has the same climate) as flat land 6 degrees closer to the equator—or the difference in latitude between Portland, Maine, and Richmond, Virginia. Yet at middle latitudes, slope orientation affects radiation rather little in midsummer, when the sun is high. It is far more critical in midwinter, when a moderate north slope may receive only half the radiation of a south-facing one.

The natural overhang at Mesa Verde is an unusual but very effective climate-moderating topography (fig. 5-2). A bowl-shaped topography provides ideal shading of the low summer sun, which is untimely and most difficult to control, particularly for sunlighting (fig. 5-3).

These large-scale natural forms can be emulated by the built environment. Plan height controls to create ideal hills or bowls. Locate the
Rhythm and Ritual

The location and form of buildings at Longhouse Pueblo, Mesa Verde, Colorado, provided ancient residents with year-round comfort. The pueblo demonstrates a remarkable ability to mitigate extreme environmental temperature variations by responding to the differential impact of the sun during summer and winter, night and day.

The primary adaptation of the pueblo to the solar dynamic is in its location. The settlement is sited in a large cave that faces south, and the built structures are nestled within. The brow of the cave admits warming rays of the low winter sun but shields the interior of the cave from the rays of the more northern summer sun. Not only the orientation of the cave itself (which measures almost 500 feet across, is 130 feet deep, and arches to 200 feet) but the juxtaposition of the structures within it are responsive to the solar dynamic. The interior structures stay within the summer shadow line, and they are arranged so that one structure steps up from another toward the back of the cave.

It is thus the location of the cave itself and the siting of structures within the cave that ensured the comfort of the pueblo dwellers. Because of orientation, the irradiation of the cave on a winter day is equivalent to that on a summer day. The performance of buildings within the cave is 56 percent more effective as a solar collector in winter than in summer, providing winter heat and summer coolness with remarkable efficiency.

5-2. The climate-moderating form of Mesa Verde. (Reprinted, by permission, from Knowles, Sun, Rhythm, Form)

5-3. Pueblo Bonito. (Reprinted, by permission, from Knowles, Energy and Form)
highest buildings further away from the equator to lessen the impact of their shadows and provide sunlighting opportunities for lower buildings (fig. 5-4). Parking and other facilities with less need for sunlight may be arranged on the shady side.

Circulation

Streets are the city's transparent voids, juxtaposed against the opaque solids of buildings, and can be used to get sunlight into densely built areas (figs. 5-5, 5-6). To an extent, the wider the streets, the greater the distance between buildings, and the greater the sunlight penetration and sky view within the urban fabric. Buildings can be taller without shading their neighbors when spaced further apart (fig. 5-7).

5-4. Locate higher buildings on the polar side of low neighboring buildings to eliminate the impact of their shadows.

5-5. Acoma Pueblo, New Mexico. Plan shows east/west rows with critical spacing to ensure solar access between the two northernmost rows, based on story height. (Reprinted, by permission, from Knowles, Energy and Form)

5-6. Top: three-story section; Bottom: two-story section with narrower spacing between rows.

5-7. When farther apart or on a slope, buildings can be taller without shading their neighbors.
The widest streets (avenues) should run east and west to minimize the shading of buildings with equator-facing facades. This will encourage orienting a building's long facades north and south, which in turn allows for the easiest shading and exposure to sunlight to meet sunlighting and seasonal heating and cooling requirements.

In temperate climates, use deciduous trees to allow winter sun to reach south facades. Place them far enough from the building that they shade the sidewalks, but not the buildings, when the leaves are out.

Narrower streets should run north and south to allow winter sun to reach east- and west-facing facades but block extreme low-angle sunlight at the beginning and end of the longer summer days.

Ralph Knowles has written extensively and very well on the subject of planning for solar access by means of what he terms a "solar envelope"—a zoning concept to preserve solar access (fig. 5-8). My few and incomplete recommendations stray from his by emphasizing the relationship of orientation to lighting rather than thermal comfort. In buildings with stringent lighting requirements (where the problems of glare control are particularly important) orienting buildings to allow for simple solar control is more important than maximum access to sunlight.

The above recommendations assume that streets are more or less aligned with the cardinal points (N-E-S-W). This is probably the most common practice throughout the world. Knowles refers to such layouts in the United States as the Jeffersonian grid. However, he suggests that the Spanish grid, used in the older portion of Los Angeles, would be more effective in getting sunlight onto all streets at some time during each day. Although this might be good for the streets and for assuring greater equality of sunlight for housing fronting directly on each street, such an orientation of streets (as exists in Montreal) makes the achievement of comfortable sunlighting of buildings with stringent lighting requirements much more difficult (fig. 5-9).
More often than not, the designer does not have a "clean slate" to work with; planning generally occurs in a developed area. In this instance, analyzing a built environment with the aforementioned recommendations in mind should reveal the appropriate degree and character of response. While the degree of influence is much more limited, several significant areas can be addressed. The implementation of such recommendations often takes the form of zoning codes; an interesting example is that of New York City, which recognizes the reflectivity of buildings as well as their bulk and placement.

When absolute government control prevails, implementation of planning decisions presents no problem, as shown in the plan of Peking's Forbidden City, in which all major buildings face north and south; only service buildings face east and west (fig. 5-10).

5-10. The Forbidden City, Peking, China. From the master plan of the city, to the site planning and the individual buildings, orientation to the cardinal points is faithfully followed. At the building scale the overhang is equal on all sides, but openings are reduced on the north, and buffer zones are placed on the east and west. (Reprinted, by permission, from Yu Zhuoyun, Places of the Forbidden City)
5.11. Energy-conserving plan (top) versus conventional site plan (bottom) for Burke county. (Courtesy of the Urban Land Institute)
SITE PLANNING/BUILDING MASSING

Goals

The goal at the site planning scale is to get sunlight onto buildings where and when wanted, by carefully shaping and locating the building forms.

Influences: Scale Specific

The ever-present influences of latitude, orientation, and climate are here joined by the decisions made at the urban design scale: street orientation, massing of adjacent buildings, and so forth. The local topography and nature of the site (microclimate, bodies of water, and trees) are dominant influences, along with the space needs and other programmatic concerns of the building. These programmatic needs define the visual and thermal comfort criteria. (For example, direct sunlight might be welcomed in a public space but not in an office or library.) Because the nature of the site and the building program have such a direct influence on the building form chosen, these topics will be examined in three subcategories: sidelighted buildings, toplighted buildings, and court, atria, and lightwell buildings. When choosing the overall building form, it is important to try to anticipate possible changes in the immediate environment.

Strategies

In designing the placement, spacing, and massing of buildings and associated landscaping to take advantage of sunlighting opportunities afforded by a master plan, consider the general characteristics of the possible building types.

Orient and shape buildings to sunlight as well as to the street (figs. 5-11, 5-12, and 5-13). This generally implies that they be elongated along an east/west axis. Buildings requiring illumination early in the day or late in the day should be oriented to sunlight coming from a side direction.
5-14. (a) On a sunny day an adjacent building can be brighter than the sky; (b) on an overcast day an adjacent building is always darker than the sky.

in the afternoon (such as indoor tennis courts) may benefit from elongation on the north/south axis. This orientation is usually desirable only for toplit buildings, where glare control is not a problem.

Place parks and plazas on the sunny side of buildings. In most climates, open areas get more use on the sunny side, and the open space allows for a substantial unshaded foreground for the building. This can increase the quantity of ground-reflected light received, or at least allow the sun to reach the full facade.

Whereas any adjacent building, wall, or trellis is an obstruction in the vocabulary of daylighting design (which assumes overcast conditions), these "obstructions" can be used to advantage when designing around sunlight. If sunlit surfaces are light in color, they will generally provide more illumination than the sky (fig. 5-14), as was discussed in chapter 4.

The location of the sunlighting aperture and the associated building form can be categorized as either sidelight, toplight, or atrium. The choice of form will often be dictated by the building's programmatic needs. For example, sidelighting provides light with views; toplighting helps to create uniform light levels; and atria create dramatic spaces in addition to providing illumination deep within building complexes (fig. 5-15).
These sunlighting methods are not mutually exclusive; each method has its own impact on a building. The selection of any of the sunlighting methods should be guided by an understanding of the implications of that choice from a planning point of view. Therefore, a discussion of the general characteristics of these three methods follows.

PLANNING IMPLICATIONS OF SIDELIGHTED BUILDINGS

The decision to use sidelighting (in the form of windows and translucent walls) has historically been encouraged by the need for exterior views as well as light (fig. 5-16). Ventilation and protection from the elements are easily achieved with wall apertures.

Sidelighting is easiest when buildings are narrow (fig. 5-17). As buildings get wider, those areas away from the perimeter receive insufficient sunlight. This can be alleviated to a degree by increasing the ceiling height or using light-redirecting devices, but the ratio of sunlight opening to floor area remains limited by the geometry of sidelighting.

Elongation of the building along an east/west axis facilitates glare control and increases the building perimeter over a square plan (fig. 5-18). Increasing the building perimeter affords more opportunities for sidelighting. Apertures can be located to create unilateral illumination, bilateral illumination, or illumination from multiple directions (fig. 5-19). Sidelighting also allows every floor of multilevel buildings to have both light and view.

The combination of light and view makes orientation very important when planning for sidelighting. Proper sidelighting design must include careful arrangement and orientation of building masses to maximize direct and reflected sunlight on principal facades when heat and light are most desirable and minimize it when undesirable. For heat control, and to make shading and redirection of sunlight most effective, orient sidelighting apertures north and south whenever possible.

Elongated east/west blocks allow for the most simple glare and seasonal energy control. Deed restriction forcing such orientation can give a unifying character to an area, much as hillside sites promote the uniform orientation of buildings.

Sidelighting is easiest when the predominant sun angle is high (south- and north-facing exposure near the equator) and most difficult when the predominant sun angle is low (high latitudes, or east and west exposures.
5-20. Deciduous trees can be used to shade hard-to-control, low-angle east and west sun in the summer (top) and winter (bottom).

5-21. Allow sun to reach south facade at all times; expect facade to do its own shading as necessary.

5-22. When possible, take advantage of topography to shade low-angle sun. Tall elements at a distance will shade many floors almost equally, whereas adjacent trees may shade only the ground floor.

5-23. Toplighted buildings are desirable when the building is too large to be lit by sidelight alone.

early and late in the day). This is mostly due to the glare problems that accompany low-angle sun.

Sidelighting can utilize not only the light from the sun and the sky, but also the light reflected from the ground and adjacent buildings. However, extensive expanses of sunlit ground or building surfaces are not often available. More often, sunlight is received directly on the building facade, making the facade itself the most important element for capturing, shading, and redirecting sunlight.

The shady sides of buildings usually receive more light reflected from nearby walls than from the sky. Wall- or building-reflected light is at a maximum when the sun is low; ground-reflected light is at a maximum when the sun is high (see chapter 4).

In densely built areas, courtyards can be designed to catch and redirect sunlight for sidelighting at facades that are in shade. A building complex can be designed to ensure light colors on those surfaces that are most important for reflecting sunlight.

The apertures of sidelighted buildings are easily obstructed by adjacent buildings and trees. Conversely, this attribute can be exploited by using deciduous trees to allow sunlight on buildings when desirable, and provide shading when sunlight is undesirable thermally and glare is difficult to control (e.g., on west facades in summer, fig. 5-20). Depending on trees and neighboring buildings for protective shading generally works well only for single-story buildings. For higher buildings, such shading will tend to be insufficient on some floors and excessive on others. Do not shade the south facade during the summer if working light is desired; instead, design the facade to self-shade, capture, and redirect the sunlight (fig. 5-21).

Sidelighted buildings will benefit most from protective shading elements at great distance, such as a distant tall building or far away mountains, because they can shade an entire building equally and reduce the need for local shading of low-angle sun (fig. 5-22). The presence of surrounding hills can be a great asset in simplifying the problems on east- and west-facing facades. If used extensively, this will create distinctive solutions in such locales.

Privacy and/or security requirements may determine the suitability or form of sidelighting desirable. A more detailed discussion of sidelighting can be found in chapter 6.

PLANNING IMPLICATIONS OF TOPLIGHTED BUILDINGS

Toplighting (via skylights, clerestories, sunscoops, and lightscoops) may be desirable when the user program calls for floor areas too large to be illuminated adequately by sidelighting alone (fig. 5-23). Toplighting allows for very high densities of development, in part because it is the sunlighting option least obstructed by other buildings.

Exterior views are severely compromised with toplighting; therefore it should be used when views are not important programmatically, or desirable views are unavailable. Sunlit interior walls can provide a sat-
satisfactory view substitute by meeting biological information needs for contact with nature and orientation in time and space.

When the predominant sun angle is low and maximum heat and light are wanted without the glare of the low sun angle (high latitudes), top-lighting is the ideal solution.

Although top-lighting is usually limited to a single story, it can be used to illuminate more than one level by expanding in scale and combining with open courts, atria, and lightwells. When used to illuminate only one floor level, however, top-lighting allows for the most efficient utilization of sunlight because uniform illumination is easiest to achieve. This freedom in locating apertures for optimum light distribution allows for the use of sunlight with minimum HVAC impact, because a minimum percent of sunlight opening is required to maintain a given minimum light level throughout a space (fig. 5-24).

A top-lighting aperture may be adjusted easily to allow for maximum light and heat at any time of day or season. Apertures can also have the flexibility of being independently oriented from the dominant building orientation (fig. 5-25).

5-24. Top-lighting can provide the most uniform light levels, hence the minimum impact on HVAC.

5-25. Top-lighting apertures can be oriented independently of the building.
Placing the aperture in the ceiling frees the walls and floors to meet other programmatic needs. Walls may be important for display (such as in museum or stores) or for security (warehouses). Toplight is useful where the height of equipment, shelving, or necessary partitioning would limit the distribution of sidelight. A more detailed discussion of toplighting is found in chapter 7.

PLANNING: IMPLICATIONS OF COURT, ATRIA, AND LIGHTWELL BUILDINGS

Programmatic Options

This sunlighting technique creates architectural spaces that can be realized in various forms. These forms include:

- occupied or unoccupied areas;
- fully conditioned spaces, thermally tempered spaces, or nonconditioned buffer spaces;
- enclosed spaces or spaces that are fully open to the sky.

If these spaces are enclosed and climate-controlled, they may be acoustically, visually, and/or thermally open to adjacent spaces or separated from them. Adjacent spaces may be designed to benefit from the light and/or heat from these shared spaces, or they can be isolated from them.

Characteristics

Shared central spaces should be used to achieve maximum development density while retaining contact with nature and sunlight. This method allows light to reach multiple levels in deep buildings, making them more pleasant than they would otherwise be (fig. 5-26). Proper atrium design can reduce the energy costs for providing visual and thermal comfort in deep buildings.

A primary benefit of this technique is the creation of dramatic use areas as focal spaces for surrounding development. The surrounding area of a successful court or atrium space is often assigned high economic value and may provide economic justification for its construction and operations costs.

If this degree of attention is not called for, this sunlighting method can be integrated into the building program in the form of major spaces (lunchrooms, conference areas) or minor shared areas, such as a stairwell or circulation spine.

When not serving adjacent spaces, sunlight may be used to serve the created open space alone. Illumination will generally be required within the space for trees and for user activities such as circulation.

Shared central spaces can provide sunlit views for the surrounding spaces. If desired, their usefulness can be increased by designing them to redirect sunlight efficiently and provide ambient and task lighting for
surrounding occupied spaces. In such cases, careful control of quantity and direction of sunlight admitted is required. A more detailed discussion of shared central spaces can be found in chapter 8.

**BASIC STRATEGIES OF SUNLIGHTING: COMFORT AND ITS ACHIEVEMENT**

Having planned strategies for getting sunlight to various types of buildings, how is this sunlight then used? The objectives of optimum use of sunlight in buildings are visual and thermal comfort. These objectives require the control of the immediate, instantaneous effects of direct sunlight to eliminate glare and radiant overheating, redistribute the visible light and infrared heat to illuminate the spaces optimally, and achieve comfortable air temperatures throughout the year. Comfort and delight also require optimizing interior and exterior views.

These concerns exist in all spaces occupied by people. The exact nature of the optimal solutions will vary according to the programmed activities that define the given environment. The following basic strategies and techniques will help achieve the "comfort objectives" to different degrees. Designers must weigh the trade-offs of cost, appearance, and function associated with the strategies chosen for a specific application.

**Shading**

Shade sunlight to prevent glare and excess heat gain (fig. 5-27). Use optimum orientation to make fixed shading and redirection more efficient and/or easier. On north- and south-facing facades, fixed shading can be effective all of the time for control of glare and HVAC loads. On east and west exposures, fixed shading cannot usually control glare at dawn and dusk. If fixed shading devices are not sufficient, supplement them with movable devices that are used as infrequently as possible. Movable shading devices should be automatically controlled; if manual controls are used, they should be dependable and nonfrustrating to operate, particularly if the movable devices are also needed for privacy, nighttime containment of the space, or control of artificial light.

Why not control the amount of light reaching the space simply by using low-transmission (mirror) glass? In my opinion, this type of thinking has shaped most of the architectural atrocities of the recent past. Mirror glass cannot eliminate the need for shading because 10 percent of the sun’s brightness is still too much. Mirror glass cannot redirect sunlight, except to neighboring buildings. (Its use is prohibited in Singapore for this reason.) Furthermore, low-transmission glass reduces the light when it is wanted as well as when it is not.

**Redirection**

Distribute light where needed to minimize the need for supplemental lighting (fig. 5-28). A high average illumination level is not efficient if it is not well distributed (i.e., if the area near the window receives most of the light). Redirect sunlight to optimize the brightness balance of the room.
5-29. Control the total amount of light reaching the space seasonally.

5-30. Optimize exterior views by using very large- or very small-scale shading elements.

5-31. Optimize interior views by creating beautiful scenes to look at.

by distributing sunlight over the largest possible area. Illuminate threedimensional objects from all directions; illuminate horizontal surfaces uniformly throughout the room. Minimize contrast with windows.

Control

Control the total amount of light reaching the space to achieve thermal comfort and minimize energy cost for HVAC (fig. 5-29). Overlight in winter when heat is welcomed psychologically and physiologically and when excess heat can be dumped easily. Provide only as much light as necessary for planned activities in summer when excess light creates cooling loads.

Efficacy

Use light efficiently. Once light energy is admitted and "paid for," preserve it with high reflectances. High reflectances are less important if there are only heating concerns (minimal lighting needs and little need for cooling).

Framing of Views

Optimize exterior views. Frame the best views and block bad views. Use sun-control elements that require no user action, or either the view or the light will suffer. Minimize pattern conflicts between shading elements and views (fig. 5-30). This is best accomplished with shading elements that are large enough to frame the view. Otherwise, the smallest scale elements that present a texture rather than a pattern may be best. Avoid translucent glazing unless it is an interesting, satisfying, artificial "view" in itself (stained-glass windows, for example).

Optimize interior views. Design and illuminate room surfaces so that they become sources of light that are enjoyable to look at. Shape the entire room as a lighting sculpture, as Aalto and Utzon have done (fig. 5-31). A beautiful interior space is also a comfortable one; to be beautiful is to be functional.
Sidelighting is the most commonly used form of sunlighting because it can provide light, view, and ventilation simultaneously.

The previous chapter discussed the ways in which urban design can make sunlighting available at the site and the architectural programmatic considerations that can ensure maximum solar access for sidelighted buildings. But how do we manipulate the light at and within the building? In this chapter, we will discuss in greater detail those strategies applicable specifically to sidelighting and the resulting techniques, design forms, and devices.

**HISTORICAL PRECEDENTS**

As discussed in chapter 5, sidelighting has historically been the predominant form of using natural light because it fulfills the need for light, views, and ventilation simultaneously. Sidelighting was also the most practical lighting method, given the difficulty of keeping out rain and snow before the development of glass and weathertight glazing systems.

Until the advent of electric artificial lighting, the forms of indigenous architecture reflected the distance that natural light could penetrate the building through windows. Narrow building blocks ensured that sufficient light was available even in the middle of the building. In the predominantly cloudy climate of northern Europe, windows were placed high to distribute diffused sky light. The Gothic cathedrals evolved to achieve the highest and largest windows possible.

It is logical and likely that stained-glass windows were used to give color and interest to the otherwise gloomy overcast sky, as well as to illustrate religious themes. Stained glass also reduces the glare of unshaded windows when the sun shines by reducing the luminance and because, unlike plain translucent material, the information-rich windows are "signal" rather than "noise" or "glare" (fig. 6-1).

In sunny locales throughout the world, the windows in all types of buildings have generally been shaded by overhanging roofs or deep window reveals (fig. 6-2). These shaded windows were generally placed relatively low in walls to best reflect sunlight, rather than extended to the ceilings, even though ceiling heights were increased in larger, deeper
rooms. In religious buildings, the light-receiving surfaces were often the ceilings, which thus became the most common and logical location of decorations. The relatively small apertures were either glazed with clear glass or left unglazed. Stained glass was rarely used (fig. 6-3).

These common design solutions evolved because they were the most logical, practical ways to use sunlight to satisfy the lighting needs of those buildings. These simple principles can be varied to achieve the more stringent objectives in today's larger buildings.

6-3. Monastery of Hosios Loukas, Stiris, Greece (ca. 1040 A.D.). Religious buildings in sunny climates decorate the light-receiving surfaces (ceilings) rather than the glazing. (Photograph courtesy of John Lam)

74 Sidelighting: Strategies, Techniques, Devices, and Forms
SIDELIGHTING GEOMETRY-OPTIMIZING INDIRECT LIGHTING

In earlier times, building forms reflected the limits of natural lighting and the expectation that critical tasks would be performed near the window. Shading provided relief from glare, and ground-reflected light provided adequate indirect lighting.

Sidelighting in today's large buildings requires maximizing the sun's indirect lighting potential as well as providing shading and glare control. While direct sunlight can be controlled and converted into diffuse direct lighting by using diffusing materials, this approach is to be avoided when possible, if freedom from visual noise and the other conditions of a good visual environment are to be achieved (see chapter 2).

The strategy for achieving the comfortable and delightful interior environments described is to redirect sunlight to primary room surfaces (ceiling and walls), which in turn will illuminate secondary horizontal work surfaces. This will also improve the brightness balance of the space relative to the window view.

To optimize the design of indirect lighting, the designer must identify where the light is wanted, where the best primary and secondary reflecting surfaces are located or can be created, and where the light can originate.

Direct light from the window and illuminated surfaces near the window will best illuminate those surfaces deep in a space that "see" or face the windows (fig. 6-4). A surface facing away from the window can only receive light indirectly (as reflected by other surfaces). Only a totally black room would have no interreflected light. An object facing the window of such a room would be completely dark on those sides that did not see the window (fig. 6-5). Without interreflected light, a person in front of a window (light source) will appear only in silhouette.

6-4. Without interreflected light, only those surfaces that "see" the window are not in shadow.

6-5. Egg in black box is lit only by aperture. Egg in white box receives interreflected light from several sides, improving perception of the object.
6-6. By redirecting light received from the ground or a lightshelf, the ceiling becomes an indirect source of light.

6-7. Increasing the ceiling height allows more light in the rear of the space.

6-8. High ceilings are more easily "seen."

6-9. Locate the light source as far from the ceiling as possible. For upward-reflected light, a low aperture (top) will provide better light distribution than one located higher up (bottom).

Major surfaces within a space must both "see" the window and be of high reflectivity to provide this desirable interreflected light. For this reason, furnishings are not dependable as reflectors; they may be of low reflectivity, and their arrangements may trap rather than redirect sunlight. In typical office buildings, even the location of walls may not be predictable. Office landscape systems may have no substantial wall surfaces to reflect light. Floors and low horizontal surfaces tend to be of low reflectivity as well as being potential sources of glare.

Using the Ceiling as the Principal Source of Reflected Light

In the majority of buildings the ceilings and upper walls are likely to be the only areas that can be depended upon as good light-reflecting surfaces. In addition, the ceiling is likely to be the best location for redirecting glare-free light downward onto horizontal surfaces and onto vertical surfaces facing away from the window (fig. 6-6). When using the ceiling as the principal source of reflected light, bear in mind the following:

D Locate the light source as far from the ceiling as possible. To illuminate the ceiling cavity area most uniformly, the light source(s) should be as far below the ceiling as possible. This can be done by raising the ceiling, lowering the light source, or both.

High ceilings can be more evenly illuminated than low ceilings because they can be a greater distance from the reflected light sources (fig. 6-7). High ceilings can also be "seen" by desk-top work surfaces more easily (fig. 6-8). However, high ceilings are not very helpful under overcast conditions, except to make higher window locations possible.

If necessary, create integrated building systems to get high ceilings economically. Most contemporary buildings waste potential ceiling height, with excess space above the ceiling (see chapter 9).

Windows and shading/redirecting devices should also be placed as low as possible after consideration of the other comfort objectives, such as glare, view, and privacy (fig. 6-9).

D Locate and shape the reflecting devices to best redirect light to the ceiling (rather than to eye level), thus avoiding glare. This will affect the device’s allowable reflectance. For example, if the device is below eye level, glare considerations will dictate that it either be of low reflectance, or shaped to direct light away from potential glare angles.

D Use high-reflectance ceiling cavities. While high reflectances on all room surfaces are beneficial for preserving the sunlight admitted, the configuration of a room determines the relative importance of a given surface's reflectance. For tall narrow rooms, the side walls may constitute the greatest surface area and therefore be the most important area in which to maintain high reflectances. For low-ceilinged deep rooms, the reflectance of the ceiling cavity is most important for light distribution. A simple diagram makes obvious the importance of highly reflective upper room surfaces.
for achieving efficient light utilization (fig. 6-10). In general, light-colored materials should be used for upper room surfaces.

Under overcast conditions, the sky itself (rather than the indirectly illuminated ceiling cavity) will always be the principal source of illumination. At such times a highly reflective ceiling cavity will not affect illumination levels and distribution as much as it will make a gloomy condition seem less gloomy by improving the brightness balance of the room.

D Maximize the ceiling's effective reflectance. This can be done by using building systems that minimize the amount of surface area making up the ceiling cavity (fig. 6-11). A given amount of light will be spread more thinly over a configured ceiling than over a flat ceiling of equal projected area. The ceiling will thus become less bright. The reduction in reflected light will be equivalent to painting the flat ceiling with a lower-reflectance paint (equal to its "effective" reflectance).

D Shape the ceiling cavity for best light distribution. Having minimized the amount of surface area by eliminating light-catching pockets, refine the ceiling shape for the desired distribution of light rather than for maximum average illumination. For instance, a low ceiling or a ceiling that slopes downward from the window will produce the highest average illumination levels but the lowest illumination levels deep in the space where they are most needed (fig. 6-12). Other shapes produce even better distribution (fig. 6-13). The best shapes are those with the least surface area, which receive the ground/facade/reflected light deepest in the space and are angled to best "see" both the floor below and the light source. Refer to generic data at the end of this chapter for more information.

D Maximize other reflectances. Maximize the reflectance of the ground and of the shading devices to allow the greatest amount of light to be reflected to the ceiling cavity, after consideration of comfort and other practical factors (fig. 6-14).

The relative influences of window placement, ceiling height, room reflectances, and room shapes are difficult to compute but can be measured easily in scale models. Examination of the generic model data presented at the end of this chapter reveals the significance of these factors.

Location of the Light Source: Windows

For the purpose of analyzing the effects of different sidelighting aperture locations, we divided a potential (model) window wall into three areas; low, high, and middle. Orientation, reflectances, scale, and ceiling configuration were assumed to be equivalent in all instances.

Low Windows

Low windows provide the most uniform illumination by distributing re-
6-10. A highly reflectant ceiling cavity is necessary for efficient utilization of light.

6-11. Highly articulated ceilings have a lot of surface area and trap light (right). Simpler ceilings, with less surface area, distribute light more efficiently (left).

6-12. Ceilings that slope up from the aperture improve illumination uniformity when the back wall is white. Sloping ceilings downward from the aperture increases the average illumination level but keeps the light closer to the window and makes the illumination less uniform.

6-13. Some ceiling shapes are better than a single slope.

6-14. Maximize primary reflectances (left) to distribute more light to ceiling cavity.

6-15. Low windows provide the most uniform illumination by distributing reflected sunlight deep into rooms. However, they have several drawbacks as well:

Low windows effectively place the principal reflected light source near or below eye level and thus maximize the potential glare for nearby work performed at desk-top level. This is not a problem in spaces where there is no specific task location or where the “task” is enjoying the sunlit scene. The area of the room affected by potential glare and local overheating from direct sunlight is minimized with a low window. Direct sunlight penetration is kept close to the window and generally below eye level, to a limited area along the perimeter wall.

When using low windows, the contrast with the unlit upper wall and the adjacent ceiling may seem gloomy. To counteract this, minimize the
unlit surface area by sloping the ceiling down to the window head and locating the low windows adjacent to perpendicular walls (fig. 6-16).

The value of the view out a low window depends on its scale. The view from the bottom third of a 24-foot wall can be very good, but the view from the bottom third of a 9- or 12-foot wall with the window head only 3-4 feet above the floor is likely to be unsatisfactory (fig. 6-17).

When used as a primary source of illumination, low windows are likely to have some view interference in the form of glare. Light-colored reflecting materials placed low in the space will always be more conspicuous than those placed above eye level. Therefore, allowable reflectance values tend to be lower. In addition, low partitions, and other furnishings may block much of the light from being reflected deep into the room.

Finally, privacy may be an issue with low windows. In low-rise buildings, combining privacy with some view and light can be difficult with a low window.

High Windows

High windows give the deepest penetration of sidelight from direct, diffuse light sources (i.e. overcast skies or translucent glazing) to a horizontal workplane and less light near the window (fig. 6-18). This advantage in the overcast condition has promoted the myth that they are best for distributing sunlight as well.

The advantages of high windows include providing light with privacy and improved security. The extra wall space can be used for display, chalkboards, bookshelves, storage, and so on. Furnishings and low partitions do not block any reflected light from reaching the ceiling, and the higher location of the zone of maximum brightness reduces the potential glare interference for VDTs. High windows permit the highest efficiency of comfortable reflected sunlight because the brightest reflecting surfaces are above eye level. Mirrored reflectors at various angles can be used to offset the disadvantages of the less favorable position relative to the ceiling.

The primary disadvantage of high windows is that they provide less favorable light distribution to the ceiling from ground-reflected light. High windows maximize the potential for glare from sky and sun, exposing more of the space to the brightest part of the sky. Light from that part of the sky must be baffled and redirected to the ceiling to minimize contrast (fig. 6-19). In addition, the view out of a high window is likely to be less than satisfactory.
Middle Windows

The middle third of a wall is not as good as the lower third for the deep distribution of ground-reflected sunlight, nor as good as the upper third for the deep distribution of diffused light from the overcast sky (fig. 6-20). However, if it provides sufficient light for the purposes of the room, it is frequently the preferred choice because it generally provides the best view. This means less discomfort glare, because even the brightest exterior scene is still considered "signal" rather than "noise."

Glare from the sunlit sills of middle windows with maximum reflectivity can be minimized by sloping the sills to be below eye level from the most important work positions, yet allowing them to be "seen" by the ceiling. If the sill is as reflective as the ground it will be equal in brightness and more reliable as a light source.

Another disadvantage of middle windows is that the brightness of the view in typical office buildings maximizes the potential for reflections on VDT screens when they cannot be oriented so as not to reflect the windows. If the light input from other windows alone is sufficient, it may be desirable to reduce the luminance or, better yet, the extent of the middle window, particularly if exterior wall surface is wanted for other purposes. Used in this way, they become "view" windows. Middle windows are easily accessible for interior cleaning and operation.

Shaped Apertures and Sloped Glazings

For a given sidelighting condition, it may be desirable to slope the glazing by moving the sill location into the building (to maximize the ground view) or moving it out (to maximize the sky view). Pulling the glazing sill in ("overbite" aperture) will tend to shade the window and provide a better angle of incidence for accepting ground-reflected light (fig. 6-21). Larger benefits may be an improvement in the view due to reduced veiling reflections and less heat gain because of the more oblique solar incidence angle. Sloping the sill out ("greenhouse-type" aperture) increases the effective sky aperture, resulting in a window that is difficult to shade and maximizes incoming daylight (fig. 6-22). This is only recommended on the north sides of buildings (as at TVA, case study B7) and in very overcast climates. In all conditions, the glazing position is much less important than the shape of the aperture. Shaping the aperture is always recommended to maximize lighting benefits and minimize problems:

D If the sill is light-colored and sunlight redirection is already provided for, slope the window sills out to minimize glare. Slope sills out on the shady side to maximize ground-reflected light (fig. 6-23).

D If there is no other sunlight-redirecting device on the sunny side, use wide-level sills to redirect sunlight, hopefully located above seated eye level.

D Slope the ceiling to the window head to minimize brightness contrast between windows and walls and improve light distribution.
Sources of Reflected Sunlight

Wherever a window is located, the source of reflected light can be the ground, adjacent building surfaces, or portions of the facade itself.

Ground-reflected light on the sunny side, and light reflected from the facing facade on the shady side, are the easiest to use. If these dependable sources are available, little is needed architecturally to take advantage of the light. An overhang is sufficient to shade the sunny side, and an unshaded window is good on the shady side.

Ground-reflected Light

It is difficult, especially in dense urban areas, to achieve the expanses of sunlit foreground necessary for the ground to be the principal source of light in buildings. "Solar envelope" zoning as proposed by Knowles (discussed in chapter 5) would increase the opportunities to use ground-reflected light (fig. 6-24).

For sufficient ground area to be illuminated, buildings must be widely spaced. Even at the equator, where the high arc of the sun allows penetration to north and south facades without much spacing, the unshaded ground area should extend at least as far away from the window plane as the window is above the ground (fig. 6-25).

It is much easier for low, single-story buildings to have enough sunlit foreground than it is for urban multistory buildings, unless the high-rise buildings tower so far above their neighbors that rooftops effectively become "ground" (fig. 6-26).
When the building spacing is sufficient, the foreground must also be relatively free of trees and other potential shading elements such as fences, walls, and bushes. This is not always possible or desirable, however. The exposed sunlit ground must be light in color to be as quantitatively effective as integral facade elements can be. Snow and concrete make excellent foregrounds. Gravel is fair. Sunlit ground cover, green grass, brick, and asphalt reflect less than 10 percent, but even this quantity of light (when the sun is high, approximately \( \frac{8000}{10}\% \times 10\% = 800 \) \( \text{Fc} \)) is as much as is received from the north sky and considerably more than is received from the shady side of buildings, trees, hedges, and walls.

Because of these requirements, ground-reflected sunlight for facades facing the equator (i.e., south in the northern hemisphere, north in the southern hemisphere) is a realistic choice only for low structures, for those fronting a beach, lawn, lake, or plaza, or for high-rise buildings protected by restricted zoning heights (fig. 6-27).

6-27. Ground-reflected light from the balcony of Frank Lloyd Wright's Robie house.
Facade-reflected Light

A building’s facade is the most likely potential source of reflected sunlight for the space it encloses. This method avoids the stricter site constraints imposed by ground-reflected light. Of course, it is valuable only as long as it is sunlit. Deciduous trees can be planted to shade the sidewalks as long as they do not shade the light-reflecting elements of the facade.

A small sunlit area of horizontal reflecting surface on the facade has the same projected area as a very large expanse of sunlit ground as seen from the ceiling of upper floors (fig. 6-28). In addition, the placement and characteristics of that reflecting surface can be controlled, as will be discussed later in this chapter.

To be of maximum value, that portion of sunlight not directed into the building can be reflected to the adjacent building blocks (fig. 6-29).

Building-reflected Light

On the shady side of a building, both ground-reflected and building-reflected light are logical supplements to diffuse sky light (fig. 6-30). Ground-reflected light is often available when the sun is high. However, when the sun is low, the ground is in shade. Building-reflected light is sunlight reflected off the surfaces of close adjacent buildings; the greatest light is reflected when the sun is low. These surfaces can be a source of uncomfortable glare because of their brightness at eye level. To take advantage of building-reflected light directly, high windows should be used. When the sunlit surfaces have intrinsic interest, low and mid-level windows are more acceptable because the view is perceived as a pleasurable experience rather than as glare. However, designers rarely have this degree of control over neighboring buildings. More often, neighboring mirror-glass buildings have a negative impact that must be mitigated (fig. 6-31).

Using building-reflected light was a very common strategy before electric lighting. For example, the narrow streets and whitewashed buildings of Greek villages allow a great deal of light in the facing windows without the heat of the sun. Larger buildings with courtyards have historically used their internal facades as sources of building-reflected light. McKim, Mead and White's Boston Public Library building is a good example of this.

These strategies are discussed in greater depth in chapter 7.
SIDELIGHTING FORMS AND DEVICES

Having discussed the theoretical aspects of window location and determined the building facade to be the most consistently viable source of reflected light for sunlighting, we can now evaluate the devices that best achieve the desired light distribution along with the other sunlighting objectives. These devices can be categorized as horizontal or vertical. The most simple, effective devices for achieving all of the sunlighting goals are horizontal shading/redirecting devices of various types (fig. 6-32).

-Shading

Horizontal shading devices can be simpler than vertical shading devices because of the apparent orbit of the sun. Examination of the sun
path diagram in figure 6–33 reveals that for window orientations parallel to the equator, the change in the solar altitude relative to the facade (profile angle) varies little during the day and by only 45 degrees from summer to winter. Thus, at any latitude, total shading can be achieved on north/south facades by quite narrow, seasonally adjusted horizontal shading devices, and even fixed devices can be of reasonable proportions in tropical and temperate latitudes. At the low sun angles of polar latitudes, the dimensions of fixed horizontal shading devices can only be reasonable when angled downward.

For east- and west-facing windows, fixed horizontal shading can be effective for most of the working day, but generally must be supplemented early and late in the day with other devices.

Vertical shading devices control low-angle sun by blocking the "troublesome" area of the aperture and the accompanying view (figs. 6–34, 6–35). They are simplest and most effective when acting as supplements to horizontal devices. An "eggcrate" facade can allow more view than vertical louvers alone (figs. 6–36, 6–37). If vertical louvers are used alone, the rapidly changing direction in the sun’s bearing angle (15 degrees per hour) will require constant adjustment if they are to remain effective. At that rate, 45 degrees of fixed vertical louvering changes from 100 percent to 0 percent effective in three hours.
6-35. Vertical shading devices control low-angle sun by blocking the "troublesome" area on the aperture and the accompanying view.

6-37. A medium-scale eggcrate shading device may disguise the scale of a building.

Redirecting Devices

Horizontal louvers can redirect light to the ceiling. Dynamic specular louvers can beam sunlight to the walls or ceiling as desired. Vertical louvering can only redirect sunlight to walls or low horizontal elements.

Glare Control

Horizontal louvers of any finish are glare-free as long as the reflecting surface is not visible (above eye level). Specular-finish horizontal louvers can direct glare-free light above eye level even when they are visible. Less control of light redirection is possible with vertical louvers. Matte-finish vertical louvers will direct as much light to eye level as to the ceiling. Glossy-finish vertical louvers will direct intense sunlight down toward eye level and can thus be a source of glare in portions of the room. Design these carefully!

Scale of Louvers versus View

Views are least interrupted by the largest size louvers (i.e., building-scale rather than hardware-scale). This allows one to be within the louver, which frames rather than disrupts the view. At the other extreme, the smallest scale of louver can be inconspicuous, appearing as a texture or screen rather than as a competing pattern, as would a medium scale-device (see chapter 11).

Other Advantages of Building-Scale Shading/Redirecting Devices

Large-scale elements are an integral part of the building fabric and can be combined with other elements. Thus, they can be built to be more durable and easier to maintain than hardware solutions. Small-scale ele-
ments tend to be more fragile and are best located within the protection of the building envelope. This also implies that any sunlight blocked will become heat in the interior of the building rather than on the exterior. Because of these characteristics, use of large, architectural-scale building elements is preferred for primary sun control. Unlike hardware solutions, which can merely be added on at any stage, they must be part of the initial building design concept. Whether located on the interior or the exterior, large-scale elements are likely to be major architectural formgivers.

HORIZONTAL SHADING/REDIRECTING DEVICES: CONTROL RELATED TO SOLAR ALTITUDE

The Overhang—Single Shading Element

While not as universally useful as some other devices, the simple overhang needed for seasonal shading and glare control can be the best design solution for some conditions. Since the overhang provides shading without redirection of the sunlight, sufficient foreground area must be available to utilize ground-reflected light as the primary source of illumination (fig. 6-38).

That assurance can be created when the foreground has a programmatic use in addition to its sunlighting function. Foregrounds might be used as circulation paths, living terraces, or balconies (fig. 6-39); on mul-

6-38. Because the overhang provides shading without redirection of the sunlight, sufficient foreground must be available to utilize ground-reflected light.

6-39. Frank Lloyd Wright’s Robie House. Horizontal overhangs provide total shading of south-facing french doors at midsummer. Very deep overhangs are effective on east and west ends. Balconies and living terraces (of medium reflectance) are effective reflectors.
tilevel buildings the overhang of the window below may be large enough to be the foreground for the floor above. Skyscrapers that stand alone "see" large amounts of foreground from the upper floors, minimizing the detrimental effect of the foreground's low average reflectance.

Historically, the most commonly used overhang has been an extension of the roof. With pitched roofs, the natural slope of the roof minimizes the horizontal extension required for shading without reducing the amount of ground-reflected light received (though reducing diffused light from the sky more than a level overhang providing the same shade—fig. 6-40). The indigenous architecture in equatorial climates throughout the world is that of sloping roofs with wide overhangs (necessary for the east and west sides to protect extensive openings that provide ventilation and ground-reflected light).

Indigenous equatorial architecture in hot, dry climates has traditionally been constructed with thick load-bearing walls. These massive walls help temper thermal loads. The windows are generally small because of the dependability of sunlight, minimum lighting requirements, and the desire to minimize solar heat gain. Under these conditions, the window depth itself can provide the necessary overhang. This design also benefits substantially from the inherently deep light-reflecting sill, particularly when white (fig. 6-41).

The floors of multistory buildings have also been extended to create overhangs. This is a natural solution if the extended floor also has value for living space, circulation, and window maintenance (fig. 6-42).

With proper orientation to take advantage of the overhead solar path at the equator, even planters are wide enough to provide total shading for full-height windows and provide delightful foreground views for hotel rooms (fig. 6-43).

Precast concrete and lightweight metal-skinned spandrels can be made three dimensional to shade windows, as they were at the Honolulu County Office Building and the Federal Reserve Building in Boston. Of course, the required dimensions for effective overhangs are determined by latitude and orientation.

Sufficient fixed shading is the most important requirement for successful sunlighting. Otherwise, largely redundant supplementary shading is likely to be needed and misused, negating the benefits of sunlight, especially with today's option of artificial lighting. The form of supplemental shading must be selected to minimize such misuse rather than for its decorative qualities alone.

6-43. Pavilion Intercontinental Hotel, Singapore (John Portman, Architect). Planters are attractive and effective shading devices for north and south facades at the equator. (Photograph courtesy of Kwong Long Tek)
When deeply recessed windows must be supplemented by curtains and blinds, an irregular array of blinds will not create a disorderly facade. Disorderly blinds in shaded windows are in deep shadow and baffled from full view, unlike disorderly blinds behind unshaded windows. Compare the windows of Boston City Hall with those of the adjacent JFK building (fig. 6-44).

6-44. Disorderly blinds behind shaded windows are in deep shadow and are less conspicuous than disorderly blinds behind unshaded windows. Compare Boston City Hall (left) and the adjacent JFK building (below).
Louvered Overhangs

Overhangs need not be solid to be effective as shading devices; they may be louvered or perforated to achieve different effects. The general characteristic of a nonsolid overhang will be an increase in the sky view over a solid overhang of the same size, thereby benefiting performance slightly under overcast skies. However, the shading pattern of a louvered overhang may allow more direct sunlight to reach the window area.

Horizontal louvers parallel to a south-facing wall will produce an effect similar to several small overhangs, with the advantage that louvers can be angled to allow penetration of sunlight at high angles and block it at low angles, or vice versa (fig. 6-45). Small-scale operable louvers are also possible, though they may be hard to justify because of high maintenance cost and limited usefulness.

Close-Up: Shaded Skyscrapers

Both the Honolulu County building and the Boston Federal Reserve building require supplementary shading because they are not oriented to best advantage.

Although located on one of the major east/west streets, the Honolulu County building faces southwest and northeast (fig. 6-46). Thus, the deeply recessed windows require the use of blinds on winter afternoons. In summer, occupants with northeast exposure must close their blinds at night to avoid arriving at an overheated space in the morning. Alignment with the street would have eliminated such problems.
Similarly, sun control in the deeply shaded Boston Federal Reserve building would have been easier if the windows did not face east and west (fig. 6-47). However, I have heard that an unusually conscientious building management is taking maximum advantage of the overhang design. The cleaning staff closes the vertical blinds on the east side and opens the blinds on the west side every evening. The office staff opens the vertical blinds on the east side in midmorning when they are no longer needed and (after some recent retrofitting) the rows of recessed fluorescent fixtures are switched off automatically when sufficient daylight is available. On the west side, the office staff closes the blinds when it is necessary in the midafternoon. Thus, with the green tinted, high-light-transmission glass kept uncovered most of the business day, this shaded building does quite well in using the reflected light from the roofs and landscape far below. However, a north/south orientation would have performed better and required less effort, although providing somewhat different views.

A nighttime view of the Boston skyline suggests the daylight utilization of the Federal Reserve building (fig. 6-48). When the lights are on, its windows appear brilliant in contrast to its neighbors, whose low-transmission glass rejects rather than admits daylight.
Horizontal louvered overhangs perpendicular to a south-facing facade can also be adjusted to favor high or low sun angles, but they will vary primarily with the daily change in the sun’s bearing angle rather than the seasonal change in the sun’s altitude. They produce radial breaks in segmental shading masks (fig. 6-49).

Combining parallel and perpendicular overhang elements produces a grid or pattern shading device. These devices can produce quite complex shading patterns, the danger being that they are often much too open and sculptural, and thus ineffective as shading devices (fig. 6-50).

Increasing the quantity of indirect sunlight is accomplished by totally shading direct sunlight and “catching” and redirecting the sunlight with reflective surfaces (fig. 6-51). The requisite geometries are primarily determined by the orientation and site conditions; on facades parallel to the equator, horizontal devices are generally appropriate. For the difficult low sun angles on the east and west, a louver parallel to the window plane is advisable. Some compromise of view to control glare is inevitable in all east/west conditions. However, this geometry does provide substantial illumination.

**Transparent Overhangs**

Mirror-glass awnings appear to give the protection of overhangs. In fact, they reduce the solar heat load but give minimal protection against glare from the sun. The Union Carbide building in Danbury, Connecticut (fig. 6-52) was retrofitted with additional blinds immediately after occupancy and thus sacrificed much of the benefit of ground-reflected light. Overhangs must be opaque or light diffusing to be effective. A 90 percent reduction in direct sunlight is not enough—glare will persist.

6-49. Louvered overhangs perpendicular to south-facing facades vary primarily with the daily change in the sun’s bearing angle. (From Olgyay and Olgyay, Solar Control and Shading Devices; reprinted by permission of Princeton University Press)

6-50. Louvered overhangs may be too open to be effective as shading devices.

6-51. “Suncatcher” baffles block direct sunlight but allow maximum indirect reflected sunlight.
Temporary Overhangs—Awnings

The functions of the overhang can be achieved using awnings. While less durable and maintenance free than more substantial building elements, awnings also have their advantages. Their first cost can be less and they weigh less, thus storing less heat and cooling off more rapidly after sundown. As translucent or louvered elements they can admit more light and view than solid overhangs.

Retractable awnings can be lowered to give buildings the benefit of shading when the sun is out and raised to provide maximum input of sky light under overcast conditions. This can be a cost-effective approach in predominantly cloudy climates such as that of England. At the Low Energy Demonstration building at the Building Research Station outside London, translucent fabric awnings are lowered automatically to the necessary position (fig. 6-53). In the cooling season, photocells lower the blinds to prevent direct sunlight from entering; in the heating season, they lower the blinds to prevent sunlight from entering above eye level.

Maximum utilization of reflected sunlight was not necessary with the very shallow offices of the double-loaded corridor scheme. For maximum benefit in sunny conditions, awnings should be large enough and opaque enough to negate the need for any additional shading. The inside of opaque awnings should also be light in color to help reflect ground-reflected light into the building and minimize contrast with the outdoor scene.
Twin Overhangs

When the required horizontal dimension for adequate shading is unavailable or becomes impractical for some reason (e.g., very large overhang dimensions are needed in high latitudes and east/west orientations), two or more overhang elements can be combined to obtain the required shading more easily (fig. 6–54). This also allows for better control of the quantity and direction of reflected sunlight reaching the glazing plane without compromising the advantages of a single overhang (minimum interference with views, air movement, or traffic when kept above door height). The double overhang for large spaces has been used throughout the world for centuries, particularly when sheltered circulation was also useful (fig. 6–55).

Even when not used for shading, major horizontal division of large windows is often used to effectively create two windows. This strategy allows the upper and lower windows to be treated differently, creating a scaling device or an organizing element in the overall design (fig. 6–56 and case study B3).

The old concept of the twin overhang can be modified to maximize its light distribution function when lighting requirements are stringent. While the reflectance of roof tiles, unpainted concrete, or the exterior cladding of the building may be satisfactory for social spaces, the best distribution of reflected sunlight in the large, deep office buildings of today is achieved through high reflectances, total control of direct sunlight penetration, and careful placement of the second overhang.

While the form of the double overhang has been used in modern buildings throughout the world, I have found few that performed as well as they could have. This is generally because the designers probably did not include optimum use of light as an objective and did not consider the control of solar impacts on the thermal environment. More stringent requirements can be met by refining historical precedents to include considerations for using the sun positively, rather than only providing protection from it.
The Lightshelf

Lightshelves, like double overhangs, provide shading with uncluttered views; they also provide excellent distribution of sunlight with minimum glare (fig. 6-57). Lightshelves reduce the illumination near the window and redistribute the light to increase illumination deeper in the space. Compared to other sun-control devices, lightshelves should be economical on a long-term basis. Their first cost may not be as low as some other devices (such as blinds), but they are likely to be more durable and simpler to maintain.

Compared to unshaded buildings with mirror glass or those with dynamic shading devices, lightshelves should pay for themselves by savings in "purchased energy" for lighting and heating and reduced load for air conditioning. They can add human scale and character to the interior of a building and visual interest to the facade.

Design Parameters for Lightshelves

Lightshelves differ from twin overhangs by optimizing the use of reflected light. To design lightshelves effectively, consideration must be given to their height, depth, shading requirements, the location of the glazing, the finishes and reflectances used, and the slope of the shelf, as well as to the actual method of construction. (Of course, such detailed analysis is appropriate when considering any sunlitgning device.)

Height. Lightshelves should be located as low as practical in the facade to reflect sunlight to the ceiling most advantageously. While lighting performance alone would dictate a height just above eye level (about 5’6” to 6’), the best height, when other factors are considered, is generally 6’8” to 7’. This height allows for clearance for doors along that wall, and, if none are anticipated, for alignment with door headers, indirect lighting units, beam bottoms, etc., thus integrating the lightshelf naturally into the room(s). An exception to this is when the lightshelf forms the bottom of a clerestory window above a solid wall. In this case, the lowest height is best. (This was my recommendation for classrooms in Saudi Arabia, case study C3.)

Depth. The required depth of a lightshelf is a function of window height and shading angle requirements (which in turn are determined by latitude and orientation). Lightshelves may also be made deeper than required for shading in order to reduce the illumination near the window and thus flatten the illumination gradient. An extreme example of this can be found in the lightshelves in the Lockheed building in Sunnyvale, California (fig. 6-58), which are thirteen feet deep—as deep as the perimeter offices—to ensure that the occupants of the interior zone will never be cut off from natural light by the partitioning, shades, or blinds used at the perimeter offices (under the lightshelves). This depth requires very high ceilings and reflectances to be effective.

Shading Objectives of Lightshelves

As described above, shading is necessary to prevent glare and local overheating. The upper clerestory portion of a lightshelf facade should block the penetration of direct sunlight onto interior work surfaces at any time of the year, thereby controlling glare and eliminating any need for sup-
6-58. Lockheed building, Sunnyvale, California (Leo Daly, Architect). The very deep lightshelves (13') ensure that the interior zone will receive reflected sunlight from the inward-sloping reflector even if the perimeter offices are walled off and have their blinds closed. (Courtesy of Leo Daly)

6-59. The clerestory portion of a lightshelf should not allow direct penetration of sunlight at any time. The lower window may allow some sunlight penetration as long as it falls below eye level.

Plementary shading (fig. 6-59). With favorable orientation, this objective can be easily accomplished by combining the overhang and intermittent vertical fins.

Total shading is less important for the lower window. If the window is sufficiently shaded to minimize cooling loads for most of the year, some penetration of direct sunlight in winter may be welcomed in temperate climates, as long as it falls below eye level. Except for those persons whose work is absolutely stationary, or involves critical visual tasks, sunlight on the floor is almost always enjoyed.

Since the clerestory window is generally smaller than the lower window, equivalent shading of both windows implies either a lightshelf that projects beyond the rest of the facade or a lower window that is further recessed.

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Projection of the lightshelf beyond the clerestory shade is helpful for capturing more sunlight when the sun is high and interior illumination levels tend to be lowest (fig. 6-60). If both projections are equal, most of the lightshelf will be in the shade during the summer on equator-facing facades when the sun is highest (fig. 6-61). This condition becomes particularly critical at low latitudes when the sun is almost directly overhead.

Extra shading can also be achieved by sloping the lightshelf downward (figs. 6-62, 6-63). However, a downward-sloped lightshelf reflects light away from rather than into the clerestory. Sloping the lightshelf inward helps bounce sunlight deeper inside, with a corresponding decrease in shading effectiveness (fig. 6-64). Care must be taken to avoid eye-level glare in inward-sloping lightshelves. For these reasons, the most effective sunlighting is often achieved with the compromise of a level lightshelf. Additional shading for difficult conditions can be achieved by adding a vertical baffle for a level lightshelf (fig. 6-65).

6-60. Project lightshelf from facade to capture high-angle sunlight and provide additional shading for low windows.

6-61. With flat facades, most of the lightshelf is in shade at high sun angles.

6-62. The Tower East building (The Architects Collaborative, Architect). Sloping the lightshelf down provides additional shading but does not reflect light inside.
Climate and Glazing Location

While the shading angles are set by latitude and orientation, the position of the glazing should be determined by climate and the amount of solar heat desired. The lightshelf facade configuration, by its division into two windows, allows the glazing of each window to be located independently to optimize the quantity of solar gain for a given condition.

In hot climates, therefore, all glazing should be shaded throughout the year, and only reflected sunlight should be allowed to enter the building (fig. 6–66). This was the objective at the GSIS Building in Manila (case study B3).

In temperate climates there are several options for positioning the glazing. Generally, both windows are shaded throughout the cooling season, and some direct solar heat gain is allowed during the heating season (fig. 6–67). Additional winter glare control can be provided by an internal lightshelf. Another option is to allow the glazing above the lightshelf to be flush with the exterior and unshaded (allowing more solar heat gain at all times) while leaving the lower window recessed to collect solar energy on a seasonal basis (fig. 6–68). This minimizes collection of snow and debris on the lightshelf and allows for easy maintenance of the most critical light-reflecting surface.

In frigid climates with minimal summer cooling requirements, both windows should be flush to the exterior for maximum solar gain (fig. 6–69). The lightshelf thus becomes completely internal, yet retains its functions of controlling glare and distributing light. This configuration is
similar to that on the shady sides of buildings in temperate climates, where the lightshelf is used for light distribution rather than for shading.

Even if the glazing is not flush with the building’s exterior, it should not be shaded at all during the heating season in cold climates. Any glazing not contributing solar gain is a thermal liability. Sloping the top of the window aperture down to align with the lowest solar angle can optimize the shading/solar gain balance. By channeling the light into the window, little reflected sunlight will be lost to the exterior.

The light distribution from a narrow band of clerestories can be optimized by raising the adjacent ceiling height. A chamfered section enclosing perimeter HVAC ducts is one way to achieve increased ceiling height over the majority of the space and to make a good transition from window to ceiling. The sloped ceiling surface will aid in light distribution and reduce aperture brightness contrast (fig. 6-70).

Reflectance—Exterior Lightshelf

The dimensions of the lightshelf are primarily determined by shading requirements. The reflectances of the lightshelf should be determined by the lighting requirements at various times (of day and of year).

The reflectance of the exterior lightshelf has a major effect on the amount of reflected sunlight admitted. Normally, maximum reflectances are desirable. Being above eye level, the potential glare of high-reflectance surfaces is never a problem. When cooling loads are important throughout the year, it may be desirable to minimize seasonal illumination variations by making the surface reflectances nonuniform. Designating the outer band of a lightshelf to be light-colored and the inner area to be darker will equalize the quantity of light reflected from the smaller area (illuminated by high-angle summer sun) with the amount reflected by the larger, darker area (illuminated by lower-angle winter sun) (fig. 6-71).

The bottom surface of the lightshelf can be designed to help balance the illumination gradient throughout the room. Darker finishes reduce the levels of ground-reflected light near the window, with minimum impact further into the room (since the back of the room receives most of its reflected light from the high ceiling). Sloping the bottom edge downward will yield somewhat similar results by reducing the quantity of light received directly from the sky more near the window than deep in the room. Turning the front edge also increases shading.

High reflectances can best be maintained on high-gloss finishes that are easily cleaned (hopefully self-cleaning by rain). With specular reflecting surfaces, a distinct inward slope can be very beneficial in distributing light deep into a building and in keeping the lightshelf clean.

Mirrored Sloped Lightshelves

When using sloped specular reflectors (high-gloss paint, glazed ceramic tiles, polished aluminum, or stainless steel) lightshelf angles must be planned so that sunlight is directed slightly above horizontal to the ceiling when the sun is lowest. It is critical that the sunlight is not directed downward, as it will create glare at working levels.

A relatively small area of high summer sun captured by the front edge of a lightshelf can be very effective if beamed deep into a room by
a small band of steeply sloping mirrors. The sloping section may shade some of the other reflecting surface when the sun is lowest, but such shading would not be harmful because illumination would normally be maximum at that time (fig. 6-72).

A note on mirrors: Perfectly polished mirrors must be very flat and uniformly clean or dirty to avoid distracting, distorted patterns on the ceiling. The familiar glass mirrors are the best optically and are the easiest to clean without scratching, but they are also the most fragile. They may be a good choice indoors.

Unbreakable polished metal sheet mirrors must be laminated to thicker backing to be flat enough. Since perfect mirrors will reflect dirt patterns perfectly, they should probably be avoided outdoors if light is to be reflected to uniform ceiling surfaces rather than to the varied surfaces of atrium balconies or floors (see case studies G1, G2). In that case, semispecular rather than perfect mirrors (as found on aircraft wings) are likely to be the best choice.

Reflectance—Interior Lightshelf

Any interior lightshelf should be of maximum reflectance. Once the light is in the building and "paid for," it should be used as efficiently as possible. If less light is wanted, it is better to keep it out of the building altogether.

Here too, mirroring can help, particularly with the deep shading necessary at high latitudes. Since all of the light reaching the inner lightshelf must then be at a low angle, mirroring even a flat interior lightshelf will distribute light inward at equally low angles. A slight downward slope to the mirror greatly benefits light distribution (fig. 6-73 and case study B7).

Close-Up: Precast Sloping Lightshelves

At the Hawaii Medical Service building (fig. 6-74), a gutter scupper system is integrated into the inward sloping precast concrete lightshelves, resulting in a richly detailed facade. The slight slope increases the reflective area "seen" by and the illumination received by the distant ceiling surfaces. Unfortunately, because the rough concrete surface of the reflective part of the lightshelf was left unpainted, much of the potential is unrealized. A white high-gloss surface would direct much more light to the ceiling, deeper into the space. The rough surface allows more scattered light to reflect at eye level. A smooth surface would have been better.

View Windows in Lightshelf Facades

As discussed earlier in this chapter and documented in the generic data, the lower "view" window in lightshelf facades can contribute valuable ground-reflected light to supplement the direct sunlight reaching the lightshelves.

Because it is lower in the visual field, however, the view window may create reflection problems on VDT screens. Reducing the transmission of the glass sufficiently to reduce potential reflections will sacrifice illumination and may create a sensation of gloom when the high-transmission upper window is seen simultaneously. To avoid reflective
glare, it is best to control the placement of windows in relationship to
work stations, VDTs, and partitioning carefully. Shading in the form of
a strategically placed banner or plant may solve a local problem without
affecting the rest of the room. Otherwise, the best solution may be to
provide shades locally when and where needed. Low-transmission glaz-
ing should only be used when high-aperture-contrast situations are un-
avoidable, such as windows at the end of hallways.

The upper windows in lightshelf facades should always be clear,
high-transmission glass. When properly baffled, they should rarely create
a glare or reflection problem.

Internal Lightshelves and Human Scale

Internal lightshelves can add a beneficial scaling element to rooms in
which high ceilings and large windows are needed for effective sunlight-
ing of deep work spaces. Internal lightshelves allow those near the win-
dow to see less sky (and sky glare), but the view deep in the space remains
unaffected. An additional benefit is a decrease in aperture contrast, as
more light is redirected to the ceiling (fig. 6-75).

Even when not needed for shading of direct sun, internal light-
shelves can improve the uniformity of illumination in a room by greatly
reducing the illumination of areas near the window and slightly increas-
ing the illumination deeper in the space.

Because lightshelves are generally at door height, they frame rather
than divide views from the interior and help building exteriors relate to

6-74. Precast concrete lightshelves for the
Hawaii Medical Services building, Hon-
lulu (CJS Group, Architect). The unusual
detail created to solve the drainage problem
of the inward slope gives the precast con-
crete lightshelves richness and elegance
both on the facade and from the interior.
Note the gutter/scupper system.
people rather than hardware, as do some other shading devices (see chapter 11).

Internal Lightshelves and Supplementary Shading

The presence of internal lightshelves tends to force drapes and blinds to be limited to the lower window, even if a gap is left to allow free air movement at the window plane. This is beneficial because the clerestory is thus kept unshaded when the lower window needs to be closed off for privacy or glare control. If the lightshelves provide total sun control, the clerestory window probably needs to be closed off only for special functions requiring blackout conditions.

Construction

There is no best way to construct lightshelves. They may be made of concrete, metal sheets, or composite curtain-wall-type metal panels; interior lightshelves may be framed and covered with drywall or plywood. The finish may be anodized aluminum, paint, or ceramic tiles, depending on how the rest of the building is fabricated. Lightshelves should be economical and durable, and their reflecting surfaces should be easy to maintain.

Construction of exterior lightshelves is simplest in warm climates where the structure can be extended to support them without creating undesirable side effects on thermal performance (fig. 6-76). A gap at the glazing plane can allow valuable ventilation of hot air at the facade, which otherwise might be conducted inside. Such a gap is also useful in reducing collection of debris and for self-washing (as well as manual cleaning) of the glass.

In cold climates, where indoor-outdoor temperature differences are great, heat loss by conduction through the exposed structure can be significant. Therefore, the simpler structural solutions should be avoided in favor of those that will provide thermal breaks to minimize conductive heat transfer (fig. 6-77). (This subject is discussed further in case studies B1, B2, and B6.)
Advantages of Scale

The inherent large scale of lightshelves, compared to smaller-scaled louvers, gives many advantages, both in construction and maintenance.

Lightshelves are large enough so that they must be an integral part of the building fabric and can be built of durable, easy-to-maintain materials. They have few parts to install or clean, and their large scale allows easy access for cleaning the windows. Lightshelves are large enough to be suspended from a few points to span between beams (case study B5) or columns (case study C1) or to be hung as prefabricated boxes.

Lightshelf elements can have multiple functions, serving as spandrel, bracing, or catwalks, in addition to shading and redirecting light. Their hangers can also be vertical louvers (case study B3). Interior lightshelves can also be duct enclosures (case studies B2, B5) or contain light coves and sprinklers (case studies B2 and C1). Lightshelves are large enough to incorporate sculpturally significant details, such as built-in scuppers to counteract an inward slope.

It is very important to make sure that lightshelves are durable, easy to maintain, low in cost, and attractive, because of their significance in the building’s construction cost, maintenance, and architectural form. Integrating lightshelves into the overall design allows them to become an element of the design rather than an additional purchased item. Additional construction costs can generally be eliminated with repeat jobs and standardization, which serve to amortize the development and tooling costs. The case studies illustrate many lightshelf constructions that function well for sunlighting and have been economical in construction cost, even in the first generation of their application. (That is, their cost has not upset any budgets, except when treated as an addition to a design already priced without lightshelves.)

Some Ineffective Lightshelves

After beginning to propose lightshelves in a number of projects, I began to look around actively, both nearby and during my travels, to see if I could find any precedents. I was interested in seeing how they looked, how they worked, and how they were constructed. I was disappointed to find many examples that had the sculptural forms of lightshelves but did not perform as such and were used with spaces not designed to use reflected sunlight.

In my neighborhood in Cambridge, Massachusetts, I examined the Smithsonian Observatory (fig. 6–78). I found concrete “lightshelves” and
ceilings that were unpainted and windows of low-transmission tinted glass. Since the shading is irregular as well, I assumed that the forms were used more for their sculptural effects than for thermal or light control. Thermal breaks in the concrete construction would have been desirable in the cold Massachusetts climate.

If one looks at the Boston University Law and Education building (fig. 6-79) one will notice the “lightsheves” on the south side—devices that one assumes will control the sun. In fact, they are not effective in controlling glare or thermal loads. The upper window is unshaded. The widely spaced, black-colored louvers do little shading in summer, some (but not enough) in winter, and reflect almost no light to the white ceiling. As a result, the interior blinds tend to be down at all times, as though the louvers were not there.

In Berlin, Germany, the IBM building (fig. 6-80) has lightsheves that have insufficient depth (even in the clerestory portion) to do much controlling of glare at that latitude (52 degrees North). At the nearby chemistry building of the Berlin Technical University (fig. 6-81), the lightsheves are much deeper but are painted black on all surfaces to match the exterior wall finish. They therefore absorb rather than reflect the light. However, the metal panel construction probably minimizes winter heat loss from thermal bridging.

The State Trade School in Zurich, Switzerland (fig. 6-82) was built with a very well integrated precast concrete system throughout. While the public spaces are quite attractive, and the perimeter corridors utilize daylight effectively, the principal spaces—the classrooms—do not capitalize very effectively on the “lightsheves” that give the exterior walls their form. These “lightsheves” are not deep enough to reduce the need for other shading significantly at that latitude (47 degrees North) and as unpainted concrete are inefficient light reflectors. The open louvered ceiling, which is efficient in delivering artificial light from the plenum above, is also equally “efficient” in allowing reflected sunlight to leak into the ceiling plenum.

More recently, I was pleased to see “lightsheves” being installed on a new building being completed in Cambridge—the Harvard Biochemical building (fig. 6-83). This is a handsome building that approaches good sunlighting design. The overall forms are right, but the details fall short. A louvered lightsheve should not have been used, as there is already too much light below the louver. (A louver that is 50 percent open will reflect only 50 percent as much light as a solid louver. However, unlike those at Sert’s Boston University building, these metal louvers were painted white.) More important, it does little good to reflect light upward in such spaces unless it is redirected downward. The light-colored ceiling near the window is a good start, but the rest of the ceiling is even more important for balancing the light in the room so as to minimize the need for supplementary artificial lighting. Dark brown paint is ineffective for this purpose.

Some Lightsheves That Work

In my search I met Alfred Roth, a Swiss architect who had always designed around climate. He showed me photographs of lightsheve buildings he had designed for lighting as well as shading. Among them was
6-79. Boston University Law and Education building.


6-82. Zurich Trade School: lightshelves are narrow on exterior; louvered ceiling inside does not reflect light.

Sabbaga Center, an office building in Beirut, Lebanon (fig. 6-84). The lightshelves covering the south facade were white and deep enough for the latitude (33 degrees North).

In Singapore, a powerful sculptural form dominating the skyline is I.M. Pei’s Overseas Chinese Bank building (fig. 6-85). The strong horizontals of the properly oriented lightshelves (deep enough for total shading at 2 degrees latitude) are skillfully employed as an articulated counterpoint to the otherwise unbroken oval shaft—a beautiful and powerful image in a city of shaded buildings. The interior is not as successful (fig. 6-86). Equally strong horizontals in the form of wider horizontal mullions or interior lightshelves might have limited any draperies used to the lower windows and given the interior the strength of character achieved on the exterior.

6-84. Sabbaga Center, Beirut (Alfred Roth, Architect). Lightshelves are appropriate to the climate. (Photograph courtesy of Alfred Roth)


6-86. Interior shading could be integrated better.
With a more positive expression of the lightshelf in the interior, industrial windows are much less noticeable in the Hong Kong school shown in figure 6–87.

**Dynamic Lightshelves and Suncatchers**

When lighting needs or conditions are extreme, lightshelves can be made dynamic for optimum performance. For example, a specular lightshelf can “lift” low-angle sunlight deep within a space above eye level and up to the ceiling. Similarly, high-angle sunlight can be “beamed” wherever it is desired (fig. 6–88). Furthermore, these lightshelves can convert to a “blocking” mode whereby glaring low-angle direct sunlight is intercepted but some indirect light is allowed to enter. This modified “suncatcher” mode is particularly useful on difficult western exposures. The dynamic nature of these devices implies that they be somewhat smaller and lighter than their static counterparts.

A promising automated system for use within the glazing plane that utilizes tracking mirrors of stretched film has been developed for production by Thomas C. Howard of Synergetics, Inc. of Raleigh, North Carolina.

**Multiple Horizontal Louvers**

Instead of a single lightshelf, a number of architectural-scale horizontal louvers can be used instead when window sizes or shading requirements make a single lightshelf impractical (i.e., too large). For example, at the GSIS building (case study B3), the normal lightshelf configuration was supplemented with fairly large louvers on portions of east and west facades to provide additional shading and redirection at low angles.

The louvers should be large enough to be individually placed for maximum redirection of sunlight to the ceiling with minimum glare (fig. 6–89). The top of the lowest reflective louver should be located so that it is just above the viewer’s eye level when seated. If located below eye level, they should be dark-colored to avoid glare. Louvers of this scale should be few enough and sufficiently spaced to create minimum interference with window washing and views (fig. 6–90).
Medium-scale Horizontal Louvers

Mass-produced louvers durable enough to be used for exterior shading are likely to be of hardware scale (i.e., 4–12"-wide blades). There are advantages and disadvantages to working at this scale. As hardware rather than architectural elements, louvers can be added on with less architectural or structural integration. They are likely to be “off-the-shelf” manufactured items that can be electrically or manually operated as well as fixed. A minimum of design effort is required to specify premanufactured louvers; they can be selected from a catalog. However, integration with window details is desirable. When well integrated, louvers fit within the window recesses. In Zurich, for example, the wall details of most commercial buildings integrate recessed pockets for blinds.

Louvres may require less horizontal space than lightshelves. This can have a significant economic impact in tight real estate markets such as in Hong Kong and New York, if the projection outside the glass is counted as part of the floor area allowed. Intelligent zoning regulations could minimize this factor in the future (see chapter 5).

Medium-scale louvers are likely to be operable; thus, the same louvers can be used on all orientations, with different operating programs for the different shading requirements. They can be totally closed at night and on holidays for maximum insulation value and total shading. In addition, they can provide physical protection and visual privacy upon demand. This is probably a principal factor in their popularity for low-rise housing in many high-density locations, such as Puerto Rico.

The disadvantages of medium-scale louvers are primarily those inherent to their scale. They are not large enough to frame views, not small enough to be perceived as a texture or pattern, and thus tend to obstruct views (fig. 6–91).

Their inherent (vertical) location is not optimal for either light distribution or glare reduction. At the upper window area, the reduced average distance to the ceiling (compared with lightshelves) reflects less uniformly to the ceiling, and at the lower window, bright louvers at eye level are good for light distribution, but bad for glare. Dark-colored louvers lessen glare problems but are useless for light distribution (fig. 6–92).
Smaller louvers require more maintenance, as they have more surfaces to clean. They create access problems for cleaning windows and reduce the self-washing of glass by rain. For example, years of trapped debris, bird droppings, and the like are highly visible behind the tightly-spaced louvers of classrooms at the Boston University Law and Education building.

Louvers as Architecture

If louvers are suspended away from the windows, space advantage and design simplicity are eliminated. Smaller-scale louvers are likely to need more frequent support than larger louvers. They cannot span between beams or columns and tend to be made from less durable materials.

The Swiss consider regular maintenance a fact of life and construct systems requiring high maintenance more readily than others. They have created a high-tech louver/wall style in which the free-standing louver/wall structure is the dominant feature of the architecture. The visible facade is the light metal frame that provides support and tracks for the raising and lowering of oversized venetian blinds. Representative of this approach is the Standard Charter Bank in Zurich (fig. 6-93).

A number of Brazilian buildings also use louvers as “the architecture.” Among the largest and most conspicuous of these is the PetroBrazil Headquarters in Rio de Janeiro, with walls of vertical and horizontal metal louvers (see fig. 11-6).

An earlier example is Oscar Niemeyer’s São Paulo Exhibition Palace (1962), designed with vertical and horizontal louvers covering the entire facade. These louvers had been removed by the time I saw this building (fig. 6-94). The deteriorated state of the louvers on similar adjacent buildings indicated the probable reason.
Both from within and without, hardware-scale louvers are unrelated to human scale. In many cases, it is hard to know how many floors a building has, when viewed from the exterior. Buildings dominated by medium-scale louvers tend to look more like machines than architecture.

Medium-scale Louvers in Double-Envelope Buildings

Double-envelope building construction, such as that used in the Hooker Chemical building in Buffalo, takes advantage of standardized operable louvers; it avoids many of the usual practical and aesthetic drawbacks and contributes to efficient use of energy (fig. 6–95).

The usual problems of maintenance and durability were minimized by enclosing the louvers behind glass and within a service walkway. Operation of the louvers is automatic and each facade is separately controlled. The louvers achieve total shading at all times and close up like a flower at night to minimize heat loss. With a well-engineered buffer space to retain or exhaust solar heat, this is a technically sound approach for buildings that must be oriented in all directions (fig. 6–96).

But while an excellent solution for east and west exposures that are impossible to control without some form of dynamic shading, such complexity was not necessary on the north or south sides. A much simpler fixed lightshelf (within the double envelope if desired) would have allowed unrestricted views with less glare and created a more delightful human environment. On those exposures, it was not necessary to look through a confining, bright, distracting screen of louvers, even though the louvers themselves were well made, and their uniform adjustment (photocell-controlled) appears very orderly compared to the usual irregular array of conventional venetian blinds. However, the expanse of floor-to-ceiling windows, made energy-efficient by the double skin construction, helped compensate for some of the visual disadvantages of the blinds (fig. 6–97).

Whatever shading/redirecting device was used, higher ceilings and glazed transoms would have helped. With the interior spaces cut off by full-height partitions at the perimeter offices, the daylight admitted seems wasted when confined to the narrow band of perimeter offices alone.
6-96. Hooker Chemical building: wall section.

From the exterior, this double-envelope, louvered building does not appear as a "sun-control machine," as do buildings with exterior, metal, operable louvers. The Hooker Chemical building also appears much more humane than the typical mirror-glass building because the floor levels are clearly defined due to the clear glass used, and one can see signs of activity within, both during the day and at night.

**Small-scale Horizontal Louvers**

Small-scale louvers (venetian blinds) are most frequently located within the building envelope. They are generally an afterthought to unshaded designs, when neither optimum view nor thermal or lighting performance were given a high design priority.

Blinds share many of the same advantages and disadvantages of medium-scale louvers. The design process for using blinds is virtually nonexistent. They can be installed at any time with no effect on facade details. They tend to screen views and produce glare if light-colored and convert light into heat if dark-colored (in exchange for better views and less glare). From a distance, blinds interfere with views less than do medium-scale louvers, especially if they are black, in which case the small scale is perceived as texture rather than pattern (fig. 6-98).

The ease with which blinds can be adjusted to control the quantity and direction of light and privacy is an advantage to be balanced against their high maintenance requirements and low mechanical reliability. Visual noise inevitably results if all the blinds in a room are not uniformly arranged. Furthermore, difficulties in raising and lowering blinds often result in their being permanently lowered, rather than being lowered only when needed. As interior louvers, venetian blinds reject less summer heat than exterior louvers that provide equal light.

One would expect blinds to have no effect on exterior architectural image when installed within the building. Because light-colored louvers are usually arranged in a disorderly fashion, however, they tend to be conspicuous on the exterior. Dark blinds are often selected or windows are glazed with dark or mirror glass to conceal this disorder as much as for the reduction in cooling loads; in either case, lighting suffers.

6-98. Hooker Chemical building: interior view of venetian blinds.
Sheet-metal screens of various patterns and degrees of aperture became architecturally fashionable in the late 1950s and are still available (though less popular) today (fig. 6-99). By combining horizontal and vertical elements in a modified eggcrate style, these screens may block much of the sunlight with no thought given to the redirection of the light. They are usually not very durable, cannot be repaired easily, and once damaged are even less attractive than they were initially.

Metal screens such as Kaiser Aluminum's Shade Screen® represent the smallest end of the horizontal louver scale. They are dark-colored screens woven of tiny (1/16" × 7/8") horizontal louvers (fig. 6-100). While actually quite effective in shading glazing to reduce glare, they are difficult to maintain outside, collect solar heat when located inside the building, and do not assist with light distribution. Once damaged, they cannot be repaired. Their advantages are that they are inconspicuous, easy to add to existing buildings, and also function as insect screens.

**Venetian Blinds within Glazing**

Researchers at the Massachusetts Institute of Technology tried to develop a venetian blind that would allow for optimal control of direct sunlight for best thermal performance. The device that resulted is an adjustable, upside-down, reflectorized blind sandwiched between two layers of glass. These blinds cannot be pulled up and out of the way like common blinds, but they can be adjusted on their horizontal axis to best redirect sunlight to dark-colored, salt-filled, heat-storage ceiling tiles (fig. 6-101). (The eutectic salts used store heat by melting and then giving up heat as they "refreeze.") They can also aid in reducing local overheating and glare (though this is harder to avoid when the convex side faces up).
Since the objective of these blinds is to store solar heat, biweekly or monthly adjustments of the specular reflectors on the south orientation is sufficient to keep the reflections onto the ceiling above eye level, preventing glare from even the lowest blind (as long as the occupant is not adjacent to the window). Adjacency to the windows at MIT Solar 5 building is controlled by placement of a wide shelf in front. The blinds are not as effective for directing sunlight onto the ceiling deep in the room, because it is impossible to avoid glare from the lower louvers at lower beam angles; this results in substantial “bleed-by” of light, which is not redirected.

Isolation of the blind between two layers of glazing lessens internal heat gains and drastically reduces maintenance problems. Similar window-blind construction may have applications for supplementary shading to large-scale devices on difficult-to-control facades. It is interesting to note that Alvar Aalto used such a construction almost thirty years ago at the National Pensions Institute in Helsinki.

**VERTICAL SHADING DEVICES: CONTROL RELATED TO SOLAR BEARING ANGLE**

The shading and light-control characteristics of vertical shading elements were discussed earlier. The specific characteristics of the devices are largely a function of scale, much the same as for horizontal devices.

**Large-scale Fixed Vertical Shading Elements—Fins, Columns, Walls, Beams**

Many of the advantages of larger scale that apply to horizontal shading devices also apply to vertical devices. In general, vertical devices are not good sources of reflected light, so larger scale is no advantage in this regard. Architectural-scale elements are likely to be more durable and easier to maintain than smaller elements. In addition, they frame rather than break up views (fig. 6-102). For panoramic views, of course, vertical shading should not be used if it can be avoided.

Larger scale, vertical architectural elements are most useful for sun control in combination with horizontal elements such as lightsheelves. Vertical elements such as fins, walls, columns (fig. 6-103), or deep beams should be integrated with horizontal elements to form “boxes” (see figure 6-77). Angling east- and west-facing vertical fins toward the north or south will increase their usefulness somewhat, with a corresponding decrease in direct east/west views.

Because vertical elements are used for blocking sunlight rather than for its positive redirection, their color has less effect on illumination levels than is the case with horizontal elements. Maximum-reflectance louvers redirect the maximum amount of illumination but may also create glare. However, such glare is likely to be short-lived, because the brightness on vertical surfaces is constantly changing with the rapid movement of the sun. When combined with horizontal shading elements, only small areas are likely to be exposed at any time (except when intentionally captured by suncatcher baffles).

6-103. Reed College Library, Portland, Oregon (Harry Weese, Architect). Columns function as vertical baffles on east and west facades. The effectiveness of the columns as shading devices (in combination with trees and lightshelves) is demonstrated by the continued lack of need for additional shades after fifteen years of use.

Unlike lightshelves, vertical surfaces cannot reflect selectively to the ceiling. Specular vertical surfaces will always reflect sunlight downward at potential glare angles (fig. 6-104). For avoidance of glare, matte surfaces are best.

Medium-scale Vertical Louvers—
Fixed and Dynamic

Medium-scale vertical louvers are similar to other vertical louvers in their inability to distribute light selectively to the ceiling and the need for constant adjustment to follow the changing direction of the sun throughout the day to control sunlight. They are most useful in east and west facades (figs. 6-105, 6-106).

In other respects, medium-scale vertical louvers share most of the advantages and disadvantages of medium-scale horizontal louvers. They are most effective in blocking low-angle sun that cannot be controlled easily with horizontal louvers (at very high latitudes), particularly in combination with a lightshelf that redirects sunlight to the ceiling. Dynamic medium-scale louvers can also be very effective in blocking low-angle sun and redirecting it to walls when needed (though at the expense of views). They become less visually confining when fully opened at other times. Because of their cost and somewhat limited usefulness, however, they
should be integrated with some other programmed need (e.g., privacy, total blackout requirements, maximum thermal performance as shading and insulation) to be justified.

**Smaller-scale, Dynamic Vertical Louvers**

Fixed vertical louvers alone cannot block direct sunlight at all times throughout the day unless they are so closely spaced that the rooms enclosed feel prisonlike. To obtain a more reasonable input of light when vertical louvers are used alone, adjustable louvers should be used. The effectiveness of vertical louvers depends on their position relative to the sun’s position on its path around the horizon (its bearing angle). For this reason they need to be adjusted hourly throughout the day; horizontal louvers respond to the seasonal changes in the sun’s altitude above the horizon and can be adjusted seasonally. In office buildings, control of vertical louvers should be automatic. In residential applications, manual control is acceptable because patterns of use are less predictable and the occupants are more likely to adjust the louvers when necessary.
Interior Louvers

Vertical louvers used indoors have some important advantages over those used outdoors, especially if they are in the form of louver drapes. Although not as efficient in heat rejection as exterior louvers, louver drapes have an important advantage in that they can be pulled aside when not needed (i.e., most of the time when supplementing large-scale shading elements).

Vertical louver drapes seem to be more reliable in operation than venetian blinds. Larger-scale vertical louver drapes tend to have more pattern than texture against the view, although when dark-colored and perforated they can be seen through more easily than one would expect. When made of fabric, they offer some visual softness and acoustic absorption. Like draperies (and unlike venetian blinds), vertical louver drapes do not look particularly disorderly when irregularly arranged (fig. 6–107).

GLAZINGS

For effective sunlighting or passive solar design we should minimize reliance on the glazing itself for sun control. Glazed areas have significant heat loss. The purpose of glazing in sunlit buildings is to let light in. Clear glazing is the best way to admit the amount of light desired (fig. 6–108). (As discussed in chapter 3, green-tinted and Low-E glazings are more expensive but are also appropriate.) Shading, rather than reflective glass, is the best way to reduce heat gain.

As discussed in chapter 2, low-transmission glass produces an effect of gloom and ambiguity, regardless of the weather and time of day. It reduces the effectiveness of daylight but cannot reduce intensities enough to provide comfort in direct sun. Thus, supplementary shading will be required with low-transmission glass despite reduced light levels and a gloomy atmosphere. Heat-absorbing glass may have undesirable reradiation effects. Mirror glass produces a particularly uncomfortable (“fish-bowl”) effect at night, whereby one sees one’s own reflection in the window, rather than the view outside.

The so-called “shading coefficient” (defined as the ratio of solar gain in BTUs to that admitted by clear glazing) is used by industry to evaluate the effectiveness of low-transmission glazing. This measure does not account for the amount of visible light relative to heat gain, or for any of the spectral characteristics of a glazing. This standard would rate an insulated opaque wall as having an ideal shading coefficient and is therefore useless as a measurement of glazing-lighting performance.

Low-transmission glass is useful when the amount of light is not as important as the view. It still must be shaded to reduce heat gain and glare, however. It is particularly valuable when a large view is desired without the brightness of the exterior—for example, a view window in a museum gallery.

Many glazing materials are available that have diffusing or directional qualities. Direct sunlight striking translucent fiberglass becomes diffuse direct light, potentially very bright and glaring. It is only when a surface of this type has enough visual interest to be attractive that it ceases
to be an unpleasant distraction (fig. 6–109). Translucent glazings are best when temporary or when privacy rather than view is desired.

Glass block was formerly produced with horizontal ridges that directed incoming sunlight up to the ceiling and away from the line of sight (fig. 6–110). Although clever and inexpensive, this directional glass block did not allow for any view, and the redistribution of light was less than ideal (usually a source of visual noise). Redirecting devices in glazings are never as good as larger-scale reflecting devices, and diffusing devices inevitably produce a shallow penetration of sunlight. For some purposes, clear glass block can be an attractive source of light, combining a degree of privacy with some view and light. When set in mortar, the width of the bed is purported to offer a degree of shading, but in practice this amount is rarely sufficient.

Clear glass maximizes views and a sense of contact with the outdoors, and allows seasonal admission of heat gain (when desirable) through correct shading geometry. More often than not, clear, insulated glass is the most inexpensive and appropriate glazing.

**FILTERING AND BLOCKING DEVICES—SUPPLEMENTARY DYNAMIC SHADING**

Devices that block and diffuse but do not redirect light tend to have a myriad of influences take priority over their sunlighting characteristics. Filtering and blocking devices are used to attain privacy, to “black out” rooms, and for security and aesthetic reasons. When these devices are used to control light, they are normally expected only to prevent a negative situation (glare or overheating) rather than to optimize the natural illumination. As such, the most important factors to consider when selecting a filtering/blocking device are its reliability and ease of use. If a device is not reliable and easy to use, it is likely to remain in place when it is not needed and prevent the utilization of natural light. For the same reason, I prefer totally opaque blocking devices to translucent ones, because they are more likely to be opened by the occupants when not needed.
Shutters

Traditional slatted window shutters offer some protection from stormy weather and vandals, but minimal view or light. In the Caribbean, the indigenous louvered awning/shutters were designed as shading devices, allowing ground-reflected light and some view when the awnings are raised (the louvers are parallel with the ground at that time), and privacy and protection with ventilation when they are closed (fig. 6-111). When dark-colored, these awning/shutters interfere with the view less than when light-colored, but must depend more on ground- and roof-reflected light.

The shutters traditionally used in early American buildings allowed infinite control of privacy and light. They were constructed with numerous individually foldable sections, the louvers within each section being adjustable. These shutters were frequently integrated with the window recesses so that they were barely noticeable when fully open (fig. 6-112). They may still be the best choice today for some residential applications but are unlikely to be properly used in a work environment where there is generally no one managing the window systems.

Window Shades

If additional movable shading is used to supplement windows already shaded by lightsheves or overhangs, it should move from the bottom up, rather than from the top down, as do traditional shades (fig. 6-113). In this way direct light is blocked and ambient indirect light is
least affected. Unfortunately, attractive hardware of this type is more complicated than the standard variety (without the doubled cord showing), but has been achieved elegantly on a custom basis (see Johnson Controls, case study B4). Hopefully, this type of hardware will become more readily available in the future.

Window shades can be designed to have a significant insulative value. In large offices, such shades should probably be automated if they are to be effective. Unfortunately, they tend to be either bulky (quilted types) or rather unattractive on the outside surface (reflective types).

**Draperies**

Draperies are the most traditional window treatment, being interesting to look at and allowing for wide variation in personal taste. Draperies are an obvious choice for view windows and are the blocking device most likely to be opened by the occupant when not needed. They can be made translucent (allowing privacy with filtered light), opaque (for total privacy, room blackout, and local shading), or insulating. When used primarily for shading (rather than for privacy or insulation), draperies should be free-sliding in small sections to allow local shading without blocking ambient light. In otherwise hard-surfaced rooms, drapes provide useful sound absorption. They do not look disorderly when not adjusted uniformly in a room or on a facade. On the negative side, when drapes are open they may block much of the light and view from individual windows unless they are stacked entirely to the side.

**Opaque and Translucent Sliding Panels**

Rigid sliding panels have an extensive history in Japan, where *shoji* have long been the window treatment of preference (fig. 6–114). Very light in weight, wooden *shoji* slide freely in waxed wooden tracks. Although the rice paper “glazing” in *shoji* is translucent and diffusing, the richly detailed and proportioned wooden frames make *shoji* a pleasure to observe—a finely crafted picture rather than an overly bright distraction.
Shoji screens often have small areas of transparent "view" glazing at seated eye level. Because of their ability to move, they offer privacy and protection as desired and can disappear when no longer needed.

In the Middle East, the traditional *moucharaby* developed as an architectural device to screen the brightly sunlit exterior views to pleasurable levels (fig. 6-115). Consisting of numerous wooden cylinders joined with spherical joints, *moucharabies* are unglazed and are placed in unglazed openings, allowing ventilation and filtered light with a minimum of heat. The rounded forms grade the light very softly, unlike screens cut out of flat surfaces. These devices can be meaningfully adapted to today's needs and context. (I endorsed their use in combination with lightshelves for classrooms in Saudi Arabia—case study C3.)

In residential applications, where one wants privacy and ventilation and where controlled redistribution of light is unimportant, the softly filtered light from rounded forms characteristic of *moucharabies* would be appropriate anywhere. Such forms could easily be mass produced in molded plastics. The principle of rounded forms could also be applied in larger-scale elements, such as concrete block units for screen walls.

Sliding panels can be highly insulative and can offer security as well. Like *shoji*, if translucent panels are used, they should be interesting as abstract designs and should be three dimensional with a louverlike quality rather than flat. (Otherwise, they may be considered visual noise.) Translucent panels have the disadvantage of not disappearing when not in use, as do window shades.

Opaque sliding panels are particularly appropriate when total blackout is often desired and good insulation is useful. They are used in a number of hotels in southeast Asia (e.g., the Jakarta Hilton).

I found the window treatment of the Fujita Hotel in Kyoto, Japan, very good for the guests and probably for the owners as well. It consisted of a combination of both traditional *shoji* for light with privacy and some insulating value and sliding wood panels for blackout and better insulation. Very logically, the window opening was only the central 50 percent of the wall width, since no more than that could be exposed at any time. Too often, full-width windows are used under similar circumstances.

**Interior Furnishing, Layout, and Partitioning**

Sunlight distribution should influence interior layouts and detailing. Partitioning, equipment, and furnishings should not block any more light.
than necessary and should be light in color when practical. (These concepts should be self-evident for the reader, but they are so often neglected that they merit reiteration.)

While premium is generally given to perimeter offices (especially corner offices with windows on two walls), it is desirable that natural light be able to penetrate into the interior zones of today's very deep buildings. The best way to achieve this is to place spaces that need complete enclosure, such as conference rooms, away from the building perimeter. Assuming a plan does call for dividing walls parallel to the window wall, these walls should be fully glazed or at least (if visual as well as acoustical privacy is needed), glazed from the transom to the ceiling (fig. 6-116). Open office planning allows for maximum use of transom-height and lower (4.5-6') walls with minimum blocking of light. Transom-height walls are also ideal for the integration of indirect artificial lighting.

Full-height partitioning obstructs less light from windows if perpendicular to the window. Such partitions are usually acoustically important, separating offices or classrooms rather than open-doored areas, corridors, or support spaces.

Light distribution should influence other aspects of interior planning as well. For example, most libraries designate a large amount of space for book storage in stacks. If these stacks are arranged parallel to the window plane, the second aisle will require supplementary artificial lighting. For deep penetration of sunlight, library stacks should run perpendicular to the window walls. This has the added benefit of providing window views to those in the stacks (see case study H1).

Light-colored furnishings can be important for light distribution and can also make a space feel well illuminated. For example, black law books on black library shelving make the stacks appear dark even if well illuminated. White shelves make the space feel well lit, even if the books remain dark. White shelves may also reflect useful light to the index numbers low on the spines. White tops of stacks provide a lot of reflective "lightshelf" area.

Luminance distribution in a room should be considered when laying out work stations and placing VDT screens. Avoid placing them so that they face windows unless there is an intervening partition.

Plants, banners, and the like can provide local shading in special cases.

6-116. Partitions parallel to windows should be glazed to allow sunlight to reach interior spaces. If they must be opaque, transom-to-ceiling area should be glazed.
GENERIC MODEL DATA

Several years ago, in order to teach my students at Harvard and MIT about the geometry of sunlighting, I built a number of generic models to help them test, examine, and communicate the relative quantitative effects of various sunlighting concepts, both sidelighting and toplighting. For this reason, the design of the models was not that of any realistic building but rather a format that facilitated the comparison of alternatives. For instance, the facade was divided into three equal sections (high, middle, and low), each equal to 10 percent of the floor area (fig. 6–117). All reflectors were white, even though the ground adjacent to a low window is, in reality, unlikely to be white.

Illumination levels and gradients of various room shapes and window locations should be observed relative to each other. Estimates of realistic illumination levels under the sunlight conditions tested—for example, noon at the equinox and 45 degrees north latitude (when the 45-degree cut-off white reflector is completely sunlit)—can be made by extrapolation from the test data. For instance, if both lower and middle windows are to be used, their data should be combined.

For estimating the effects of seasonal change, one can assume that midsummer levels of illumination would be 50 percent of the test values, since the sun would be 22.5 degrees higher at that time and only one-half of the reflector surfaces would be illuminated. Similarly, 30 percent should be added to the test values for the winter, assuming that the louver width would be increased accordingly to provide complete shading and redirection.

In examining the data presented, remember that light has no scale factor. For the same reasons that measurements of an accurate scale model can be completely accurate in forecasting the performance of a real building, the values shown for a 40' × 40' × 16' room are essentially the same as those for a 20' × 20' × 8' room or an 80' × 80' × 32' room. The only difference is the position of the plane of measurement, because of difference in scale; the light meter should be placed at desk height for the scale intended. (Measurements at floor level need no adjustment for scale.)
To minimize this factor, the plane of measurement was level with the top of the lower window (figs. 6-118, 6-119). This assumption made little difference, except for those measurements that were taken near the window. The light meter should have been lower for these measurements (i.e., at a scale such that the top of the window was higher than thirty inches). At this height, the meter would have "seen" more window and hence more light.

6-118. The model interior from above showing location of Li-Cor photo sensors.

6-119. The model interior as seen from a viewing port.

Much can be learned by actually doing such generic model studies divorced from a real design in which one limits the alternatives. For example, if one were testing an actual design and comparing design alternatives, one would not divide a window into three areas—a procedure used for theoretical analysis only. My students have been able to get useful results using fairly crude instrumentation—hand-held light meters. The measurements presented here, however, were obtained with automated, computerized instrumentation that is not only infinitely faster but eliminates the potential errors from the wide daylight fluctuations common to all but the clearest or most heavily overcast days.

The generic data for sidelong light under sunny conditions demonstrate the effects of various elements on the room's illumination. The curves plot illumination at the center line of the room. Tabulated results indicate efficiency (average illumination in footcandles) and uniformity (average/minimum).
Group 1: Ground, Facade, and Room as Reflectors

These data illustrate the potential value of the facade (horizontal reflectors) as the most dependable source of reflected sunlight, unless the foreground would be equally free from shadows and could be of equal reflectance (e.g., white sand beach or consistently snow-covered ground):

☐ If the foreground is white, it is as effective as white reflectors at the building facade.

☐ If the foreground is black (or in shade), sunlit white reflectors can increase illumination by 500 percent.

☐ When the reflected sunlight introduced into a room from white foreground or white louvers is effectively utilized, most of the illumination at the workplane away from the windows comes from indirectly illuminated room surfaces (white walls and ceiling) rather than directly from the window.

☐ In deep, wide rooms (as modeled) the ceiling is the most important room surface for redirecting light to the workplane. Light-colored walls increase illumination near the walls and thus improve uniformity and total illumination. The percentage effect on average illumination is understated because measurements were taken only at the center line of the room and not near the side walls.

☐ When reflected sunlight is well utilized, the lowest window can be the most efficient for total illumination provided as well as the most effective in providing uniform illumination.
A  BLACK FOREGROUND

<table>
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<td>20</td>
<td>9.1</td>
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<tr>
<td>C White Ceiling &amp; Back Wall</td>
<td>20</td>
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<tr>
<td>D White Ceiling, Back &amp; Side Walls</td>
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B  WHITE FOREGROUND

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<td>158</td>
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</tr>
<tr>
<td>D White Ceiling, Back &amp; Side Walls</td>
<td>173</td>
<td>5.1</td>
</tr>
</tbody>
</table>
Group 2: Changing Ceiling Heights

These data confirm the value of increasing ceiling height to increase illumination away from the window, reduce illumination near the window, and thus make illumination throughout the room more uniform wherever the windows are located (i.e. high, middle, or low).

☐ The higher the ceiling, the more uniform the illumination:

☐ The most uniform reflected sunlight is always from the lowest window. Changing from an 8-foot ceiling to a 16-foot ceiling improves the uniformity by a factor of 4. Increasing from 8 to 12 feet improves uniformity of illumination by a factor of 3.

☐ In high spaces, the least uniform illumination is from the upper windows.

☐ The greatest degree of uniformity is achieved from the lowest window with the highest ceiling and room reflectances (avg/min. of 1.5).
Group 3: Changing Ceiling Shapes

These data show that changing from a flat ceiling to a shaped ceiling with the same average height can improve uniformity very noticeably:

☐ The best uniformity is attained when most of the ceiling slopes upward from the window and some portion of the ceiling best "sees" both the window and the work plane at the rear of the room. The most effective shape is arranged on the left, the least effective on the right.

☐ The most effective shape improves uniformity by a factor of 3, compared to a flat ceiling.

Group 4: Beamed Ceilings

These data show that:

☐ Widely spaced beams perpendicular to the windows can improve average illumination and uniformity compared to a flat ceiling with equal height clearance. The averages are reduced because of reduced levels near the window.

☐ Beams perpendicular to the windows are more efficient and produce more uniform illumination than those parallel to the windows.

☐ Increased spacing improves efficiency and uniformity.

☐ A two-way grid provides somewhat more efficiency and better uniformity than similarly spaced beams parallel to the windows, but is not as good as beams perpendicular to the windows.

☐ A two-way grid is less efficient than a flat ceiling.
3 CHANGING CEILING SHAPES (Sunny Condition)

REFLECTANCES: ceiling 80% walls 50% floor 20%

4 BEAMED CEILINGS (Sunny Condition)

REFLECTANCES: ceiling 80% walls 50% floor 20%

PARALLEL

PERPENDICULAR
Group 5: Combined Effect of Room Shape and Color

These data compare the effect of ceilings sloping upward or downward from the window in rooms with light ceilings and dark walls and those with dark ceilings and light walls:

- Sloping the ceiling downward will always make illumination less uniform because it always increases the light near the windows.
- Sloping the ceiling upward always makes the illumination more uniform.
- The best uniformity from upper windows is achieved with the lightest colored upward-sloping ceiling.
- The best uniformity from the windows is achieved with a dark-colored ceiling sloping upward to white walls. The dark ceiling reduces illumination near the window. The upward slope allows the light to reach the large area of white wall deep in the space to get the best uniformity along with the lowest average illumination levels. This combination is characteristic of many buildings in sunny tropical climates.
COMBINED EFFECT OF ROOM SHAPE AND COLOR (Sunny Condition)

A REFLECTANCES: ceiling 80% walls 20% floor 20%

B REFLECTANCES: ceiling 80% walls 50% floor 20%

C REFLECTANCES: ceiling 20% walls 80% floor 20%
Group 6: Overcast Conditions

Under overcast conditions, illumination levels are reduced, and the effects of window height and room reflectance are quite different than under sunny conditions. The effects are those of direct lighting from the sky rather than indirect lighting from the ceiling and walls. For these reasons, the data show:

- The upper window provides most of the illumination.
- The lower window provides little illumination (unlike under sunny conditions, when it can be the most effective).
- Lightshelves can improve uniformity by reducing illumination substantially near the window and boosting it slightly deeper in the room.
- For upper windows, lightshelves improve the uniformity but they also reduce the average substantially.
- For lower windows, lightshelves can improve both the uniformity and the average illumination.
- Under overcast as well as sunny conditions, increased ceiling height improves uniformity from any window when room reflectances are high.
OVERCAST CONDITION

REFLECTANCES: ceiling 80% walls 80% floor 20%

A Flat Facade

B Light Shelf
Overview of Generic Sidelighting Data

- For best illumination under both sunny and overcast conditions, use a combination of low windows (best for sunny conditions) and high windows (best for overcast conditions).
- Use reflectors at the facade to reflect light into the room as well as to provide shading and glare control; use high reflectances and high ceilings to distribute light to the workplane most efficiently and uniformly.
- Use shaped ceilings or widely spaced beams perpendicular to the windows to improve light distribution.

SUMMARY

Concepts and devices for sidelighting have been discussed at length in this and the preceding chapter. While those most applicable to various buildings will vary, there are some concepts and devices I find universally useful:

1. Orient most windows to face north or south to make effective use of sunlight easiest. Such orientation allows the simplest fixed shading/redirecting elements to provide complete control. In contrast, east and west exposures require at least some use of dynamic shading devices to control glare and overheating.

2. High room reflectances, particularly those of upper walls and ceilings, are essential for efficient use of reflected sunlight. Avoid highly configured ceilings with many light-catching cavities that reduce the effective reflectance of the ceiling. Keep exposed beams widely spaced and perpendicular to the window walls.

3. High ceilings are necessary to distribute light more uniformly to the deep spaces characteristic of many modern buildings. They are beneficial but less necessary for shallow rooms. High ceilings can be achieved economically if given high priority in the integration of building systems (chapter 9).

4. Large-scale architectural shading elements such as the classic overhang are the most effective, dependable, durable, and economical over time. They frame rather than compete with views. They add interest and richness to a building’s exterior form, but as major elements, they need to be well designed and integrated into the building fabric. This is most likely to happen if they are included from the beginning of the design process.

5. Lightshelves, combined with high ceilings, are the best devices for shading and redirecting sunlight in a manner that integrates with other elements of the architecture, fulfills user needs, and creates comfortable, spacious, delightful sunlit spaces. To be effective for distributing light, high reflectance on the top surfaces is essential. On north and south exposures, lightshelves can be designed to
require no additional movable shading for control of glare or heat. On other exposures they can be effective most of the time but need to be supplemented for short periods. As large-scale architectural elements, they are an important formgiver for sidelite buildings. The many case-study examples in which they are used indicate how widely applicable they are and demonstrate the range of design expression possible.

6. **Reliability is very important for dynamic shading devices.** If unreliable, they remain in place (and adjusted for the worst condition) permanently. Although best on the exterior for heat control, an interior location is preferable if reliability and maintenance are better. Hence, my preference for using large-scale fixed elements when possible, with smaller-scale movable devices only as a supplement or as an unavoidable alternative.
For low-rise buildings, toplighting can be the most efficient form of sunlighting, as measured by illumination levels in relationship to HVAC loads (heating and cooling). This is due to the fact that the distribution of illumination can be made very uniform while the glazing area can remain minimal (fig. 7-1).

**CHARACTERISTICS AND CHALLENGES OF TOPLIGHTING**

Toplighting is of minimal use in tall multilevel buildings because it can illuminate only one or two floors. Its multilevel implementation is discussed in detail in chapter 8.

The most obvious advantage of toplighting over sidelighting is the freedom to place natural light sources wherever illumination is desired, either uniformly distributed or in whatever pattern is dictated by the programmed activities of the space. This flexibility makes it simple to achieve uniform illumination. Unlike sidelighting, there is usually no need, when toplighting, to overlight one area in order to get sufficient light for the adjacent areas. Despite these advantages, other challenges remain for toplighting design, both quantitative and qualitative.

The quantitative challenge is that common to all sunlighting—to optimize the relationship between lighting and HVAC under the wide daily and seasonal variations in sunlight availability. The best toplighting solution is likely to be different for each particular building configuration and each set of programmed activities and related lighting and thermal comfort requirements, latitude, climate, and microclimate.

The qualitative challenge is to create beautiful, pleasant, appropriate visual environments that satisfy the occupants’ needs for orientation in time and space. Sunlighting should be used to create delightful environments rather than simply to save energy. Direct sunlight on interior walls can be used to give the occupants of windowless spaces a “view” that provides some information as to exterior weather conditions and time of day.

As explained in chapter 1, office and factory buildings should maximize long-term worker satisfaction and thus productivity—a primarily qualitative challenge. Therefore, the highest priority should be to provide
enjoyment from sunlighting, particularly in spaces that tend to be dreary and can only be rectified by toplighting.

These challenges were either not present or were less important in earlier periods of history, before air conditioning and artificial lighting had made large floor areas feasible, and when the criteria for human comfort and/or the visual demands of the programmed work were less stringent. The design solutions that evolved worked well for the conditions and the available technology of those times. We must now meet today’s increased expectations by combining historical precedents for sunlighting forms with the potential of current technology.

HISTORICAL PRECEDE NTS

Skylights

The precedents for skylights include unglazed apertures open to the sky overhead for light and ventilation, as in the extensive bazaars of ancient Persia and the Pantheon of Rome (figs. 7-2, 7-3). These openings were small (2-5 percent of floor area) but adequate, particularly on the sunny days that prevail in these climates.

In visiting the bazaar at Isfahan, Persia (now Iran) I found the illumination on a sunny day functionally adequate for public circulation but somewhat gloomy to my taste and contemporary Western expectations. This condition could be easily rectified by more highlighted displays in the bordering shops. Lighter colors on walls and ceilings would also help distribute interreflected light.

The dullness of the dark ceiling and wall surfaces was largely offset by the biologically important information that was provided. The unglazed openings overhead gave an absolutely clear view of the blue sky, and the small, changing patches of sunlight on room surfaces were infinitely more satisfying than the same average quantity of illumination would have been from translucent skydomes or fluorescent light fixtures. The occasional windows and doorway openings to courts were more important for their information value than for the additional illumination they provided.

The use of small horizontal openings to provide light and ventilation in thermally massive, vaulted roof structures is uniquely appropriate to the predominantly sunny, dry, desert climate, with its hot days and cool nights. Small horizontal openings in high, vaulted ceilings are still logical today under similar conditions. This combination ensures that the ceiling vault and upper walls will be the primary reflecting surfaces, minimizing glare and providing visual interest.

In contrast, extensive areas of skylights were used in late nineteenth-century European and American museums. The sunlight reaching the galleries was controlled by an attic full of operable louvers above a glazed ceiling. The negative effect of such large areas of skylights on thermal comfort in summer was reduced by the thermal isolation of the gallery space from the independently ventilated attic. (See museum case studies for comparison with some contemporary museum designs.) In present-day America, skylights are most commonly used in industrial buildings with minimal heating, cooling, or lighting requirements.
Clerestories

Early in history, the interior zones of large spaces were also supplemented by toplighting from clerestories in the form of open (Isfahan) or glazed (Hagia Sofia) apertures. Sunny climate and function dictated that the openings be small (fig. 7-4).

In eighteenth-century England, while skylights were the common solution for circulation spaces, shopping malls, and railroad stations, industrial buildings were more likely to use north-facing clerestories in sawtooth roofs. The form of toplighting selected might have been dependent on considerations of glare control rather than control of solar gain. Even under dirty, smoggy conditions, the glare of sunlight was not welcomed in work spaces. However, direct and indirect solar heat gain from skylights or south-facing clerestories would probably have been welcomed.

7-4. The dome of the mosque at Isfahan, Iran. (Photograph courtesy of Tom Lam)

GEOMETRY OF TOPLIGHTING: FORMS OF TOPLIGHTING FOR TODAY’S CONDITIONS

Both skylights and clerestories are applicable today, but their selection, size, detailing, and relationship to other room surfaces need to be reconsidered for each application, recognizing the differences in objectives and means. Optimizing the performance of toplighting today implies using light indirectly. As with sidelighting, incoming sunlight must be baffled and redirected in order to avoid glare and local overheating and to provide the light distribution and delightful interior environments desired.

In toplighting, the walls are often the most important illuminated surfaces. By intercepting direct sunlight, walls can redistribute the light to the desired surfaces and areas. Because of the crisp and changing patterns of sunlight on these illuminated walls, they can be a satisfying substitute for a window view. Walls can be seen throughout large spaces, satisfying biological information needs for orientation. By contrast, a patch of sunlight on the floor coming from a shared central skylight may be visible only in a local area.
Ceiling height is also important with toplighting. Unlike sidelighting apertures, toplighting apertures can be distributed as needed. Fewer apertures are necessary, and the light distribution will be more uniform with increased ceiling height, especially when the sunlight is diffused by reflecting surfaces or diffusers (fig. 7-5). Sloping the ceiling up to meet the aperture will minimize contrast between the aperture and the space receiving the illumination. These geometrical considerations can be met with a variety of shapes and devices.

7-5. Diffused light distribution from toplighting apertures increases in uniformity with increased ceiling height (fewer apertures are necessary).

**Horizontal or Near-Horizontal Glazing for Toplighting: Skylights**

Horizontal skylights favor overhead light, and their performance is independent of orientation. Their performance under sunny conditions is dependent on solar altitude (fig. 7-6).

**Advantages**

The advantages of horizontal skylights include the following:

- They can be placed almost anywhere on any roof with minimal impact on structure or framing. Like window blinds, they can be added at any stage of the design process, even after the building is completed and occupied. Little design effort is required beyond size selection of cataloged or standard details. Larger-scale greenhouse-style glazing is also simple to specify as a premanufactured item.

- For a given glazing area, skylights are likely to have a very low first cost because they need little architectural provision beyond omitting an area of roof and installing a mass-produced product.

- They can provide the most efficient lighting for dark, overcast conditions when the sky vault is uniformly bright. Under these conditions, a skylight oriented directly overhead "sees" the most sky and receives and distributes the light most directly to the space below (fig. 7-7).

- Clear skylights give maximum views of the sky. Translucent glazing will help distribute light on clear days but must be in a well to baffle the glare of the overly bright, sunlit diffusers.

7-6. The performance of skylights under sunny conditions is dependent on solar altitude.

7-7. Horizontal skylights "see" the most sky and are therefore the best method for collecting and distributing diffuse, overcast sky light.
Skylights may be the best option in equatorial locations where their horizontal orientation will maximize collection of the incident sunlight from a high solar altitude. Under such conditions, a very small area of glazing in a deep well can illuminate a large area effectively. The skylight should be no larger than necessary to provide the desired illumination under sunny conditions (i.e., the aperture should be \(+/- 1\) percent of the floor area). If sized for overcast conditions, the overheating that would occur under sunny conditions would create additional cooling requirements and offset any savings from lighting.

Disadvantages

The disadvantages of horizontal skylights include the following:

They perform poorly in temperate and frigid climates (high latitudes). This is not a problem at the equator where there is little seasonal difference and one can design for the overhead condition. Horizontal glazing admits maximum sunlight and heat in summer when the sun is high and minimum sunlight and heat in winter when the sun is low. Clearly, this is the reverse of the generally desired condition for both thermal and lighting considerations. Many of the best-known architects have created dramatic toplighted sculptural statements that must have assumed sunless skies and then attempted to ameliorate the self-imposed problems with technical solutions, sometimes with little success. One example is the fully glazed greenhouse ceiling/roof at the Cambridge University History Faculty building (James Stirling, 1967). This building is an environmental disaster, cold and drafty in winter and hot as an oven in summer. A fraction of the glazed area, if well employed, could have created a more comfortable thermal and visual environment at a fraction of the construction and operating cost (figs. 7-8, 7-9).
They have the potential to create glare problems. If clear glazing is used, beams of direct sunlight from overhead are welcomed in circulation areas but unacceptable in most work areas. The high angles of sunlight received by horizontal skylights are difficult to redirect by naturally occurring architectural elements, such as beams and walls (fig. 7–10). Sunlit translucent glazing can also be a source of glare and, like informationless translucent fluorescent fixtures, much more annoying than similar areas of reflected light from interesting “real” surfaces. As sources of direct lighting, translucent surfaces are bright relative to other room surfaces. Translucent glazing that diffuses the light to the space and reduces direct glare also eliminates the beneficial information of sunlight (time, weather conditions).

Unit skylights, either clear or translucent, placed to illuminate the workplane directly with maximum efficiency (i.e., centered in a space) tend to leave the wall and ceiling surfaces unlit and gloomy. Shaping the ceiling cavity to improve light distribution offsets the initial economy of off-the-shelf skylight units (fig. 7–11). The use of unit skylights does not encourage architectural integration between beams, ducts, and the like.

Horizontal glazing is more vulnerable to leakage problems than vertical windows; building codes may require expensive wired or laminated safety glass.
Using Skylights to Best Advantage

The following guidelines will help optimize skylight performance:

- In temperate climates, tilt and orient skylights as much as possible to reduce the seasonal disadvantages. For example, a south-facing skylight at a 45-degree slope in Boston would improve the summer/winter ratio (of light to heat admitted) from 5:1 to 2:1 (fig. 7-12). With a 60-degree slope, illumination at noon in summer and winter would be equal.

- Coffer the ceiling up to the skylight to improve light distribution and reduce aperture contrast. A small skylight can have remarkable impact if integrated with a large coffer. Lift the entire ceiling around the skylight, or whatever area is possible. It is better to use fewer skylights with good distribution than a large number with poor distribution.

- Except in public spaces where views of the sky or adjacent buildings are a principal objective, use small areas of clear glazing rather than large areas of low-transmission glass. Smaller areas of glazing are less expensive, need smaller areas of shading devices, are easier to control, and permit less heat transfer in and out of the building. Achieve visual connection with the external world through visible penetration of sunlight rather than maximum area of visible sky.

- Locate skylights to bring sunlight against walls or other light-directing surfaces (fig. 7-13). These will then illuminate the work surfaces indirectly, minimizing contrast with the skylights, and helping to create bright, cheerful spaces. Sunlight and skylight falling on a wall will benefit a much larger space than will the same-size opening in the middle of a room. Reflecting pools, sculptures, or even polished nontask floor areas can be effective in redistributing the light from clear skylights (fig. 7-14).

- Design baffling to control glare and redirect light to large areas of room surfaces. Baffling can be located outside the skylight, at the glazing plane, or in the zone of transition between the aperture and the end-use surface (figs. 7-15 through 7-20). Local interior shading devices such as trellises, trees, banners, and umbrellas offer selective protection.

- Control the amount of light entering the space with dynamic shading that redirects unwanted light back to the exterior, rather than converting it to heat within the space (fig. 7-21).

- For best performance, use adjustable louver/reflectors that redirect the light precisely where desired.

- Unless functional glazing system elements are interesting or beautiful, baffle them from view with large-scale architectural or decorative elements. Avoid the visual noise that results from complex structural forms juxtaposed with uncoordinated glazing details.
7-16. Skylights may be shielded by exterior louver system as those at the Mellon Gallery at the Yale Museum (Louis I. Kahn, Architect). However, louver systems visually busy, require constant maintenance, and greatly reduce the efficiency of the skylights in exchange for steadier illumination. This seems to be a very inefficient and convoluted way to get the effect of a simple north-facing clerestory. (Photograph courtesy of John Lam)

7-17. Interior control at the glazing plane: (a) fixed or operable louver; (b) larger fixed or operable louver or beams; (c) deep well openings alone.

7-18. The reflector used in the skylight system of the Kimbell Art Museum (Louis I. Kahn, Architect) is a sound concept inefficiently executed. The relatively dark-colored surfaces of the unpainted concrete skylight well and ceiling vault give a pleasant glow that is insufficient for lighting the exhibits even at noon on a sunny day in midsummer. There would be more light if the skylight well was painted white.

7-19. The library of this Middle Eastern University (case study A2) employs the same reflector wedge concept as the Kimbell Museum. However, because all surfaces will be white and the space between the skylight and reflector much greater, it should deliver much more light. (Courtesy of Campus Consortium)
**Vertical Glazing for Toplighting: Clerestories, Sunscoops, and Lightscoops**

**Clerestories**

Clerestories favor low-angle light, either facing the equator at high latitudes (winter in temperate climates), or at dawn and dusk on east and west exposures. Orientation is the critical determinant of their thermal performance (fig. 7-22).

Clerestory monitors for toplighting have advantages over skylights for energy conservation and ease in controlling glare. Since they are more difficult to add on than are skylights, and have a greater effect on architectural forms, they must be integrated with the overall design at an earlier stage.

**Sunscoops**

Sunscoops are clerestory monitors oriented toward the sun (fig. 7-23).

In temperate climates and high latitudes, clerestory monitors oriented toward the equator will automatically achieve the usual temperate climate objective of more light in winter than summer to reduce heating and cooling loads. A suncoop can get twice as much light in winter as in summer; a horizontal skylight might get only one-fifth as much (see fig. 7-9). Such orientation also makes glare control simple. Glare control can be best provided by a nearby parallel wall that blocks and redirects any sunlight penetrating at any angle from large unshaded clerestories (see case studies F1 and H1). Such a construction allows occupants to enjoy seeing sunlight on wall surfaces without receiving direct glare.

Because of their ability to provide glare-free lighting much more easily than windows, sunscoops are ideal in very high latitudes where the sun is very low in the winter and maximum light and heat from the sun is always desired (e.g., in Alaska, where the sun is at 10 degrees elevation on a December noon) (fig. 7-24).

Sunscoops can control the quantity of sunlight with the same shading devices used in sidelighting—overhangs, louvers, and the like (fig. 7-25)—and baffle the light by using deep monitor shapes in combination with beams, coffered ceilings, high placement of the clerestory within the monitor, and deep, interior lightshelflike sills (figs. 7-26 through 7-30).
For maximum efficiency, use a minimum area of clear glazing in continuous bands for easiest summer shading and minimum heat loss in winter. When the roof is the immediate foreground, white marble chips or polished reflectors can be located to increase light selectively in summer or winter. The light input through sunscopet can also be increased by maximizing reflections from adjacent walls. The actual shape of the monitor has little effect on performance; orientation and effective reflectances are much more critical.

**Lightscoops**

Lightscoops are clerestory monitors oriented away from the sun (north in the northern hemisphere) (fig. 7-31). Of questionable value in frigid climates, lightscoops utilize sky light and roof-reflect ed sunlight and require little if any shading to eliminate all direct sunlight (fig. 7-32). Both sunscopet and lightscoops are useful and can be easily shaded in equatorial latitudes.

The advantages of lightscoops are as follows:

- They give the steadiest level of illumination with a minimum of glare. If adjacent roofs are dark-colored, lightscoops will receive more light on overcast days than on clear days. Light-colored adjacent roofs (or suncatchers) can alter that balance.

- They contribute virtually no solar heat gain.

- They require minimum shading and baffling to control light.

The disadvantages of lightscoops are as follows:

- They admit the lowest amount of light per unit of glazing.

- The light admitted is diffuse sky light, which is nondirectional and does not penetrate as deeply into a building as sunlight. The color of sky light is "cooler" than that of sunlight, and although steady, may be uninteresting.

- Little or no solar heat gain is achieved in heating season. Heat lost through lightscoops can be significant. Highly insulative glazing should be considered.
7-30. Portland Museum of Art (I. M. Pei and Partners, Architect). Exposure to sunlight from all directions can make illumination levels steadier from dawn to dusk. However, symmetrical treatment of fixed louvers is extremely inefficient. Louvers designed for the lowest sun angles from the east and west provide excessive shading on the south side and are redundant on the north side, where no louvering is necessary. (Reprinted by permission of Progressive Architecture)

7-31. Lightscoops are clerestory monitors oriented away from the sun, receiving sky light and roof-reflected light. They provide the lowest and steadiest light levels with minimum annual heat gain.

7-32. North-facing lightscoops with tinted glass at Boston University Library (Josep Luis Sert, Architect) are an unfortunate choice in Boston, where the heat and light of winter sunlight are always desirable.

Lightscoops can be used to advantage under the following conditions:

- In museums, where steady light levels may be more important than winter thermal gain.
- In warm climates, where heat is never needed. (See, for example, case study D3.)
- In buildings such as museums, where high light levels are never desired.

The decision to orient a clerestory monitor away from the sun is often determined by architectural necessity rather than by lighting needs. If more light is desired, reflect light into the windows from a high-reflectance roof when the sun is high and from suncatcher baffles when the sun is low.

Suncatcher Baffles

A shading/redirecting device of exceptional usefulness in toplighting is the suncatcher baffle (fig. 7-33). This is an exterior device that converts direct sunlight to indirect sunlight. Positioned to redirect sunlight into a window, suncatchers can significantly increase the illumination in north-facing windows (fig. 7-34). On east- and west-facing windows, suncatchers both shade and redirect sunlight, significantly reducing daily illumination fluctuations (fig. 7-35). Although they also reduce illumination on overcast days, on sunny days suncatchers always increase the illumination on the shady side.

A suncatcher in combination with a lightscoop can reduce the inequality between sunny (south) and shady (north) exposures and also increase the average illumination of the space.
Lightscoop/Sunscoop with Suncatchers

When monitors face east and west, they act as both sunscoops and lightscoops during a sunny day (fig. 7-36). In this case, suncatcher baffles can make the light fairly uniform during the course of a day by blocking some of the light from the sunny side and capturing it on the shady side. At noon, suncatcher baffles increase the illumination by redirecting much of the roof-reflected light that otherwise would have gone into the sky into the space.

The design of suncatcher baffle proportions is similar to lightshelf design in that it is a compromise between the optimum conditions for receiving and reflecting sunlight. To minimize reductions in illumination under overcast conditions, suncatchers should be kept some distance away from the window. A good rule of thumb is that the suncatcher-to-window distance should be more or less equal to the size of the suncatcher (fig. 7-37). Projecting the suncatcher above the roof maximizes the amount of low-angle light captured; projecting it below the roof maximizes the amount of baffle "seen" by the interior. Therefore, a single blade is more efficient than multiple fins with an equal cut-off angle because more area is sunlit, and all of the sunlit baffle area is seen by the window (fig. 7-38 and case study B5.)

7-38. For a given surface area, one large louver is more efficient than several small ones both in capturing and redirecting sunlight.
12 PM (noon): high sun angle

2 PM: medium sun angle

4 PM: low sun angle

12 PM (noon): overcast condition

Roof is main source of reflected light

Roof on west and suncatcher on east provide reflected sunlight. East side is brighter than west side in the early afternoon

Suncatcher baffles even out the difference between east and west at the end of the day

Suncatcher baffles reduce light levels slightly under overcast conditions
7-36. Suncatcher baffles in east/west orientation. The effectiveness of this device was illustrated by model studies for renovating at Cummins Engine Factory in Madison, Indiana (Eisenman and Robertson, Architect). With east-and west-facing clerestories above the two adjacent production lines, the illumination and heat gain at 4 P.M. (c) would be sixteen times greater on the sunny side (j) than on the shady side (k). With the addition of suncatchers (solid line), both sides would be about equal (l,m). The suncatchers increase illumination by 100 percent at noon (a), but reduce illumination by 50 percent on an overcast day (d).
TOPLIGHTING GENERIC STUDIES

The toplighting studies on the following pages compare equal areas of glazing (10 percent of floor area) with a range of configurations at the center of a space and at two edges. Designs tested were based on the supposition of no direct sunlight penetration to the workplane. Therefore, glazing was clear only if the sunlight would be controlled by the lightwell or walls; otherwise, the glazing was translucent. Assumed location was 42 degrees north latitude (Boston).

**Group 1: Central Fenestration Oriented N-S**

- Horizontal skylights (A) admit the most light when the sun is high (summer noon) and the least when it is low (in winter). Usually this is not desirable for lighting or HVAC.

- Vertical clerestories oriented south admit the most light when the sun is low (in winter) and a fraction of that in summer. This is good thermally, but there may not be enough light in summer.

- Sloping skylights to the south (B and C) maximizes light at the equinox and gives the steadiest level of light throughout the year. This may be the best choice when equal light is desired in summer and winter to minimize lighting-energy cost without HVAC penalty.
TOPLIGHTING STUDIES (Sunny Condition)

REFLECTANCES: ceiling 80% walls 80% floors 20%

1 CENTRAL FENESTRATION ORIENTED N-S

A DIFFUSE HORIZONTAL SKYLIGHT

B DIFFUSE 45° SKYLIGHT

C DIFFUSE 60° SKYLIGHT

D DIFFUSE VERTICAL CLERESTORY

Toplighting Generic Studies 153
Group 2: Central Fenestration Oriented E-W

- As would be expected, horizontal skylights (A) admit many times more light in summer than in winter, with large variations throughout each day.
- Clear vertical clerestories with suncatchers (C) provide much steadier illumination throughout the year and throughout each day, although at much lower levels than the horizontal skylights.
- Clear double clerestories (B) with total glazing area equal to (C) also provide steady illumination but less efficiently.

2 CENTRAL FENESTRATION ORIENTED E-W

A DIFFUSE HORIZONTAL SKYLIGHT

B CLEAR VERTICAL DOUBLE CLERESTORY

C CLEAR VERTICAL CLERESTORY WITH SUN CATCHER
Group 3: Edge Fenestration Oriented E-W

In this group the diffuse skylights were sloped to illuminate the adjacent walls, with the diffuser surface largely out of sight. This was compared with vertical clear glazing with direct sunlight controlled only by the walls.

- The diffuse skylights (A) provide the most light at noon but provide less at the beginning and end of each day than do clear vertical clerestories (B).

- The addition of suncatchers to clerestories (C) achieves the steadiest illumination throughout each day and the most uniformity throughout the room. The suncatchers increase the illumination at noon and make both walls equally bright whatever the direction of the sun, with some sacrifice in total efficiency.

3 EDGE FENESTRATION ORIENTED E-W

A DIFFUSE 45° EDGE SKYLIGHTS

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JUNE 21

EQUINOX

DECEMBER 21

B CLEAR VERTICAL EDGE CLERESTORIES

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C CLEAR VERTICAL EDGE CLERESTORIES WITH SUN CATCHERS

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8

Toplit Shared Central Spaces: Courts and Atria, Lightcourts, Littria, and Lightwells

While the previous chapters were concerned with the particulars of fenestration for sidelite and toplit buildings, this chapter is concerned with the potential for massing a large building or complex of buildings around a central space. Courtyards and atria are central spaces created primarily for human pleasure, though they do have some sunlighting implications; they will be discussed briefly. Lightcourts, littria, and lightwells have evolved from the courtyard and atrium forms. They express the utility of sunlighting; the light-reflecting and controlling qualities of their central spaces are maximized in order to provide sunlighting for the surrounding spaces. These spaces will be examined in detail.

DEFINITIONS OF SHARED CENTRAL SPACES

Court: an outdoor area open to the sky and largely or entirely surrounded by buildings or walls (fig. 8-1).

Atrium: the central room of a building open to the sky at the center; today, the atrium is usually multistoried and glazed (fig. 8-2).

Lightcourt: a courtyard that is designed to optimize the sunlighting in the enclosed building(s) (fig. 8-3).

Litrium: an atrium that is designed to optimize the sunlighting in the adjacent spaces (fig. 8-4).

Lightwell: a vertical opening through one or more floors in a building, created for the primary purpose of distributing natural light to adjacent spaces (fig. 8-5).

HISTORICAL PRECEDENTS

Designing to accommodate the sun through the use of toplit central spaces has been a feature of architecture for many centuries. Greek houses faced into courtyards. The Roman "atrium" was a skylit space within the house that served as the center of the home and contained the family shrine.
The Romans also often extended their houses out, enclosing the back garden with a colonnade to create a peristyle (fig. 8-6).

An interesting example of the atrium building form is found in the ancient Roman underground houses of Bulla Regia in Tunisia (fig. 8-7). The open atria in these structures (more like our modern courtyards) usually contained a tiled mosaic reflecting pool, which, in addition to providing a degree of evaporative cooling, served to reflect sunlight into the adjacent underground rooms. The Bulla Regia structures are also noted for their careful use of lightwells (fig. 8-8). These asymmetrical wells gathered the maximum amount of sunlight possible, but because the solar gain would have been unwelcome in this hot, arid climate, the light was used indirectly with less heat gain. Many of the wells were constructed so that one could not see a line of sight up to the sky; direct sunlight had to bounce several times within the well before entering the space.

Later in history, and a continent away, cast iron and steel structures supported large areas of overhead glazing to keep out rain, snow, and cold in the shopping malls and railroad stations of London, Milan, and other northern cities (fig. 8-9), where cloudy climates prevailed and large expanses of glass were affordable. For such spaces, any direct sunlight that could penetrate the smog, fog, and dirty glass was probably more than welcome at any time. Natural ventilation provided sufficient summer comfort.

In qualitative terms, much can be learned by observing the design of these malls. Looking directly overhead at the glazing in these structures is not a pleasant experience. One sees a clutter of small, dirty panes of glass with cracks patched with tar and a disorderly array of partly open windows. But these details are not normally noticed because of the extent of large-scale architectural elements (girders and beams) that baffle the views of these unattractive details. One perceives illuminated building surfaces with interesting details, not glazing hardware.

8-9. (a) Galleria Vittorio Emmanuele, Milan. (b) Burlington Arcade, London, glazing baffled by structure. Light-washed architectural surfaces appear less dull and gloomy than the overcast sky outside. (Photograph a courtesy of Victor Olgyay)
In those structures where extensive areas of glazing and hardware were totally exposed, the skylights tended to be handsomely executed, interesting, positive design features, rather than purely functional ones. Some prominent examples of such structures include the Royal Pavilion in Brighton, the Crystal Palace, and the Galleria Milan. These public spaces were generally not specifically designed to temper the adjacent spaces.

Grand buildings were also created around courtyards, often for the pragmatic purpose of increasing the amount of building perimeter with natural light and ventilation. The Boston Public Library, designed by McKim, Mead and White (1887-95), is typical of this building form. Appearing from the street as a large bulk, it is actually perforated by a central courtyard that creates a thin cross section (figs. 8-10, 8-11).
In densely built areas, these perforations often occurred on a less grand scale; uninhabited lightwells were commonly used to make deep buildings habitable. To maximize their usefulness, the spaces needing ventilation and light were clustered around these wells. Lightwells were also occasionally used as circulation areas.

An example similar to the Boston Public Library is Adler and Sullivan's Wainwright building in St. Louis (1890–91); in this case the building is U-shaped rather than O-shaped in plan (figs. 8–12, 8–13, and 8–14). Subsequent renovations of the Wainwright building have created a more efficient building envelope design by glazing the open courtyard and creating an enclosed atrium. Frank Lloyd Wright's Larkin Soap building in Buffalo (1904–5) effectively anticipated the renovations of the Wainwright building with its modern toplit atrium (figs. 8–15, 8–16). Because this space was conditioned, the floor of the atrium could be used as additional functional work space. Ironically, the Larkin building, with its sensitive environmental design (sealed and mechanically ventilated), also assisted in the evolution of sealed buildings and the accompanying electrical and HVAC systems that eventually would allow twentieth-century designers to virtually ignore external environmental forces.
COURTS

Courtyards are used for circulation and informal "al fresco" relaxation. Their use is dependent on season and weather. Landscaping can create a courtyard out of "leftover" space between buildings (fig. 8-17). Courtyards can be large for relatively little cost because landscaping is the only cost. They should be enjoyable spaces for people (fig. 8-18).

Sunlighting and Courts

Courtyards are useful to sunlighting because their open spaces preserve the solar access of the adjoining buildings; they allow sunlight to reach the facades so that sidelifting strategies can be used. Depending on the distance across the courtyard, the buildings may use each other's facades as sources of building-reflected light. If the ground materials are light-colored, courtyards are good foreground sources of ground-reflected light. Remember that courtyards are primarily for human enjoyment; the facade or ground materials are to be chosen for reasons of human comfort and delight in the courtyard itself, rather than to provide reflectances ideal for sunlighting surrounding buildings.

ATRIA

The design and construction of atria and courtyards are very different, although similar activities may take place within them. An atrium results when the interior space of a building is "opened up" to the outside. Atria in warm climates may be unglazed, as the original Roman atria were. Atria are usually isolated from the outdoors by glazing. Activities may take place year round in an atrium, depending upon the extent to which the space is heated or air-conditioned. The need for mechanical ventilation or total air conditioning makes it important to control the amount of sunlight admitted according to seasonal heating or cooling needs.
When atria are sealed and fully air-conditioned, glazing areas should be minimized to reduce the thermal penalty; it is important to use whatever light is admitted efficiently. To minimize the benefits relative to the costs, atria are often tall and thin. There is a great difference between the economies of a given amount of sunlight for a given floor area of a two-story hotel lobby and for a fifty-story atrium with the same floor area at lobby level. Tall hotel atria often slope in at the top to a minimal aperture. Despite the cost, a dramatic and delightful atrium is cost effective because of the premium-value space it creates.

**Sunlighting and Atria**

The qualitative lighting objective in atria is to create sparkle—the visual interest of a sunlit outdoor scene. To help accomplish this, some direct sunlight should be allowed to hit the architectural surfaces to create sharp shadow lines (fig. 8-19). Clear glazing will allow a glimpse of sky to be seen. In cold climates, more sunlight in winter than summer is desirable, both for cost savings and the positive emotional response it evokes.

The most stringent quantitative objectives are to optimize growing conditions for trees and plants and to maintain thermal comfort for minimal energy cost. The minimum light levels should be determined by what is necessary to sustain trees and plants. Direct sunlight on trees will eliminate the greatest need for supplementary artificial illumination.

![Image 8-19: Direct sunlight on architectural surfaces will create sharp shadow lines and read clearly as "sunlight."
The form of an atrium sunlitg aperture reflects its application. Low, wide atria are easy to illuminate and can benefit from selective strategies such as clerestories (figs 8-20, 8-21). As with any sunlitg application, reduce light and solar gain by reducing the glazed area or by orientation, rather than by using mirror glass. Narrow atria require careful attention to receive sufficient light. "Beaming" the sunlight with mirrors can be invaluable (fig. 8-22). When sizing the glazing in narrow atria, remember that the benefits and costs are shared by the whole space. A skylight that is 30 percent of the lobby floor area may be less than 0.5 percent if the fifty floors of balcony corridors are figured in. On this basis, clear glass can more often be justified if it makes the space more pleasant.

Frequently, the challenge is to get sufficient light down to lobby level where the plants and people are (fig. 8-23). To maximize the reflectances of surfaces such as balcony railings, make them light-colored and solid.

Light-reflecting sculptures can also be used to provide focus, interest, and scale to an atrium and can assist in the distribution of sunlight (fig. 8-24). Because sculpture is usually interesting, it can be very bright without being glaring (fig. 8-25).

While plants provide much of the excitement of an atrium, it is important that they not obstruct the glazing or important light-reflecting surfaces. Otherwise, the plants on lower floors will need to be replaced constantly.

8-23. The proportions and orientation of the atrium at the Marriot Marquis Times Square Hotel in New York City allow very little direct sunlight from the main skylight to reach the floor; a smaller lower skylight makes a significant contribution by directing sunlight to the garden.

8-24. In the atrium at Park West, Dallas (Haldeman, Miller, Bregman, Hamam, Architect), the addition of reflective sculpture could balance the sunlight and aid tree growth on the shady side.

8-25. A Michio Ihara sculpture at the Pavilion Intercontinental Hotel, Singapore (John Portman, Architect).
LIGHTCOURTS

Lightcourts are courtyards that maximize the potential of using sunlight to light adjacent buildings. They are open exterior courts intentionally designed to capture and deliver controlled light to the surrounding buildings. The shapes and reflectances of lightcourts will respond to sunlighting requirements rather than to the desire to create lush landscaping. Of course, lightcourts can be designed to provide for circulation and seasonal lounging as well.

Unlike courtyards, lightcourts may be designed exclusively to provide light and not as attractive outdoor living spaces at grade or for the creation of pleasant views for the surrounding buildings. Therefore, lightcourts may be built in a purely utilitarian manner. For example, the old Waldorf Hotel in London was built around a lightcourt that supplied light and ventilation to the surrounding guest rooms as well as to a greenhouse attic and the decorated translucent ceiling of the garden court at lobby level. While the publicly visible exterior walls of the building were richly detailed (fig. 8-26), the exterior walls around the lightcourt obviously were not intended to be seen except hazily through fixed translucent curtains of guest rooms and stained glass windows of public spaces. Without these filters, one looking across the lightcourt would see unattractive walls covered with exposed plumbing and would look down onto ventilation equipment and the crudely detailed greenhouse roof (fig. 8-27).

I was interested to note the use of front lightcourts in the townhouses of London and Bath. These courts are sunken to basement level and generally contain no trees (there were trees in the park across the street, however). Open iron rails and light wall finishes maximize the light available to the lower-level kitchens and work spaces.

Sunlighting and Lightcourts

Lightcourts should be designed to allow the maximum amount of direct and reflected sunlight to reach adjacent facades. In addition, lightcourts should shade low-angle sunlight that is difficult to control at the facade and redirect that light into the buildings (case study B3).

Forms and Devices to Achieve Sunlighting Objectives

Optimizing sunlighting in lightcourts requires that all elements be considered for their possible contribution to redirecting light into the enclosing buildings.

Orientation and Massing

In planning for lightcourts, the massing of the adjacent buildings should be adjusted to allow the lightcourt to capture sunlight when and where it is desired. Orienting the lightcourt axis east/west will result in the equator-facing facades receiving the maximum number of hours of sunlight. The north/south facades receive sunlight at high angles that are easy to shade and redirect into the building.
Reflectances

Any light not accepted into the sunny-side facade should be redirected to the shady side by the use of light-colored surfaces. This is of increased importance in narrow spaces, where the upper building surfaces that first "see" the light must be light-colored. Ground materials should be selected and placed to reflect light into the adjacent buildings; pavement, water features, sitting areas, and sculptures should all be sensitive to the concern of reflected light. Trees may be used to provide shade in the courtyard as well as pleasant views, but they should be placed carefully so that they do not shade critical light-reflecting surfaces such as the building facade.

Suncatcher Trellises

Light-colored trellises may be better than trees if shade is necessary, as trellises can simultaneously redirect the sun onto the surrounding building surfaces above themselves.

Suncatcher trellises are best used to shade windows from low-angle sun that is difficult to control with fixed shading at the facade itself (fig. 8-28). Lightshelves and suncatcher trellises make a splendid solar-control combination. North/south trellises allow high-angle sunlight to penetrate but convert low-angle sunlight from the east and west to diffused reflected sunlight. It is important to shade only as much as necessary. At the GSIS building, for example (case study B3), the cut-off angle is 45 degrees one way (fig. 8-29). Light above 45 degrees is controlled with lightshelves at the facade. There should be no shading of the high-angle sunlight reaching the north and south light-directing facade elements at midday. Solid spandrels of high reflectance may be shaped and oriented to act as suncatchers, to redirect light to adjacent and facing facades if not into the room they enclose. When more precise control is desired, tracking mirrored louvers can be used in lightcourts. With outdoor exposure, however, maintenance is more difficult and wide movements of reflected light by wind action are unavoidable.

LITRIA

A litrium is a form of atrium that provides the benefits of sunlighting to its adjacent spaces. While an atrium provides the delight of a glimpse of sunlight to people in the atrium, a litrium admits sufficient sunlight to illuminate the spaces adjacent to the litrium.

Architectural Context

Litria are useful when lighting in adjacent spaces is qualitatively and economically important (in offices, classrooms, etc.), and the space of the litrium itself is a desired architectural feature. Depending on the HVAC and programmatic considerations, the adjacent spaces may be physically open to the litrium or thermally and acoustically separated. The litrium floor may be used either as a work space or a public space.
In order to minimize shadows and open the space to sunlight, litria should have a geometrical form that is equal in width at top and bottom or wider at the top than at the bottom (fig. 8-30). They should never be narrower at the top. The orientation of the litrium space and aperture is critical to maximize control of light; the guidelines for massing and orienting lightcourts are appropriate to litria as well.

**Lighting**

Litria are fundamentally different from atria in that much more light is desirable. This is due to the much greater area (the surrounding floors) that is using the light and the working illumination requirements of this area. The direction, quality, and quantity of light must be carefully controlled for maximum effectiveness. It is generally better to distribute light in litria to the interior facades, into work spaces, and onto the shady side, rather than to the floor (fig. 8-31). As in lightcourts, glare control in litria is important for the adjacent offices, but is also important at floor level if there is a work space there.

**HVAC**

Efficient use of light and high reflectances are more important in litria than in lightcourts because they are enclosed spaces. As with atria, the enclosed spaces in litria may be conditioned, tempered, or buffered as necessary to suit the programmatic needs. As a by-product of the additional light they receive, litria will usually have a larger solar/HVAC load than atria. It is therefore very important to take advantage of seasonal light variations to get as much sun as possible during the heating season. This will help save money in electric lighting and heating as well as increase the pleasure of “basking” in the sun during the winter (fig. 8-32). Conversely, severe operating cost penalties can result if litria are incorrectly designed, and more sunlight is admitted than is useful.
If light is being well utilized during the summer, the cooling load necessitated by the additional sunlight can be justified economically (see case study H1). There is an unfortunate tendency to reduce the amount of light too much in summer to minimize the cooling load, necessitating the constant use of purchased electric light (which produces more heat than a similar amount of sunlight). If litria use sunlight efficiently, they can have a more positive effect on cooling loads than atria, because they require electric illumination both for themselves and for the surrounding spaces.

In litria, even more than in atria, it is important to use whatever sunlight is admitted as light before it becomes absorbed by darker surfaces as heat. Use it twice.

**Forms and Devices to Achieve Sunlighting Objectives**

The specialized lighting requirements of litria begin with careful design of the sunlight aperture to suit the intended use and climate. Skylights, clerestories, sunscoops, and lightscoops should all be considered; more often than not, however, the most appropriate aperture will be a combination of sunscoops and lightscoops. A well-designed sunscoop-shaped aperture will flood a litrium with sunlight in the winter and allow an appropriately limited amount of summer sun to enter. The effectiveness of lightscoops can be augmented with the addition of suncatcher baffles. Other exterior architectural elements such as overhangs, fins, baffles, and roof reflectances should be exploited as well (figs. 8–33, 8–34).

The glazing considerations and recommendations for litria are identical to those described for atria, with an increased emphasis on the actual quantity and distribution of the sunlight.

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The exacting degree of light control required in a litrium may merit the use of tracking mirrored louvers to beam sunlight (fig. 8–35). Litria provide an ideal environment for locating louvers so that they are sheltered from wind and pollution. An interior location will sacrifice some thermal benefit compared with an exterior location, but this will be more than offset by the vastly simplified maintenance. The louvers should have a polished specular surface on one side (to beam sunlight) and a light matte finish on the other (for the heat-rejecting mode). Dynamic louvers may have insulative value for reducing nighttime heat loss. When beam-
ing sunlight from litria to work areas, use secondary specular reflectors at the work space/titra interface to ensure the sunlight is beamed to an appropriate receiving surface above eye level (see case study B7).

Because litria supply light to adjacent interior work spaces, the interface between work space and litrium deserves special consideration. The interior facades of the litrium can be glazed to isolate it thermally and acoustically from the work space, while still allowing light to enter. If the litrium is to be conditioned, the facades may be left open and unglazed (see case studies B1, B5, and B7). This option is somewhat more energy efficient, as the light loss incurred by the second layer of glass is removed. However, this option may be restricted by fire codes.

With or without glazing, the configuration of the interior sunny wall of the litrium should be designed as an exterior sunny wall: it should be shaded and may have lightshelves. Litria provide a protective environment in which mirrored lightshelves may be used without excessive maintenance. The interior shady facade will receive light reflected from the sunny wall and will benefit from increased atria view and interior lightshelves that reflect light up to the ceiling.

It is reasonable to assume that not all areas of the litrium and surrounding work areas will have the same lighting needs. After general ambient light is provided, local conditions should be attended to. As in atria, litria should use local shading as needed. Fabrics can be used on the interior for this purpose, as can trees and furniture.

Litria and atria almost always contain plants, which should be arranged to work with the sunlighting system. Keep them clear of important light-reflecting surfaces, and use them for shading as needed. This may create a conflict since most plants can be maintained most easily with direct light.

LIGHTWELLS

A lightwell is generally a utilitarian, uninhabited shaft or slot within a building, whose primary purpose is to provide natural light and ventilation to adjacent spaces. As such, lightwells have fewer architectural considerations than the other types of toplit shared spaces.

Architectural Context

Small lightwells can add excitement and relief to the interior of deep buildings. With a relatively small planar area of 25 to 400 square feet, the "event" of a lightwell may be emphasized or remain discreet. Lightwells may have operable glazing opening into them from the work space, or mirrored lightshelves and other sunlighting elements may form an interface between the lightwell and the work space. When lightwells are glazed and uninhabited, maintaining maximum reflectances (specular surfaces) can be easy. A common programmatic use of lightwells is their integration with vertical circulation. When this is the case, glass block or open steel mesh can be used for stair treads and platforms. This will allow deep penetration of ambient light.

The aesthetic benefits of lightwells are somewhat limited. At best,
they offer views of sunlit surfaces that provide some biological information and communication with the outdoors. Lightwells can provide minor communication across their width, via small windows, although they are not noted for this. In many buildings, they are so discreet that they are not visible at all.

**Lighting**

Lightwells can provide sidelight to adjacent spaces and toplight to bottom spaces (figs. 8-36, 8-37). When used only for toplighting, the interiors can be mirrored for maximum reflectance (fig. 8-38). Because of the small size of lightwells, the sunlighting aperture is almost always a full skylight. Tracking mirrors can be used to maximize collection and control of sunlight in narrow apertures and spaces; however, this is rarely cost-effective at this scale. Because of their tall, narrow proportions, glare is unlikely to be a problem.

**HVAC**

Lightwell apertures may be glazed or open to the sky. When open, lightwells can offer ventilation and vertical circulation of building systems. They may also be glazed or open to the work space. When the area between lightwell and work space is glazed, lightwells serve as thermal buffers with no thermal penalty for overlighting.


8-37. New York State Education building: the grand first-floor rotunda ceiling, toplit from lightwell.

8-38. Mirrored lightwells have been proposed for the Canadian National Gallery (Moshe Safdie, Architect) to light the lower galleries.
In chapters 6 and 7, the importance of high ceilings for optimizing the distribution of sunlight was explained, and the forms and devices that can be used in conjunction with higher ceilings were presented. However, relatively low ceilings (8'–8'6" or, on occasion, 9') are what one generally associates with those buildings that could most benefit from optimum sunlighting—office buildings.

Why are these ceiling heights typical? Low ceilings have become the norm because they are easy to design. No coordination of building systems is required when four to six feet of building height are used between the ceiling and the floor above. A flat low ceiling does make partitioning simple and economical, and high ceilings are not so important if daylight is not being used and illumination is from closely spaced recessed fluorescent fixtures.

However desirable they are for sunlighting, can owners afford higher ceilings? I believe they can not only afford them on a cost-in-use basis, but that they can be had with no increase in first cost or in total building height. Essentially, there are two ways to achieve higher ceilings:

1. add to floor-to-floor height;
2. make more efficient use of building volume (ceiling space).

The first way (adding to the floor-to-floor height) is costly and therefore is rarely used for general building types. Floor-to-floor heights are usually minimized to reduce construction costs or to increase the rentable space within the allowable building volume.

The second way of achieving high ceilings requires that all building systems be designed to meet the goals of efficient space utilization. If building system designs are integrated, most of each floor can have 11' to 12' ceilings with no increase in floor-to-floor height over a conventional building. In some cases it is possible to actually reduce floor-to-floor height simply through more efficient integration of systems.

Most contemporary air-conditioned buildings are very wasteful of building volume. Look at a typical building just before the acoustic ceiling tile is installed; you will find that the low ceiling height was established by the combined depth of the deepest duct, beam depth, and recessed lighting, even though the major ducts actually occupy very little area (less
than 5 percent) of the ceiling area (fig. 9-1). In such homogenized designs (fig. 9-2), each system—structural, mechanical, lighting, and ceiling—is given its own layer so that designers need not bother to coordinate their placement. The result is a waste of valuable ceiling height. A building with a floor-to-floor height of 14' typically devotes 5' to the above systems.

Two undeniable benefits of this wasted volume are flexibility in placing partitions against the flat ceiling and almost unlimited freedom to move services within the ceiling due to the great redundancy of volume. By physically integrating the concerns of the primary structural and HVAC systems (and, to a lesser degree, partitioning, secondary structure, acoustics, plumbing, and so on), spatial efficiency can frequently be increased even with flat ceilings and no sacrifice in flexibility. Integrated systems with exposed structures can achieve the ultimate spatial efficiency. I believe that their beauty and operating economy outweigh any associated loss in flexibility.

This chapter will discuss how to achieve articulation and harmonious ordering of the various building systems and how these principles can help achieve the goals of sunlighting.

While the following principles and techniques are economically indispensable in sunlit buildings, most other buildings can benefit as well.

**OBJECTIVES AND BENEFITS OF INTEGRATING BUILDING SYSTEMS FOR SUNLIGHTING**

**Maximum Ceiling Height**

As previously explained, high ceilings improve the distribution of reflected sunlight and indirect supplementary electric light, as well as allowing for high windows.

**High-reflectance Ceiling Cavity**

High reflectance means maximum lighting efficiency. It is easier to ensure high-reflectance finishes throughout ceiling cavities when they are distinctly articulated from other surfaces. Natural architectural breaklines (e.g., from deep exposed structures) can help ensure achievement of the desired finishes in the coffer regardless of the finishes (fig. 9-3).
Integration of Sunlighting Elements

This is the primary opportunity to integrate sunlighting elements into the architectural form. In addition to allowing high ceilings, integrated structural and HVAC systems can provide physical support for large sunlighting elements such as lightshelves, vertical fins, and suncatcher baffles and help achieve visual cohesiveness, so that these devices appear to be a natural part of the architecture instead of tacked-on devices.

Structure as Shading

Exposed structures can become an integral part of a building’s total shading pattern. Columns can provide vertical baffling; girders can be used for lightshelves (fig. 9-4).

Integration of Electric Lighting

Supplementary electric lighting elements can be integrated, aligned, and supported by making them a part of the architecture, illuminating the same surfaces as the sunlight.

In addition to the above, there are numerous distinct architectural and perceptual benefits to articulated/integrated designs. High ceilings give visual spaciousness and less constriction and claustrophobia in large spaces. Perception of structure is reassuring, and delegation of services to certain areas can improve service access for maintenance. Architectural diversity and interest is encouraged, and options are created by the addition of elements and lines.

To achieve these objectives, we have to work with the following systems (usually covered up with ceiling tile):

- Primary structure—girders, beams;
- Secondary structure—slabs, joists;
- HVAC—main ducts, feeder ducts, VAV boxes, flex ducts, pneumatic lines, hot and cold water piping;
- Electrical—lighting fixtures, conduits;
- Plumbing—sprinkler piping, roof leaders, sanitary piping, etc.

The degree to which these systems can be integrated is often dependent on the amount of design (actual or conceived) that has occurred prior to the establishment of effective sunlighting or high ceilings as a design goal.

**First Strategy** (if general design of building is set)

This strategy involves no change to the structural system but requires more efficient organization of elements below the structural plane. The controlling element, HVAC ducts (the largest, most challenging system to integrate), should be concentrated in areas less critical to sunlighting performance.
HVAC Treatments (with no change to structure)

The discussion of HVAC systems is limited to those that have centralized air handlers and a network of ducts. Other systems, such as a four-pipe system with fan coil units, take up much less space, although placement of the equipment should be coordinated with the needs of sun lighting.

HVAC elements can be organized in two general ways: the most common is a radial pattern in which the perimeter is served by ducts emanating from the core (fig. 9-5). The second pattern consists of two or more "loops" connected by several radial "spokes" (fig. 9-6). With either method, ducts running out to the perimeter (perpendicular to windows) are best placed parallel to the primary structure. Ducts that must run perpendicular to the structure should be smaller and carefully placed to minimize the combined depth. The largest ducts should be routed between beams; duct size should be reduced before rather than after crossing the deepest structural members. Ducts and recessed lights should be planned so that they do not overlap. In many buildings, these steps alone can serve to increase the height of flat ceilings.

Ceiling heights can be articulated in the following ways to provide high ceilings where desired and lowered ceilings for services, where needed:

- □ Raise ceiling at perimeter (fig. 9-7). Relocate ducts if necessary to increase the width of the raised perimeter zone. Keep large ducts in the interior;
- □ Use separate ducts for interior and perimeter zones (fig. 9-8);
- □ Create false beams to enclose ducts in order to maximize the high ceiling area (i.e., to feed the perimeter zone).

Ducts can be moved out of the ceiling plenum to decrease the thickness of the ceiling sandwich:

- □ Float ducts in space and expose them with minimum blocking of light (see case study B4);
- □ Combine ducts with lightshelves to help glare control and light distribution (fig. 9-9 and case studies B2 and B5).
**Lighting Treatments**

Interior building surfaces can be streamlined for maximum effective reflectances:

- Enclose highly articulated ceiling structures (waffle slabs, exposed joists) to minimize trapped light;
- Avoid recessed fixtures where they would cause ceilings to be lower; use indirect lighting mounted lower in the space. Also consider surface-mounted or pendant fixtures and local task lighting.

**Other Systems**

Other systems should be located in such a way as to minimize interference with sunlighting:

- As with HVAC, concentrate placement of plumbing, sound systems, and the like in areas less critical for sunlighting performance; avoid excessive system depths.

**SECOND STRATEGY (if design can be integrated from the beginning)**

A structural system should be selected and developed that is totally integrated and articulated. This is the most effective strategy, allowing the underside of the floor slab above to be the ceiling.

When selecting a structural system, the building program is a primary consideration; for example, the large spans in a gymnasium will necessitate a different system from that required for fully partitioned offices or classrooms. The physical requirements of proposed types of mechanical and electrical systems must be allowed for, and the *net perceived ceiling height* should be considered (i.e., a 12' ceiling may feel like an 8' ceiling if a network of pipes and ducts exists at the 8' level).

Some structural systems that favor integration and articulation are listed here and described in detail below.

For unilateral and bilateral sidelighting:

- Flat slabs
- Deep exposed concrete beams
- Paired beams
- Boxed steel framing, trusses
- Two-level structures

For multilateral sidelighting:

- Flat slabs
- Modified slabs
Haunched beams
Steel framing with haunched beams
For toplighting:
Concrete "tree systems"
Large-scale channeled concrete structures
Boxed steel structures

STRUCTURAL SYSTEMS FOR UNILATERAL OR BILATERAL SIDELIGHTING

When a space is sidelit from two opposing sides, the most important requirement is that the primary structural system run perpendicular to the primary window wall(s). This will ensure the greatest daylight penetration. One-way structures are perfectly suited for the requirements of bilateral sidelighting.

Concrete Slab Systems

Flat Slabs
For short spans, flat slabs are the thinnest system. When the primary structure is a flat slab, there is freedom to locate services, but a suspended ceiling is still necessary unless all services can be exposed or services can be organized and boxed into lowered soffits or false beams. Use the thinnest flat slab possible to leave the most space available for services. Flat slabs can be combined very successfully with paired beams to channel services.

Waffle Slabs
Waffle slabs should be avoided. They require depth but do not allow horizontal services to penetrate. Waffles are very good at trapping light because of their extensive surface area (fig. 9–10).

One-way Joists, Ribbed Slabs, Pan Joists
The structural benefit of one-way joists, ribbed slabs, and pan joists is a somewhat reduced weight for increased spans. Some services can be contained within them, they are thicker than flat slabs, and their additional surface areas trap light (although somewhat less than do waffle slabs). Pan joists are somewhat better for lighting than waffle slabs and may be adequate for enclosing local services (fig. 9–11). Minimize shadows by running ribs perpendicular to fenestration.

Deep Exposed Concrete Beams

Beams must run perpendicular to the primary windows for reasonable light penetration.
Consideration should be given to the perception of space created
when placing beams. Wide beam spacing gives a more open feel than close beam spacing (fig. 9-12). Widely spaced beams (even if much deeper than smaller, closely spaced beams) do not reduce the effective ceiling height and relate better to human scale, but are worse for hiding services.

The spacing of beams is critical to their effect on sunlighting. Widely spaced beams trap less light and are better for light distribution than closely spaced beams, which are inefficient in reflecting light. To distribute light effectively from a lightshelf, beam spacing should be no less than $\frac{1}{2}$ to $\frac{3}{2}$ of the maximum seating distance from the window (fig. 9-13). Closely spaced beams will trap more light.

There are also advantages to increasing the depth of widely spaced beams. Deep exposed beams at maximum spacing oriented perpendicular to windows channel light into a space (case studies B1, B7). In the interior of a building (distant from windows), widely spaced beams are likely to receive more light than the adjacent ceiling because light from continuous windows will strike the beams at a less oblique angle. As important potential reflecting surfaces, such beams should be light in color. Light-colored deep beams will modulate light and improve brightness and illumination gradients. Deep beams can frame large clerestories and provide vertical louvering for them, minimizing sky glare. They can also be cantilevered to support lightshelves at the correct height (case studies B5, B7). Deep beams provide an opportunity for inconspicuously and economically integrating supplementary indirect electric lighting elements at the maximum distance from the ceiling, allowing for good light distribution. Beams may be made (or appear to be made) deeper than structurally necessary to achieve the above advantages. This may be particularly important in conjunction with the relatively shallow cross sections of steel constructions (fig. 9-14).

**Paired Beams**

A structural system of paired beams is proving to be one of the best systems for sunlighting. The unequal spacing provides regular channels to enclose ducts and other services and leaves the wider space 'clean' for distributing and controlling light. Paired beams can therefore have higher effective ceilings than smaller, more closely spaced beams (fig. 9-15). The combination of paired beams and lightshelf-as-duct can allow the ceiling height to be virtually floor-to-floor (case study B5). The beam spacing module must be developed to accommodate the programmed space requirements. For example, a school's structure must be easily partitioned for standard-sized classrooms. To increase the depth of the ser-
vice channel and create a larger natural clerestory, paired beams may also be oversized. Although making beams deeper than necessary will add to the structural cost, the total building cost may be lower because of reduced partitioning cost and simplification of other details such as support of lightshelves, better alignment or window framing, and so forth.

**Boxed Steel Framing**

**Beams**

Speed of erection, the need for thermal breaks, cost, or other reasons may make a frame of steel beams advantageous. In this case, the spatial and light distribution of deep exposed concrete beams and the service enclosure features of paired structures can be combined by boxing in the beams with fireproofing much larger than otherwise necessary to create false "deep beams" with sufficient clear space for the mechanical and electrical services (case studies B1, H1).

**Trusses**

If trusses are dictated by longer spans or economics, they too can be enclosed to contain services neatly and make deep one-way channels good for unilateral and bilateral sidelighting or for effective and efficient top-lighting (case study D2). If the desired finished form is triangular, delta trusses may be the best choice because their lateral stability eliminates the need for cross bracing and provides the most unobstructed service channels.

**Two-level Structures**

For very large unimpeded blocks of bilateral sidelighted space, two-level structural systems may be the most logical. In such cases, the major structure of widely spaced deep beams can run perpendicular to the window walls, and a secondary structure can be placed on top to create a plane of continuous service channels connecting vertical service cores at the ends of the building. This secondary structure could be of steel beams and decking or concrete double ‘T’ s (case studies B1, B7).

**STRUCTURAL SYSTEMS FOR MULTILATERAL SIDELIGHTING**

For multilateral sidelighting, where windows on at least two sides are perpendicular to each other, flat ceilings are the only practical solution. If exposed beams run parallel to the windows, sunlight will be limited to the perimeter. Articulated systems are only acceptable for small buildings...
where most of the floor area is effectively perimeter. For larger buildings, the best solution is to use a flat ceiling and attempt to limit the thickness of the ceiling sandwich as much as possible. The best structural systems are modified two-way systems or columnar type systems. Two-level structural systems are not useful for achieving flat ceilings with minimal building volume.

**Flat Slab**

The ideal multilateral sidelighting system is a thin flat slab, with the largest ducts and services located in areas less critical for sunlighting. However, unless spans are very small, slabs cannot remain very thin, as they will not be strong enough to span large distances. (fig. 9-16).

![Diagram of Flat Slab](image)

**Modified Slabs**

Larger spans can be achieved by using slabs of varying thickness. Dropping the column caps and thickening the slab at those points will allow the slab to be thinner in the middle. The thinner slab areas are used to run the ducts and other major services to minimize the thickness of the ceiling sandwich. A suspended ceiling can then be used to reduce surface area and improve acoustics (fig. 9-17).

![Diagram of Modified Slabs](image)

**Haunched Beams**

For larger spans or greater earthquake resistance, use haunched concrete beams instead of dropped column caps to allow for duct space with minimum average ceiling depth (see fig. 9-18 and case study B3).

**Steel Framing with Haunched Beams**

Even though a structure of steel beams can be shallower than one of concrete beams, the most efficient use of building volume would be to use the haunched beam principle suggested above for concrete. According to structural engineer William LeMensurier, such structures are most
efficient in the use of steel because the material is placed where most needed. However, the extra fabrication cost over standard beam systems probably cannot be justified unless the cost of wasted volume would be very high (as in buildings with many floors).

**STRUCTURAL SYSTEMS FOR TOPLIGHTING**

**Concrete Tree Systems**

"Tree" systems are integrated building systems with great potential for toplighting vast areas with great flexibility in planning. As independent cantilevered structures related to Frank Lloyd Wright's "mushrooms" in the Johnson Wax building and Felix Candella's "umbrellas," modules can be omitted to form courtyards or irregular edges, or individual units may be at different heights.

However, unlike the "mushrooms," tree structures contain coffers for integral indirect lighting or for skylights and are created to edge services placed between them neatly, in totally unimpeded open channels that can run in both directions. These functions are achieved by having "branches" radiating from the "trunk" to support perimeter edge beams. With such a structure, the panels filling the tops of the coffers can be omitted or pierced at any time for toplighting, and continuous clerestories or skylights can be placed between trees whenever the entire gap is not needed for mechanical ducts. In either case, the beams provide beneficial baffling. Great unity can be given to a project by the structural consistency of being able to use the same coffer form for indirect artificial lighting, daylighting, or a combination of the two, and by having unimpeded and neatly enclosed service channels in between or around every tree (figs. 9-19, 9-20).

![9-19. Systems can be routed between structural "trees."](image)

![9-20. The slabs of "tree" structures may be pierced at any point for toplighting apertures. (Governor State University, Park Forest, Illinois—Caudill, Rowlett and Scott, Design Architect).](image)
Large-scale Channeled Concrete Structures

Other large-scale channeled concrete two-way structures can be flexible in routing services, but they are generally not as good as tree systems because the continuous clear spaces are likely to be limited. They are, however, more rigid. Similar to “trees,” large-scale channeled concrete structures are better for toplighting than for sidelighting (fig. 9–21).

Boxed Steel Structures

Steel systems should follow the same rules of direction and spacing as outlined for concrete structures. Because of the greater strength of steel, there is more flexibility in the sizes and shapes of the structural members used. Steel structures should be enclosed to maximize the desired light distribution characteristics (case study D2). Beams that must be fireproofed may be boxed in to increase their depth and hide services as well (case studies B1, H1). Long-span delta (triangular) trusses may be a good way to frame sunscoops when the lighting design suggests a triangular shape (figure 9–22). Boxed steel structures are easily insulated (a significant advantage over concrete), and provisions can easily be made for thermal breaks.

Secondary Structure

Secondary structures spanning major beams and girders are likely to be closely spaced. They may be steel beams or bar joists supporting steel decking or concrete slab, or they may combine beams and slabs in the form of single or double “T’s” (fig. 9–23). Whether or not the secondary structures are used to enclose HVAC ducts or other services, they should be covered by ceilings to achieve efficient sunlighting or indirect artificial lighting. Minimizing the surface area maximizes the effective reflectance (see fig. 3–16).

Hollow-cored Slabs

Cored slabs (poured in place or precast planks) can span significant distances inexpensively. It is possible to run some limited services (such as wiring) through the cores one way; however, this is generally impractical as access is difficult (fig. 9–24). The bottom of precast plank may be an attractive high-reflectance finished ceiling. Because of their limited
value for enclosing services, hollow slabs are logical only in building types with a limited need for these secondary service channels (i.e., houses, schools with through-the-wall air conditioning—see case study C1) or in more demanding buildings in which the plumbing, ducts, and other larger and more accessible requirements are accommodated within the primary structure via double beams, boxed steel beams, or within floating elements such as hollow lightshelves (case study B2).

In summary, building systems should:

- Control light distribution and glare;
- Enclose ducts and other HVAC equipment with a minimum of wasted volume;
- Integrate lightshelves, other sunlighting devices, and supplementary lighting elegantly.

Such integrated building systems cannot be achieved by the usual sequential design processes but require a team process in which all disciplines are involved with the project simultaneously and from the beginning.

**SUPPLEMENTARY ELECTRIC LIGHTING SYSTEMS**

Artificial lighting should be designed to supplement daylight selectively—to maintain a moderate level and distribution of ambient light that will dispel gloom and provide for the range of ordinary activities. Ceilings and other large areas of room surfaces can be illuminated so as to flatten out the normally uneven daylight gradients on these surfaces (figs. 9-25, 9-26). This will also improve indoor/outdoor contrasts. Indirect lighting minimizes the contrast and color difference between daylight and electric light. Downlighting does not help in this respect (figs. 9-27, 9-28).

Lighting hardware and the brightness patterns it generates should be designed to harmonize with the architectural forms and sunlight patterns of a given condition (fig. 9-29). Supplementary illumination should

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9-25. Indirect lighting fixtures on beams do not interrupt spaces; they provide brightness gradients that blend well with reflected sunlight because they illuminate both beam and ceiling.


9-27. Direct lighting along beam illuminates only the beam, not the ceiling.
continuously fill in illumination gradients, following the "fit" of the sunlighting curves. For example, a bilaterally illuminated space produces a characteristic "saddle-shaped" sunlight distribution curve; supplementary illumination should therefore be greatest in the middle of the space and more moderate toward the perimeter (fig. 9-30). Similarly, sun-scoops, skylights, and other apertures will all have distinct sunlight distribution curves for a given configuration and should be supplemented accordingly.

Locally controlled "task lighting" can be provided for special tasks for which the ambient light is insufficient or inappropriate. Such task lighting can be in the form of ceiling-mounted spots, pendant lamps, table lamps, and under-the-shelf fixtures.

Integrating lightcoves with the structure almost guarantees a high-reflectance ceiling cavity by making the beams an integral part of the lighting coffer. Fixtures should be contained in the beams or lightshelves if possible (or attached to or aligned with them). Electrically illuminating the same surfaces as the sunlight illuminates is the simplest solution visually speaking. When using the ceiling as a source of indirect illumination, it is important to use high-quality ceiling materials and careful detailing. For example, matte-finish T-bar joints are discreet when illuminated, but gloss-finish T-bar joints are glaring and distracting. Integration of electric lighting fixtures with beams and lightshelves should follow the alignment of the header/transom lines.

**SUPPLEMENTARY LIGHTING CONTROL SYSTEMS**

**Interface between User and System**

Electric lighting control systems provide the economic and energy savings in sunlighting designs. The amount of savings increases as more ambient light is provided by natural means and a similar quantity of electric light is displaced. Depending on the given condition, energy controls can be either manual or automatic.
In small buildings, or buildings where a maintenance staff (or persons with a vested interest) can be depended on to operate them, manual controls can be adequate. Controls should be provided that encourage use by providing switching for lighting in small areas, with switches located to discourage thoughtless use. User adjustment of sun-control devices (opening drapes, shades) can be "forced" by providing photoelectric controls that do not allow supplemental ambient lighting when adequate daylight is available.

Automatic controls can adjust sun-control devices as well as supplementary electric lighting. Sun-blocking devices (shades, movable insulation) and dynamic sun-directing devices can be controlled by simple time clocks or by photosensitive relays. So-called smart buildings can provide total energy management systems, which, controlled by a central computer, can start HVAC systems just prior to the advent of the working day, control electric lights based on occupancy and exterior conditions, and monitor security as well.

In most daylit office buildings, our primary concern is to coordinate the quantity of interior supplemental illumination with the amount of illumination provided by sunlight. This can be accomplished easily with a combination of photosensors to measure the quantity of sunlight, a microprocessor-based "logic" unit (which can be programmed to know how much natural light should be present in each area in relation to the exterior sensors), and a switching/dimming system to control the electric lights accordingly. Such systems should provide for some user control by providing a manual override for switching small areas.

**Location of Light Fixtures**

As previously explained, supplemental electric lights should be an integral architectural element, their location conforming to the forms and needs of the building. Generally, fixtures nearest the sunlighting apertures will be required the least; in sidelighting, for example, this implies that the perimeter lighting will be switched off first, and the center lighting last. This can be accomplished with fixtures running either parallel or perpendicular to the windows, as long as the switching arrangement is consistent with the predominant light gradient (fig. 9-31).

**Location of Sensors**

If the building is of an extruded nature, the spaces are open, or the partitioning is regular and the occupancy uniform, sensors can be located
on the interior to measure illumination and switch or dim lights in large areas when the illumination exceeds a certain level. Illumination should be measured from a surface of interest (such as a desk top) and be consistent with the needs for that area as delineated in chapter 2. If partitioning or occupancy is very irregular, switching and dimming should be in small areas.

Sensors can also be located in a scale model of the space, mounted on the exterior of the model building. This is a very reasonable approach to take if there are many different facade conditions or if the space is particularly complex. (See case study B3.)

**Dimming and Switching Systems**

Switching is the least expensive lighting control system and can provide a large savings in energy use if properly used. Switching also produces the most noticeable changes in illumination (“lighting discontinuity”), which can be distracting for the occupants. If the switch occurs only once or twice a day, however, switching may be the best option (fig. 9-32).

With the natural fluctuations of sunlight, the quality and distribution of daylight in the room allows the light levels to drop below the established level for short periods of time without being noticed.

Dimming achieves the most graceful blending of artificial and natural light and can be virtually unnoticeable in use. Savings are generally more than with switching because they occur over a wide range, providing a more even overall lighting of the space. Dimmers consume some energy even when the lights are effectively “dimmed off.” In addition, some lamp manufacturers will not guarantee their lamp if on a dimmer circuit. Unfortunately, most dimmers do not operate over the full range of light levels but switch on at the 50 percent light level. Improvements in dimming equipment and the eventual reduction in prices will probably make dimming systems more universal.

Dimming can be combined with switching for maximum energy savings and graceful transitions from artificial to natural illumination. This system is more expensive initially than either switching or dimming alone; however, it is a tiny part of an overall building budget and should provide a quick payback.

Don Aitken determined that dimming systems were cost-effective to a 50 percent dimming level and provided a three-year payback in retrofits for lighting energy saved. This payback period decreased to one year when cooling load savings were included. In a study for the Denver Tech Center (case study B6), the simple payback for the proposed dimming system (integrated with sunlighting and reduced installed cooling equipment) was determined to be thirteen months for the lighting cost alone, had the proposal been realized.

**UTILITY LOAD MANAGEMENT**

The final opportunity for integrating building lighting systems occurs beyond the walls of the building—within the surrounding buildings, community, and utilities. In large buildings where the peak load is for summer
cooling, utility peak-load-demand switching can provide substantial savings for both the building and the utility. When the utility experiences peak load demand for the entire system (usually on summer afternoons), the building receives a ripple signal from the utility, which switches off the perimeter lighting. This reduction in peak demand means that the utility does not have to invest in expensive new reserve power plants, and the building will avoid paying for the most expensive peak energy price (see chapter 1).

In sunlit buildings, however they are controlled at other times, perimeter lights should be turned off during peak utility load times—on sunny summer afternoons.
Sunlighting Design Processes and Tools

Previous chapters have introduced the basic principles and forms of sunlighting. The case study section of the book will describe some actual buildings and their sunlighting features. This chapter examines the processes and tools that my firm and its clients have used to develop and test these forms.

THE TEAM DESIGN PROCESS AND SUNLIGHTING

The idea of design by team is not new. As William Caudill discusses in his book Architecture By Team, his firm (Caudill Rowlett Scott) began to talk about and refine the team design process in the early 50s (fig. 10-1). Their concept of the “squatters’” brings the important people—client, architect, and other specialists—together in one place to design the building as a team in a few days. The benefit of the “squatters’” process for any building is that it helps the architect and the client clarify at an early stage the values the project should exemplify. Because key representatives of the client are involved in the design process, the design that results becomes “our” design (as opposed to “the architect’s” design). This often turns the clients into advocates for the design.

In chapter 9 integrated building systems were discussed. It should be clear that their level of complexity demands a team design process from the beginning. When designing sophisticated buildings with the kind of multiple, simultaneous goals discussed in chapter 1, the value of a team process becomes self-evident.

Using sunlighting adds another layer of complexity to the building’s design. Not only must a building fulfill the client’s needs; it must also respond to the variability of the sun’s changing direction and intensity. People’s reactions to the sun are also variable, according to the context. The decision to use sunlighting as a design strategy has an impact on, and must be followed through on, many levels. The sun affects the orientation and massing of the building on the site. Using sidelighting demands the high ceilings that integrated systems can provide. It is difficult to integrate structural and mechanical systems to achieve the high ceilings needed for indirect lighting economically; incorporating sunlighting makes it even more difficult. The direction of structure relative to the fenestra-
tion thus becomes a major factor. The type of interior partitioning can aid or compromise sunlighting.

Follow-up on the final details of a project is essential—I have seen many designs fall short of their potential because the reflecting surfaces of lightshelves were never painted white or white gravel was not used on the roof surrounding a sunscoop. Sunlighting cannot be just the domain of another specialist—its values must be shared by all members of the team: they must want to create “our” sunlit building. It is ideal when members of the team can evaluate existing buildings together. It is well worth the expense, because it will develop common objectives and make it less likely that they will be unwittingly compromised later in the process.

SUNLIGHTING TOOLS

Sunlighting designs are site specific. They must respond to the context, both of the exterior site and of the interior program.

While the context and the principles outlined in this book may suggest sunlighting solutions, it is necessary to develop and evaluate solutions specific to the building being designed. The information provided here and your own further modeling of generic concepts will provide the basis for developing specific designs. Quick thumbnail diagrams based on sun angles derived from consulting Graphic Standards or using the L.O.F. sun angle calculator (available from Libby, Owens, Ford Company) will help you to understand the geometries involved. Examples of diagramming light have been given in chapter 3 and throughout this book. Using scale models is the best way to evaluate the designs that are developed.

Remember that the tool you choose should be appropriate to the task at hand. For the conceptual design phase, design tools need to be quick and interactive in order to allow the evaluation of alternatives without a great investment of time or effort. They can be quite crude; you need only information that is accurate enough to allow rational choices between alternatives. If we know that option A will produce better daylighting than option B, we need not, at the conceptual design stage, have very accurate values for either. In some cases, the important information is not really quantifiable at all, but is qualitative or perceptual. During the concept refinement phase, more accurate information may be needed, and more investment of time and effort is justified in evaluating the chosen concept. For the presentation phase, the client needs to be convinced of the effectiveness and success of the design. Since this success is often measured both quantitatively (in illumination gradients, KWH, or dollars) and qualitatively, a combination of tools may be required both to develop accurate quantitative projections and to express the qualities of the environment designed.

Programming

Once the actual process of design begins, the programming stage is obviously critical. Specific details about the use of each space or class of spaces will help determine their shape and detailing. As discussed in
chapter 2, a descriptive performance criterion for lighting is much more useful than numerical footcandle specifications. Such a process can be extremely tedious and time-consuming. However, the exercise of having gone through such a systematic, detailed conceptualization process once is invaluable. An experienced designer goes through such a process almost unconsciously in the design of every space and is able to sum up occupants’ activities, their biological needs, and the respective environmental implications in simple summary statements of objectives and design concepts.

**Site Analysis**

After the project’s program has been well defined, the actual design can begin with the evaluation of the site and the exploration of architectural options. As many of the largest decisions in terms of overall form are set by the combination of program, site, and climate, this is the context within which the integration of building and comfort objectives must be considered. Site evaluation should include an analysis of microclimate and solar access. In the case of a building that is intended to rely on the sun and the sky for some of its light or heat, it is important to determine the shading on the site from surrounding buildings, vegetation, and terrain. A 360-degree map of the site horizon as seen from points of interest in the proposed building is needed. This can later be used in section studies, model testing, or overlays on sun path charts. While this information can be obtained with a compass and transit or Abney level, a device such as the one illustrated greatly simplifies mapping the local horizon and shading (fig. 10-2).

**Concept Diagrams**

After the relevant site characteristics have been noted, the conceptual design phase can begin with the integration of building and comfort objectives in the context of program, site, and climate. At this phase the directional nature of sunlight makes architectural section drawings an appropriate method of studying sunlighting designs. Buildings of a simple extruded nature can often be adequately explored by a single typical section (fig. 10-3). More complex geometries require multiple sections, plans, models, and so forth.

Plotting sun angles in section studies can evaluate the needs and suitability of sun control and redirection strategies. By diagramming light (chapter 3) it is possible to draw the intended effects of a given architecture and then adjust the architecture to produce the desired lighting condition. Since any window view is a potential source of glare, it is necessary to plot the actual sun angles for a given condition to find out if a problem exists. The sun angles relevant to a given situation can be ascertained quickly using a L.O.F. sun angle calculator or similar device.

**Scale Models**

It may seem surprising to advocate the use of physical models for testing in an age when we have come to rely with confidence on mathematical models in many fields. In the case of daylighting, however, much
or most of the lighting calculation data base was in fact derived from
model studies, and these were of a limited number of conditions, some
not realistic. Obviously, the most relevant model study is of the proposed
design itself rather than an extrapolation from other studies.

Due to the extremely short wavelength and high speed of visible
light, there is virtually no scale factor for lighting in scale models. This
means that in a scale model constructed with reasonable accuracy and
with representative glass transmission and surface reflectances, mea-
sured light levels from daylight will be identical to those in the real build-
ing modeled, given identical exterior illumination. In addition, by tilting
the model, sun angles representative of a variety of latitudes and times
of day may be simulated.

Both qualitative observations and quantitative measurements may be
made from models. Since controlling the sun is the key to design studies,
they should be conducted outdoors in natural light conditions. Artificial
skies give a false sense of security in that they are steady and easily con-
trolled, but they do not simulate the sun and sky accurately, if at all.
Constantly varying light conditions make outdoor testing more difficult,
but the benefits are worthwhile. The evaluation is much more realistic
because of the similar variations in real buildings. Lighting differences
that are hard to observe in a model will be equally difficult to observe in
a building. The educational experience of doing real sky testing only once
should create an indelible recognition of this phenomenon.

Making the Model

Crude "generic" models are useful to increase the base of understanding
and experience for both experienced designers and students. They are
also an effective quick way of evaluating alternatives during the concep-
tual design phase. They should be constructed out of sturdy and forgiving
materials (such as homosote) to allow and encourage easy testing of
alternatives (fig. 10-4). The geometries and surface reflectances should be
approximately correct. I cannot overemphasize how important the re-
reflectances are.

The typical white foamboard model makes any lighting arrangement
seem reasonably even—a false impression unless the room will actually
be all white. As with all sunlighting models, generic models should be
light tight. Particularly with window areas that are small in relation to the
floor area, small pinholes or cracks, or even the translucency of "solid"
materials, can affect the results of testing. Light leaks will tend to even
out illumination levels and obscure places where the variation in light
levels within a space might prove objectionable.

Design models are the mainstay of the design evaluation, refine-
ment, and illumination estimation processes (fig. 10-5). Accuracy is now
of primary importance in modeling window size and mullions, in rep-
resenting exterior reflecting surfaces and interior reflectances, in details,
and in the massing of interior furnishings. Certain aspects of the model
may be made interchangeable to test the effects of different facade de-
signs, clerestory shapes, or the qualities of a sloped lightshef. To re-
terate: if a design model is accurately constructed and tested, the normalized model
illuminance measurements will correspond accurately to those in the final
building.
The following is a helpful checklist for model construction:

- **Reflectances** of surface finishes should be modeled accurately to ensure representative appearance and data. Color need not be accurate except for presentation purposes. Specularity of a surface (i.e., the degree to which it is specular or diffuse) is also important.

- **Materials** used to make solid portions of the model must not be translucent to any degree nor have any light leaks. Some common materials such as foam board and thin cardboard transmit light and must be covered or painted to be opaque.

- **Openings** must represent the actual glazing area and position to be used. Ideally, a plastic glazing with equivalent light transmitting and reflecting characteristics should be used in a model. As a practical compromise, openings in the model may be left unglazed and a glazing transmission factor may be applied to the data afterwards.

- **Scale** of the model should be as large as convenient for handling, such as $\frac{1}{2}'' = 1'0''$ for large spaces or $1'' = 1'0''$ for small spaces. This will permit control devices such as louvers to be modeled accurately and facilitate the use of meters and cameras in the model.

- Provide **access and viewing ports** for meters and cameras. A lightproof hood or dark cloth is necessary during viewing for measurements or photography.

- **Scale furnishings** should be included in the more finished models to gauge their effect on illumination and glare control. They also enhance the model's appearance, giving scale and realism to the space. Realistic furnishings should make photographs of the model almost indistinguishable from the real space.

- Build the model strong enough to withstand moving, tilting, wind, and moisture.

**Test Conditions—Orienting the Model**

As explained in chapter 4, the sun's location and intensity vary throughout the day and the seasons. Because the variations are predictable, they can be simulated by tilting the model relative to the sun. Fixing a sundial to the model is the easiest way to determine the degree of tilt necessary (fig. 10–6). It is best to tilt the model no more than necessary; it is better to time the tests to take advantage of natural changes in the sun's altitude throughout the day. When a model is very large (as it was for TVA—case study B7 and GSIS—case study B3) it may also be impractical to tilt the model very much.

Comparisons of alternate designs will be most accurate if the geometric adjustments are minimal. For instance, if a model needs to be tilted only a few degrees to attain the desired sun angle, changes in the horizon characteristics will be less. Fortunately, when testing designs that utilize sunlight effectively, the contribution from direct sunlight is so dominant.
that errors from inaccurate simulation of the rest of the ground and sky are minimal. Thus, if the time available is short, we can tilt the model as much as necessary instead of waiting for the ideal conditions under which little tilting is needed.

Variations in the sun’s expected intensity relative to its intensity during testing conditions must be adjusted or “normalized” mathematically. (For example, if you are testing in July with 8,000 footcandles and the condition you are simulating is a December morning with 3,000 footcandles, the measurements must be multiplied by 3/8). If the actual glazing was omitted from the model, a glazing factor must be applied. A maintenance factor is applied to reflect loss in transmission due to dirty windows or atmosphere.

Ideally, tests and observations of the model should be conducted under totally clear and totally overcast skies, as these are the extreme conditions. At those times the illumination is likely to be very stable and the adjustments easier. Observing the model under partly cloudy skies is also useful to get a more complete understanding of real-world conditions, with the widely varying illumination that one normally does not even notice.

**Observing and Testing the Model**

When the model is properly constructed and oriented, both qualitative observations and judgments and quantitative measurement can occur.

**Qualitative Observations.** Qualitative judgments are important. It is necessary to “put oneself inside the model” as much as possible. View and photograph through viewing ports, using blackout cloth to prevent extraneous light from entering the model (fig. 10-7). Careful observations may suggest alternative schemes or adjustments to the model that should be made before the laborious process of quantitative testing is begun. Consider if the light distribution is as desired. Are there distracting shadows or dim areas? Evaluate the contrast between the brightness of room surfaces and the window’s brightness. How will artificial lighting be integrated?

Photographing the different schemes and the different seasonal and time-of-day scenarios will facilitate direct comparison. A wide-angle lens (e.g., 20 mm) is essential for photographing the model. It is very useful to place a legend describing the sky condition, time of year, and time of day within view on the model; otherwise, trying to reconstruct which slide represents which condition can be quite an experience. The inclusion of scale figurines and furnishings will help make your model indistinguishable from the actual building (see figs. B4-9, B4-10, D2-7, D2-8). Although the model itself is not constructed specifically for presentation, photographs of a sunlit design model can be a powerful presentation tool. Slides of the model may bring the concept alive in a way that drawings and sketches do not, particularly for laymen unaccustomed to visualizing in three dimensions. Visualizing the impact of light gradients is difficult even for most designers.

Model photographs are more useful for presenting design alternatives than viewing of the model itself. While viewing the model can create interest and excitement, problems of logistics and timing make comparative viewing and discussion of alternative designs under varying condi-
tions almost impossible. With a photograph, everyone can be looking at and discussing exactly the same scene.

Quantitative Testing. Quantitative testing of the model is useful for several reasons. While we do not believe that single-number footcandle requirements are the criterion to describe what we like in a space, numerical measurements facilitate comparison of different schemes and evaluation of their respective economic impact. For one thing, mathematics is the only practical way to compensate for differences in the sun’s intensity during model testing conditions relative to site conditions. Numerical measurements allow comparison of different conditions and of the distribution of light within the space. Careful modeling can be used to predict how much supplementary (electric) lighting will be required and when—sunlighting’s economic impact.

Occasionally, when specific footcandle levels are relevant—as in museums with conservation requirements—model testing is an excellent way to determine if sufficient but not excessive illumination levels can be achieved. Modeling makes it possible to try various forms of dynamic shading and evaluate their impact on light levels (see case study D7).

Instrumentation

While the instrumentation required for quantitative testing and the concepts of adjusting the data are very simple, the practical realities are quite different. The number of steps involved in measuring, recording, adjusting, and presenting the data in a useful format make the process time-consuming and labor intensive. An additional complication is the fact that in most locales, perfectly clear days are quite rare. Even on days that appear perfectly clear to the naked eye, unnoticeable clouds make the sunlight intensity fluctuate rapidly and constantly and thus can multiply the number of measurements necessary to get consistent results.

Nevertheless, although time-consuming and expensive, real sky testing can be accomplished with nothing more than a simple hand-held or remote-reading illumination meter, worksheets, and a programmable calculator. Because I was forced to come up with data quickly on my initial sunlighting design projects, most of the data produced (and presented in the case studies) was gathered in this manner. Fortunately, we had sufficient budgets.

The problem with real sky testing is the fluctuation in sky conditions; for each test the different sensor locations need to be read under identical conditions. In addition to interior readings, you need an exterior reading in order to normalize the data. The exterior readings from before and after each test should be within 10 percent; otherwise, the variation has been too great and the test must be done over. If you have only one sensor, you will need a good system for repositioning it quickly and accurately. We used a stick with markings that slides back and forth in a track in the model (fig. 10-8). If you have a multichannel meter and several sensors, you will not have to move the sensors (fig. 10-9). Even this manual reading of the meter and hand recording of the data is a process infinitely slower than a microprocessor-based system that can read and record the sensors almost simultaneously (fig. 10-10). It is important that the sensors be located at an appropriate site such as horizontal at desk height for offices or vertically at picture location for museums. It is also important that the sensors are color- and cosine-corrected.
Recently, William Lam Associates has made accurate model testing more affordable by creating a portable computerized instrumentation package that will work under the constantly changing light of the real world and rapidly check and normalize the figures, even under partly cloudy conditions. This eliminates many of the inherent advantages of an artificial sky with simulated sunlight, of which there are very few in the world.

Our system is based on a portable microcomputer that automates much of the data-gathering process. The computer takes repeated high-speed scans of the sensors inside and outside the model, averages the interior readings, normalizes the data for the simultaneous exterior conditions, and prints out both the numerical values and a graph of the data, saving all important information for that test on diskette (fig. 10-11). With this system, a single test takes only a few seconds, so that accuracy can be maintained without interference from the variations inherent in real sunlight and other exterior conditions. The immediate availability of results also makes the model an interactive, “what if” design tool. With
this system, the most time-consuming task for the tester is to change design options in the model or to tilt it to obtain the proper bearing and altitude relative to the sun.

Presenting and Interpreting the Data

Some information can be read directly from the raw data, but it is easier to evaluate the significance of the data if it is organized in a format that facilitates easier comparison, such as a graph.

The graph should show levels of illumination at different places in the space. If illumination is graphed versus distance, the design's illumination curve will show the changes in the distribution of light in one dimension. It is helpful to place a scaled section drawing of the model above the data. This immediately indicates the relation of illumination values to the space (fig. 10-12). As explained in chapter 2, the perceived variation in illumination intensities will be more accurately conveyed if footcandle values are plotted on a log scale. The flatness of the curve represents the evenness of distribution of light. This is the most important qualitative characteristic of a lighting design.

With an irregularly shaped plan or a scheme that uses multilateral illumination, it is important to represent the changes in intensity in more than one dimension/axis. In this case, an isolux graph should be drawn over a plan view. This is similar to a survey map; it shows changes in levels through the use of contour lines (fig. 10-13).
In addition to the consistency of distribution, the amount (magnitude) of illumination is also important. Remember that we are most interested in data within the working range of human perception. Therefore, the difference between 1 footcandle and 10 footcandles is very significant, but the difference between 10 and 40 footcandles is barely noticeable. A change from 50 to 200 footcandles is even more insignificant in interior spaces, and measurements above 200 footcandles are generally not relevant for most spaces. The average illumination in a space is a useful number, especially if excessively large numbers are discounted. (Excessively high levels may represent small pool of direct sunlight falling on the sensor or measurements too close to the window, for example.) In qualitative terms, one number that is useful is the average to minimum ratio, because it indicates the perceived differences in brightness within a space.

Data from the model that indicate the average levels achieved by sunlighting is quantitatively important, because it is often necessary to maintain a minimum level of general, “ambient” illumination. If sunlighting is not sufficient, the artificial lighting will be turned on. If we can predict when artificial lighting will be turned on or off, we can quantify one aspect of how sunlighting will save energy. In practice, the nature of control systems and user actions have an equally important (and unpredictable) influence on whether the lights are turned on or off.

For this reason, modeling only provides the basis for a very crude “guesstimate” of lighting energy use. The lighting designer’s guess—“Gee, we think that a fourth of the artificial lights will be switched on half of the time on overcast days”—is then combined with other data (such as weather data and HVAC analysis) in megacomputer programs such as the D.O.E.’s #2, or BLAST to create predictions as to building energy use and operating cost (fig. 10-14).

In some cases it is necessary to calculate the dollar benefits of sunlighting strategies in order to sell their increased initial cost. This was the case with several of the buildings discussed in the case studies. In any case, I believe that it is easier to sell the qualitative benefits of sunlighting, because calculating the economic benefits rests on many complex and “soft” assumptions. This may change over time as more buildings are monitored to see how actual performance compares with the predicted performance.

Mock-ups
The ultimate in modeling is a life-size mock-up. If the complexity of the project justifies it and the design concept has been established with confidence, building a full-scale mock-up of a representative portion of a building can be invaluable for studying the design details as well as for client communication. Although often perceived as an extravagance, the cost of a mock-up can sometimes be absorbed in the competitive bidding process. The mock-up used for the GSIS building in the Philippines (case study B3) was felt to be worth every penny, both by the owner and by the contractor who built it, because it provided the opportunity to test and finalize construction details (see fig. B3-20).

The mock-up also conclusively showed the client the desirability of the interior lightshelves and the importance of matte-finish T bars—con-

10-14. Energy use prediction. From left to right, graph shows installed BTU capacity; operating BTU use; and dollar cost.
cepts that are difficult to communicate without being in the space. In addition, there are always unexpected benefits in building a mock-up.

The greatest danger when creating a mock-up is that not enough care will be taken to finish the space accurately. If the mock-up is left unfurnished or unpainted, it is likely that the client will have a very negative impression, for reasons quite unrelated to what is being tested, and the original intent will be jeopardized. Care and forethought in communicating the mock-up's limitations can help to prevent this. Access to an incomplete mock-up should be carefully controlled to ensure that the necessary briefing has taken place.

**Final Comments**

Models are an easy and commonsense way to evaluate complex designs. Too often, models are only built to present finished ideas or to evaluate the building facade. The bias against exploiting the potential of models is strong. I have actually sat on a jury for a museum competition and listened to other members of the jury argue at length about the natural lighting potentials of the various schemes when a trip outdoors with the already available models would have instantly resolved their questions. For this reason, I believe that slides of the models under real conditions would facilitate discussion and comparison and should be required along with the models.

A useful exercise that will improve your understanding of daylight modeling is to model and test an existing space. This allows you to compare your perceptions and test results from a model with its full-scale version (figs. 10-15, 10-16).

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10-16. Photo of actual building.
POST-OCCUPANCY EVALUATION

In any building, a post-occupancy evaluation is useful to see how well the design intent has been carried out and to examine how the building and its occupants interact. It is particularly helpful in assessing the value of techniques created for a new combination of objectives, such as sunlit buildings. Some quantitative criteria you might use are:

□ Is the building meeting its lighting and energy goals as expected?
□ Are there conspicuous areas of excess light or underlighting?
□ Are the supplementary shading devices and electric lighting control systems functioning effectively?
□ Is the lighting functionally adequate?
□ How might the building be made more efficient?

Some qualitative criteria are the following:

□ Is the lighting comfortable and enjoyed by the occupants?
□ Is it attractive?
□ Are there areas that are gloomy or dim?
□ Are there areas that are glaring? Has it been necessary for additional shading (such as blinds) to be installed?
□ How might the building be made more pleasant?

A thorough scientific post-occupancy survey is an ideal but infrequent occurrence. A casual hour or two walk-through by an observant member of the design team can produce much essential information. It can remind the building's management to follow up on incomplete details; it can provide issues to consider for future designs. In the case of sunlit buildings, it is particularly important to notice whether people move shades and turn off lights in response to changing conditions. It is often necessary to encourage the occupants to regain control over their environment. Participation in the control of shading and lighting by the occupants can improve their feeling of comfort. Sensitive building management can make a significant impact on building energy use. Visits to finished buildings will influence my assumptions for future buildings. For example, for designs in the U.S. I would now prefer automatic control of dynamic shading and lighting with local override possible.
11 Sunlighting and Architecture

The aesthetically successful use of sunlighting in buildings requires that the associated forms and devices be conceived as an integral part of the architectural design, as much as floors, walls, and beams. Materials and finishes that have a role in shading or redirecting light must be in harmony with the total palette selected for the building. The scale, proportion, and rhythm of sunlighting devices should contribute to the whole, in deference to the larger order of the design (fig. 11-1).

My field observations and evaluations of a number of completed sunlit projects, both successful and otherwise, suggest that there are some general guidelines that can be applied to the design of sunlit buildings.

11-1. The Ventura Coastal Corporation headquarters office building in Ventura, California (Rasmussen & Ellinwood, Architect) gets its character from the horizontal lightshelves and the interesting transition to the unshaded north side. Each orientation’s interior and exterior forms are directly expressive of sunlighting design. The window-façade treatment of the offices is appropriately interrupted for a buffer-space lobby area. (Photograph by Michael Urbanek; courtesy of Scott Ellingwood Associates)

USE A SINGLE, EFFECTIVE SUNLIGHTING/ENERGY CONCEPT

Designers working with sunlighting for the first time may become over-enthusiastic and attempt to use as many methods and devices as they can include in the design. The result can look like a catalog of all the possible sunlighting forms and devices, sometimes combined with passive and active solar devices as well (fig. 11-2). As with any design, the use of a strong central theme with variations is more unified and satisfying.
SELECT AND OPTIMIZE THE SUNLIGHTING METHOD FOR A GIVEN DESIGN PROGRAM

It is very important to select a sunlighting technique that is in harmony with the intended character and program of the building. For example, forms such as atria have an enormous impact on the entire design; they create a major central space which in turn orders the entire space-planning process. The first and most critical requirement of a successful sunlighting technique is the enthusiastic support and commitment of the client. A client who is opposed to the open office landscaping or glazed partitions necessary for light distribution from a litrium cannot derive maximum benefit from a litrium building.

The successful technical design of a sunlighting system will not ensure an elegant and satisfying work of architecture. Good sunlighting performance can be optimized by the proper building orientation, by having shading redirecting devices of the right proportions for that orientation, climate, and programmed needs; and by having an appropriate amount of aperture. But producing good architecture requires that sunlighting performance be balanced against other design considerations such as site conditions, views, placement, and design features of neighboring buildings. Order, scale, proportion, and clarity are additional design considerations. The technical design considerations of successful sunlighting only add to the already overwhelming complexity of architectural design and challenge the talents of the best designers.

The scale and volume of atria welcome the addition of major sculpture, as part of the building forms themselves as well as independently created sculptures (fig. 11-3). Interior landscaping of an atrium enhances the sense of contact with the exterior and takes advantage of the high light levels within such spaces. If the atrium is intended to have the character of an outdoor space, selection of materials and finishes should be appropriate to an exterior environment (fig. 11-4).
If a litrium is created to provide lighting for adjacent office spaces, it cannot, as a by-product, help be the major space and focus of a building, demanding a high level of design quality in terms of materials, finishes, and detailing.

If the work spaces illuminated by the litrium are open to it without glazing, the intimate relationship between the offices and the litrium makes the design quality of all elements of the litrium, including its landscaping, even more important than that of a courtyard within sealed buildings. In the latter case, one might look out of the window or walk in the courtyard. The litrium demands that one does.

But both the landscaping and the materials and finishes of the litrium should not handicap excessively the use of natural light in the adjacent spaces—the major purpose for which the litrium was created.

SELECT SUNLIGHTING ELEMENTS WHOSE SCALE IS APPROPRIATE TO THE OVERALL BUILDING CONTEXT

As discussed in chapter 6, sunlighting devices of various scales may be employed; the scale chosen must be considered in relation to the occupants of a building, to the structural system and module, and to the overall building context. A small number of larger-scale elements are best for sunlighting performance. A facade that utilizes overhangs and light-shelves or larger-scale louvers to shade and redirect the sunlight is more effective than one that relies on medium-scale louvers. More important to building users, large-scale devices tend to frame views, while medium-scale devices break up and compete with views (fig. 11-5). At the other extreme, very small-scale louvers (miniblinds) are relatively inconspicuous, appearing as a texture or screen rather than as a competing pattern.

Architecture versus Hardware

A seeming fascination with hardware is evident in many buildings where shading or redirecting of light is accomplished by add-on devices such as louvers. These devices seldom have any inherent visual interest yet tend to attract attention by their incongruity with the forms and materials of the building. They thus assume undue importance within the context of their use. While the light weight and the temporary appearance of brightly colored canvas awnings are appropriate and attractive for sidewalk cafés or even low-rise office buildings, they would be hopelessly out of place on the sides of a granite high-rise office building. Similarly, the use of relatively fragile metal awnings or louvers on an otherwise "permanent" facade will seem contradictory at best; the entire sense of building quality will be affected. While these devices are designed to be operable, it is important to recognize that they are subject to failure and misalignment (fig. 11-6). Off-the-shelf items often have a character of anonymous ubiquity that lessens the individuality of a design.

A more satisfying solution is to design the building to perform functions of shading and redirecting light, within the context of the structural
system and exterior materials of the building. Extended beams and floor slabs can provide shading and baffling. Lightshelves of concrete or metal can provide both shading and redirection of light, and at the same time be an integral and permanent part of the building facade.

**Textural Scale**

When it is necessary to provide small-scale operable shading devices to supplement permanent devices (such as on a west facade where the complete shading of late afternoon sun is difficult to achieve), they should be located on the inside of the building for protection, exterior appearance, and ease of operation and maintenance. Such interior shading devices generally sacrifice very little in terms of energy performance (compared with exterior devices) when they are supplemental rather than primary shading devices.

It is important to remember that when retracted, small-scale devices such as roll-up shades and venetian blinds are not things of beauty or visual interest; emphasizing them only detracts from the architecture. Visual baffling in the form of a valance or ceiling pocket will make such devices less conspicuous by placing them outside of the normal field of vision (fig. 11-7).

On the exterior, the deeply shaded windows of sunlit buildings help bring order to a facade because they shadow any interior disarray. For example, recall the contrast between Boston City Hall and the adjacent JFK building, where disorderly blinds behind unshaded windows form a dominant pattern on the facade (see fig. 6-44).

**BE SENSITIVE TO THE ARCHITECTURAL IMPLICATIONS OF SUNLIGHTING FORMS**

The most pervasive implication of sunlighting design is the three-dimensional articulation of building elements. The spatial qualities of light require that its use and control be three-dimensional. The most efficient and economical way to obtain the forms necessary to control sunlight is to make them an integral aspect of the architecture, articulating beams, floors, and columns, to achieve sunlighting goals. The resulting forms are in direct opposition to the planar, smooth-skinned, scaleless boxes designed in defiance of the sun. Because these forms are highly articulated, they may be conspicuously ugly if ungraciously designed, or very handsome in the hands of skillful designers.

**Environmental Influences**

Sunlighting design implies careful control of solar gain and interior climatic conditions. As such, each building should reflect the environmental conditions of the site. Granted, there will always be solutions that can defy any environmental influence on their form by a technological tour de force (like the double envelope of the Hooker Chemical building, see fig. 6-95), but the more economical and reliable approach is to adapt the building’s form to the site. This implies that the different elevations of a building will have different configurations or proportions. Regional
differences will evolve as designers respond to local sunlight availability and climate.

**Human Scale**

Sunlighting performance benefits from the high ceilings created by the integration and articulation of structural and mechanical elements. The resulting interior spaces are more generous and interesting, and there is a genuine relationship between structure, space, and human scale. The value of a lightshelf as a human-scale reference device should be self-evident—the proportions that determine the size and location of the lightshelf are those of human beings. In turn, interior lightshelves can serve to establish an organizing line for door heads, window mullions, glazed transoms, partial-height partitions, and indirect or valance lighting (fig. 11-8). Regardless of the absolute dimensions, the addition of elements proportioned for the use and needs of humans will result in a more comfortable and intimate space.

This is true on exteriors as well as interiors: the human-scale influence “demystifies” buildings by enabling people to count the number of floors a building has and thus establish a sense of their relationship to the building. At night, the depth of the sunlighting aperture creates lantern forms, illuminated by the interior lights spilling out through the high-transmission glass (fig. 11-9).

![Diagram](image)

11-8. The human scale determines the location of organizing lines.
INTEGRATE AND COMBINE DEVICES
FOR VISUAL SIMPLICITY

If you were to ask an architect about his or her design for a particular room, it might be described in terms of its spatial or emotional character, its programmatic “fit,” or even the contextual, historical basis for the color scheme. The architect would probably not address the issues of light fixtures, speakers, air diffusers, or venetian blinds. In many buildings, however, these items inadvertently command more visual attention than any other design element. In part, this is due to architects’ abandonment of their role as designers in the areas of lighting and HVAC. These areas are ceded to engineers and salesmen, whose priorities are quite different, and who are not likely to be sympathetic to the design.

It is my belief (and probably that of any architect who cares about the quality of the interior environment) that these supplemental hardware items are similar to small-scale shading devices in that their visual presence should defer to the architectural elements and furnishings. (A chandelier or other light source that is intended as a focal point is an obvious exception.) The only way this can be assured is for these elements to be recognized and planned for as part of the building. Integrating these elements into the design will allow them to be visually baffled.

For example, in buildings designed for sunlighting, a major portion of the supplemental artificial lighting should ideally illuminate the ceiling and blend imperceptibly with the reflected sunlight. While suspended linear indirect fluorescent fixtures could provide such light efficiently, such fixtures tend to break up the space and create a lower, implied ceiling plane. A better strategy is to make use of the available architectural elements to support, blend with, house, and conceal lighting hardware. Inexpensive fluorescent strip fixtures can be combined with lightshelves and beams by providing an architectural pocket for the purpose. All the elements we do not want to see (light fixtures, speakers, air grilles) should be hidden in the shadows of pockets or reveals. Conversely, the surfaces and objects we enjoy seeing should be highlighted.

11-9. The “lanterns” of the Tarble Arts Center (case study D2) at night.
USE HIGH-QUALITY MATERIALS

More often than not, sunlighting design designates the ceiling as the primary source of indirect lighting from sunlit sources or fluorescent fixtures. As the most apparent source of illumination, the ceiling materials used are critical to the character of a space. When there is a choice, use the highest quality materials and craftsmanship in those areas where they will be noticed. When acoustical tile ceilings are used, concealed spline grids are preferable. If exposed "Ts" are used, they should have a non-glare, matte finish. Tiles with regressed edges tend to make "Ts" less dominant.

Acoustical tile is often chosen as the ceiling material not for its acoustical properties but to allow easy access to the ceiling plenum. With a carefully integrated building system, the areas requiring access are confined to a small area, freeing up the majority of the ceiling for installation of plaster or gypsum board (fig. 11–10). In concrete framed structures, the ceiling finish can be as minimal as paint on the underside of the floor slab above (except for office landscape areas requiring maximum acoustic absorption).

Integrated systems create ceilings with variety and visual interest. In addition, integrated systems, by their nature, require less ceiling material than monolithic suspended ceiling systems, and thereby make more expensive, higher quality materials more affordable.


DIAGRAMMATIC DESIGN VERSUS POETRY

A good technical solution is not necessarily aesthetic, of course, but it need not be an impediment to beauty either. Looking at the schematic diagrams of sunlighting techniques in this book, you might think that the proposed architectural devices and forms could become very monotonous if widely applied. I must confess that the case studies presented suggest that trend at first glance. This is not surprising, since they represent the first generation of such applications in the work of a single consultant. However, the rigorous application of sunlighting concepts should increase rather than decrease the opportunities for design talent and taste.
to be demonstrated. There is no reason for all sunlit buildings to look alike; indeed, they need not "look" obviously sunlit at all.

Understanding the concepts involved allows designers to achieve diagrammed sunlighting goals with the poetry of inspired means. The work of Aalto and Utzon is exemplary; their beautiful sweeping curves function without compromising their diagrams, which may well have shown straight lines (fig. 11-11). The dominant horizontal exterior lines of Wright's Robie house were enhanced by the need for deeper shading on east and west facades. The elegant floating lightshelf forms and their interruption by a central greenhouse-buffer entrance lobby at the Ventura, California, office building designed by Scott Ellinwood create a delightful contrast to the typical boxlike buildings of the area. When integrated solutions are sought to solve multiple problems in the most economical attractive fashion, enrichment of details naturally occurs. Witness the elegance of the lightshelves at the Hawaiian Medical Services building, which are sculptured to channel rainwater (fig. 11-12).

Solving interior problems adds richness as well. Steps in the ceilings to accommodate pockets for flexible museum lighting, as at the Tarble Arts Center in Charleston, Illinois, make much richer, more interesting forms than the monotonous pure geometric coffer forms of I.M. Pei's West Wing addition to the Boston Museum of Fine Arts (figs. 11-13, 11-14).

Perhaps new, unexpected forms will evolve as sunlighting concerns are blended with other programmatic requirements. Problem solving can create interesting designs based on simple diagrammatic concepts. Affection for preconceived forms should be avoided. Buildings should not
seek their identity and beauty from faddish styles and arbitrary abstract forms; many creative solutions can result from responding to multiple goals such as the energy and human comfort aspects of sunlighting, local context, and site restrictions.

Designers should be able to use sunlighting strategies without creating a conspicuous "sunlighting building" look. Perhaps the best design is one that appears to be an adaptation of local indigenous building forms (figs. 11-15, 11-16).

11-15. HOK's airport design in Riyadh is an excellent example of sunlighting as an integral part of an elegant work of architecture. The toplighting aperture, in particular, is integral to the structure. Clerestory windows and light-reflecting ceilings are richly composed and detailed. The forms created seem appropriate to the character of Middle Eastern architecture rather than a mere imitation of historical details.

SUNLIGHTING AND ARCHITECTURE—AN EXAMPLE OF POSITIVE INTEGRATION

In his design for the new National Gallery of Canada in Ottawa, architect Moshe Safdie has illustrated that following the rules of good sunlighting design with balanced judgment need not restrict a designer to mechanically repetitive forms.

Although the greatly reduced glazing areas and the consistency of their orientation make this museum quite different from those following the classical mold of the last century (such as the Louvre and the Boston Museum of Fine Arts), it will be appreciated no less as a "classic" piece of architecture from without and has far superior galleries within (figs. 11-17, 11-18).

11-17. Safdie's National Gallery of Canada, model view. The design is a "classic" museum form with visible skylights. (Photograph courtesy of Moshe Safdie)

11-16. In his Dharmala Office Building, Paul Rudolph created a high-rise variation on the indigenous roof forms, which utilize overhangs for shading and ground-reflected light for illumination. In this building, the facade will provide shading and building-reflected light; the soffits will be finished with white tiles to maximize reflected light. Indirect fluorescent light will blend with reflected daylight on the high ceilings of the perimeter rooms. (Courtesy of Paul Rudolph)
While the galleries within the impressively scaled multistory block are consistently oriented to face only north and south (for easiest sunlight control), Safdie has created an interesting variety of interlocking gallery cross sections. Tested in models and full-scale mock-ups, these gallery types will all use the modest amount of sunlight and skylight admitted efficiently and simply (figs. 11-19 to 11-22).

Unlike Kevin Roche’s overglazed Lehman Wing at the Metropolitan Museum of Art in New York, extensively glazed roofs at the National Gallery of Canada are limited to public circulation spaces where the sunlight from such extensive glazing can be used and appreciated without handicapping displays or damaging art objects. Judging from the variety of spaces and structural forms combined in a building with a classical demeanor, it appears that thoughtful consideration of sunlighting principles need not handicap the invention and aesthetic judgment of the most talented architects.

I believe that some of the following case studies similarly demonstrate this potential. Others accomplish at least some elements of note.
11-21. Model view of typical toplit gallery. (Photograph courtesy of Moshe Safdie)

11-22. A typical side/toplit gallery: (a) model; (b) mockup. (Photographs courtesy of Moshe Safdie)