As a design feature, the use of daylighting within a building creates a more pleasing and productive atmosphere for the people within. Daylight provides a direct link to the outdoor environment and natural light delivers a dynamic evolving distribution of light. The moderation of light levels is often subtle and usually unnoticed, and the result is one of visual richness, creating an environment that is stimulating and more comfortable.

Successful daylighting is more than simply adding large windows or skylights. It involves thoughtful integration of design strategies, which address heat gain, glare, variations in light availability, and direct-beam penetration into a building. Design considerations will often address details such as shading devices, aperture size and spacing, glazing materials, interior finishes, and reflectance. In large measure, the art and science of daylighting is not so much about how to provide enough daylighting as how to do so without its possible undesirable effects.

As an efficiency measure, daylighting is most effective during bright sunny afternoons when it can supplant the need for electric lighting entirely. Because an electric utility must provide enough generating capacity to serve the highest demand predicted for its service territory, daylighting has the potential not only to reduce the building’s overall energy consumption but also to lower the peak demand.

Electric lighting directly accounts for approximately 20% to 25% of the total electrical energy used in the United States. In the commercial sector, lighting accounts for 37% (34% interior, 3% exterior) of electrical energy consumption (see Figure 1.1). Lighting also has an indirect impact on the total energy use because the heat generated by electric fixtures alters the loads imposed on the mechanical cooling equipment. As a rule of thumb, each unit of electric lighting contributes to an additional one-half unit of electricity for space conditioning because of the contributions from the heat generated by electric lighting. The energy savings from reduced lighting loads can directly reduce air-conditioning energy usage by an additional 10% to 20%.

There seems to be a strong interest in efficiency issues not only from a technical standpoint but also as they relate to social and

Architecture is the masterly, correct and magnificent play of volumes brought together in light. Our eyes are made to see forms in light . . . cubes, cones, spheres, cylinders or pyramids are the great primary forms that light reveals to advantage . . . It is of the very nature of the plastic arts.

LE CORBUSIER
behavioral issues. These issues often involve enhanced comfort, satisfaction, and productivity and may even have a relationship to the number of workers’ compensation claims filed against an employer. The Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon has conducted many building surveys and postoccupancy evaluations to better understand the effect of design features on occupants. Appendix G contains a survey form developed to assess the impacts of perceived comfort for a series of postoccupancy evaluations conducted at the College of Environmental Design at California Polytechnic State University at Pomona.

Daylighting may potentially play a key role in supporting “sustainable” development. As clients begin to demand sustainable solutions and the design community embraces these challenges to produce buildings that reduce environmental impacts, daylighting solutions have the opportunity to play a significant role through pollution avoidance. By virtue of improving a building’s efficiency, you would expect to see a reduction in annual kilowatt-hours so the amount of pollutants emitted at a utility generating station will reduce the amount of airborne pollutants, including nitrogen oxide ($\text{NO}_x$), carbon dioxide ($\text{CO}_2$), and sulfur dioxide ($\text{SO}_2$), all of which contribute to reductions in air quality. The Environmental Protection Agency and most utilities have data on the relationship between kilowatt-hours and pollution avoidance values. Table 1.1 represents the latest conversion values for the United States.

A key concern the design team confronts is visualizing various design solutions and quantifying the impacts of fenestration-related decisions. Some design firms regularly perform this type of service as a “basic service,” whereas other firms consider it an additional service and obtain additional compensation to cover any added design and analysis time and sell the client based on anticipated reductions in operating costs. Many utilities offer design assistance or incentives to optimize buildings, and these may include assistance to solve for daylighting-related issues. It is important to remember that the daylighting design process involves the ideas of many disciplines, including architectural, mechanical, electrical, and lighting (see Figure 1.2). These design team members need to be brought into the process early to ensure that the concepts and ideas are carried through the entire design, construction, and operating process (see Figure 1.3). Ample opportunity exists for

Figure 1.1 Commercial electricity use in the United States. (Courtesy of the Electric Power Research Institute of Palo Alto, California.)
miscommunication throughout the daylighting system design process. The way a building is designed versus how it is built versus how it is operated is important to integrate. Building commissioning is often a critical function to ensure a building performs as designed. See Appendix B for a commissioning specification and prefunctional test protocols.

**DESIGN ISSUES**

Architects and designers who are sensitive to basic daylighting fundamentals can achieve an aesthetically pleasing space without sacrificing cost or creativity. An awareness of certain issues that can occur when daylighting is employed will assist in the success of an effective design.

**TABLE 1.1 Emission Factors**

<table>
<thead>
<tr>
<th>STATES</th>
<th>CO₂ (lb/kWh)</th>
<th>SO₂ (g/kWh)</th>
<th>NOₓ (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT, ME, MA, NH, RI, VT</td>
<td>1.1</td>
<td>4.0</td>
<td>1.4</td>
</tr>
<tr>
<td>NJ, NY</td>
<td>1.1</td>
<td>3.4</td>
<td>1.3</td>
</tr>
<tr>
<td>DE, DC, MD, PA, VA, WV</td>
<td>1.6</td>
<td>8.2</td>
<td>2.6</td>
</tr>
<tr>
<td>AL, FL, GA, KY, MS, NC, SC, TN</td>
<td>1.5</td>
<td>6.9</td>
<td>2.5</td>
</tr>
<tr>
<td>IL, IN, MI, MN, OH, WI</td>
<td>1.8</td>
<td>10.4</td>
<td>3.5</td>
</tr>
<tr>
<td>AR, LA, NM, OK, TX</td>
<td>1.7</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>IA, KS, MO, NE</td>
<td>2.0</td>
<td>8.5</td>
<td>3.9</td>
</tr>
<tr>
<td>CO, MT, ND, SD, UT, WY</td>
<td>2.2</td>
<td>3.3</td>
<td>3.2</td>
</tr>
<tr>
<td>AZ, CA, HI, NV</td>
<td>1.0</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>AK, ID, OR, WA</td>
<td>0.1</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>National average</td>
<td>1.5</td>
<td>5.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Veiling reflections obscure the details seen by reducing the contrast. Thus, avoid creating conditions within the building where disabling veiling reflections may occur, particularly in spaces where there are critical tasks.

There are many types of visual tasks with various degrees of criticality (see Figure 1.4). A receptionist may not require the same level of illumination as a graphic designer. Many spaces in a building can be lighted that do not require a high degree of illuminance. The Illuminating Engineering Society of North America (IESNA) published a paper titled “Guidelines for Sustained Visual Comfort in Daylit Spaces” which provides guidelines for daylighting design.

**VEILING REFLECTIONS**

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**Figure 1.2** Standard design process.

**Figure 1.3** Integrated daylighting design process. (Courtesy of Scott Ellinwood, FAIA.)
America publishes illumination guidelines for various types of spaces.

**QUANTITY**

Introduce as much controlled daylight as possible, and as deeply as possible, into the building interior. Generally, the human eye can adjust to high levels of luminance without producing discomfort. In fact, the more light available, the better people can see. Veiling reflections and excessive brightness differences are often problematic and should be addressed.

**GLARE**

The aim of an efficient daylighting design is not only to provide illuminance levels sufficient for good visual performance but also to maintain a comfortable and pleasing atmosphere that is appropriate to its purpose. Glare, or excessive brightness contrast within the field of view, is one aspect of lighting that can cause discomfort to the occupants of a space (see Figure 1.5).

Although brightness and brightness contrast are important in providing a stimulating visual environment, excessive contrast between foreground and background may disrupt the eye’s ability to distinguish objects from their background and to perceive detail. The human eye can function quite well over a wide range of luminous environments, but it cannot function well if extreme levels of brightness are present in the field of view at the same time.

Some contrast in brightness levels may not be undesirable. Dull uniformity in lighting, although never harmful, can lead to tiredness and lack of attention—neither of which is compatible with a productive environment. However, it is necessary to ensure that glare is kept under control and that extreme levels of brightness are not present in the field of view at the same time.

Glare is not a design issue most of the time; it is critical only when certain viewing conditions occur. In this regard, understanding the conditions that might cause glare is the first step toward finding a design solution to deal with it or to avoid the problem altogether.
Glare is a subjective phenomenon and as such is difficult to quantify. Nonetheless, a generalized form of glare quantification can be derived by studying changes in the contrast ratio. The study quantifies the average response of a large number of people to the same glare situation. This type of analysis is used to determine a glare constant for individual apertures and a glare index for all light sources in the field of view.

However, assessments of the physical factors can be correlated to the magnitude of the described sensation so that glare discomfort can be estimated. Studies of these factors have resulted in the development of glare indices, which can be utilized at the design stage to address glare discomfort and are integral to many computer-based design tools.

**DESIGN VARIABLES**

**SITE ELEMENTS**

Sky conditions vary the nature and quantity of the light entering a building. Three types of sky conditions are utilized to estimate illumination levels within a space.

The overcast sky is the most uniform type of sky condition and generally tends to change more slowly than the other types. It is defined as being a sky in which at least 80% of the sky dome is obscured by clouds. The overcast sky has a general luminance distribution that is about three times brighter at the zenith than at the horizon. The illumination produced by the overcast sky on the earth’s surface may vary from several hundred footcandles to several thousand, depending on the density of the clouds (see Figure 1.6).

The clear sky is less bright than the overcast sky and tends to be brighter at the horizon than at the zenith. It tends to be fairly stable in luminance except for the area surrounding the sun, which changes as the sun moves. The clear sky is defined as being a sky in which no more than 30% of the sky dome is obscured by clouds. The total level of illumination produced by a clear sky varies constantly but slowly throughout the day. The illumination

*Figure 1.6* Typical bar graph indicating cloud cover measured in tenths. (*Additional climatic data are provided in Appendix C.*)
levels produced can range from 5,000 to 12,000 footcandles.

The *cloudy sky* has a cloud cover that may range from quite heavy to very light. The cloudy sky is defined as being a sky in which 30% to 80% of the sky dome is obscured by clouds. It usually includes widely varying luminance from one area of the sky to another and tends to change quite rapidly. The cloudy sky may provide periods when direct sun reaches the building site and some periods when, for all practical purposes, the sky appears overcast.

Appendix C gives weather data for a variety of climate zones, including average clear-cloudy conditions. It is quite valuable to perform a climatic analysis to formulate proper design responses.

*External obstructions* surrounding a window will affect the amount of daylighting entering a space. Many of these conditions, such as cloud cover and sun position, are purely a function of the climate. External obstructions, on the other hand, such as trees and other buildings, can permanently alter the amount of daylight allowed to enter a window opening (see Figure 1.7). The patterns of obstruction will normally vary for each window. They can have different shapes, different positions relative to the window, and different light-blocking or reflecting characteristics.

**DESIGN STRATEGIES**

**INCREASE PERIMETER DAYLIGHT ZONES**

Extending the perimeter form of a building may improve the building’s performance by increasing the total daylighting area. The trade-offs between an increased perimeter exposure and a compact building form are shown in Figure 1.8. The thermal impact of
electric lights and the increased linear footage of window wall should be given careful attention when these strategies are considered.

**ALLOW DAYLIGHT PENETRATION HIGH IN A SPACE**

With the location of an aperture high in a wall, deeper penetration will result. There will be less likelihood of excessive brightness in the field of view by reflecting and scattering light before it gets to task level.

**USE THE IDEA OF “EFFECTIVE APERTURE” FOR INITIAL ESTIMATES OF THE OPTIMUM GLAZING AREA**

When the effective aperture, the product of the window-to-wall ratio and the visible transmittance of the glazing, is around 0.18, daylighting saturation will be achieved. Additional glazing area or light will be counterproductive because it will increase the cooling loads more than it will reduce the lighting loads.

**REFLECT DAYLIGHT WITHIN A SPACE TO INCREASE ROOM BRIGHTNESS**

Although the source of daylight is the sun, surfaces and objects within a space reflect and scatter daylight. An increase in visibility and comfort can be achieved through increasing room brightness by spreading and evening out brightness patterns. A reduction in intensity occurs from reflecting and partially absorbing light throughout a space. A light shelf, if properly designed, has the potential to increase room brightness and decrease window brightness (see Figure 1.9 and 1.10).

**SLOPE CEILINGS TO DIRECT MORE LIGHT INTO A SPACE**

Sloping the ceiling away from the fenestration area will help increase the brightness of the ceiling farther into a space (see Figure 1.11).

**AVOID DIRECT-BEAM DAYLIGHT ON CRITICAL VISUAL TASKS**

Poor visibility and discomfort will result if excessive brightness differences occur in the vicinity of critical visual tasks. It is a fallacy to believe that good daylighting design entails merely adding large apertures of glazing to a building design. Fenestration controls should be considered if direct-beam illumination is undesirable (see Figure 1.12).

Figure 1.9 Section through typical light shelf.

Figure 1.10 Detail of fenestration control. (Photograph courtesy of Olson/Sundberg Architects.)
USE DIRECT SUN CAUTIOUSLY IN AREAS WHERE NONCRITICAL TASKS OCCUR

Patterns of light and shadows from the sun tracking across the sky can add an exciting and dynamic feature to a space. A feeling of well-being and a sense of time and orientation often impact the occupants of such a space. However, if they are integrated poorly, the occupants may have difficulty in seeing, and, in addition, unwanted heat gain may result (see Figures 1.13 and 1.14).

FILTER DAYLIGHT

When harshness of direct light is a potential problem, filtering can be accomplished by vegetation, curtains, or louvers. This will help soften and distribute light more uniformly (see Figures 1.15 and 1.16 and 1.17).
CONSIDER OTHER ENVIRONMENTAL CONTROL SYSTEMS

Fenestration systems can potentially allow light, heat, air, and sounds into a space. Ventilation; acoustics; views; electric lighting systems; and heating, ventilating, and air-conditioning (HVAC) systems all need to be considered during the design process (see Figure 1.18).

DESIGN ELEMENTS

Several design considerations impacting light affect a building in terms of form and shape. Probably the most significant design determinant when implementing daylighting strategies is the geometry of a building’s walls, ceiling, floors, windows, and how each relates to the other. An understanding of the effects of the various building elements will provide the basis for manipulating form to achieve adequate lighting levels. It is also important to understand geometric relationships in terms of lighting functions, as well as to comprehend the quantitative relationships that accompany various geometric forms. A review of measured or calculated illumination levels for various design functions will be helpful, as will the experience. Designers need to manipulate the configurations and measure the

Figure 1.15 Section showing vegetation and lattice to filter daylight.

Figure 1.16 Exterior facade with lattice system.

Figure 1.17 Interior of a university bookstore showing suspended fabric diffusing elements below the aperture.

Figure 1.18 Glazing-related decision point diagram. (Courtesy of Steve Selkowitz.)
results before they can properly understand the quantitative relationships. This can be accomplished through physical model tests, computer simulations, or both.

EXTERIOR ELEMENTS

Overhangs can be useful controls for fenestration. In addition to blocking the direct beam from the sun, they will also reduce the amount of sky seen from within a room, thus reducing the amount of diffuse skylight admitted through the opening.

Reflected light from the ground or other surfaces can also be caught by an overhang and directed back into the interior of a room (see Figure 1.19). The result will be a slightly higher illuminance level and a more even distribution of light in the space.

Light shelves are typically horizontal devices located near the window area. Successful fenestration systems have integrated both exterior and interior light shelves. They are used primarily to reduce window brightness by blocking direct-beam sunlight from entering the conditioned space. Light shelves also have the potential to increase room brightness by reflecting light into the building. As a design element, light shelves often introduce a strong horizontality to the building facade (see Figure 1.20). Fenestration systems may have exterior or interior light shelves. These devices may be combined so both exterior and interior work together.

Horizontal louvers are an effective method of blocking direct-beam light during the summer when sun angles are high while allowing some sunlight penetration during the milder seasons. Movable louvers can be controlled electronically or mechanically to respond to changing sky and weather conditions.

Vertical louvers or fins are advantageous for east and west orientations to block direct-beam light and to reflect light into the interior (see Figure 1.21). The louvers or fins can be fixed or movable (see Figure 1.22).
Daylight tracking and reflecting systems are designed to enhance the daylighting potential of skylights by tracking and reflecting sunlight through the aperture and into the open spaces below. This type of equipment can be either dynamically controlled to follow the path of the sun or completely stationary, using strategically placed mirrors to capture the direct-beam daylight.

Because low-angle daylight can be better utilized, the use of this equipment is able to extend the hours within a day, as well as the months within a year, that natural light can effectively replace or complement electric lighting.

**Glazing Materials**

Historically, the simplest method to maximize the amount of available daylight within a building was to increase the total amount of glazing present in the building envelope. In many cooling-dominated climates, admitting more light has, until recently, meant admitting unwanted heat gain as well. However, recent advancements in glazing technology have specifically reduced this liability.

The physical properties of glazing materials need to be well understood (see Figures 1.23, 1.24, 1.25, and 1.26). Selective coatings or low-emissivity (low-e) window systems can be specified which are transparent to daylight and are opaque to potentially detrimental ultraviolet and/or infrared radiation. A more detailed discussion of these properties is located in Chapter 3.
Effective Aperture

In the simplest of terms, as the area of an aperture increases, the amount of daylight received in a space also increases. However, the glazing material within that aperture can effectively reduce the amount of visible light that is allowed to enter. Therefore, aperture size alone is not an effective determinant to measure illumination levels. If the glazing in an opening is a perfectly transparent material, the “effective aperture” size would be equal to the area of the opening [because the visible transmittance (VT) of the glazing would be 1.0]. If, however, the glazing has a VT of 0.50, the opening will transmit only half of the light striking it, and the “effective aperture” will be half of the actual size of the opening.

The “effective aperture,” or light-admitting potential of a glazing system, is determined by multiplying the visible transmittance (VT) by the window-to-wall ratio (WWR). The window-wall ratio is the ratio of the net window glazing area to the gross exterior wall area.

\[
EA = WWR \times VT
\]

This attribute can be useful in evaluating the cost effectiveness and the daylighting potential of a schematic building configuration.

Aperture Location

The location of an aperture will affect the distribution of the light admitted through the aperture.

The height of a window from the finished floor will dictate the depth of penetration. The higher the window, the deeper the daylight will penetrate. One rule of thumb states that the depth of daylight penetration is about 2½ times the distance between the top of a window and the windowsill (see Figure 1.27).
INTERIOR ELEMENTS

Room Geometry
The depth that daylight will penetrate is dependent on the ceiling height relative to the top of the window. A high window height will allow entering daylight to strike the ceiling plane and be reflected into the interior of the space.

The depth of the room has a direct effect on the intensity of illumination as well. If a space is modeled, keeping the floor-to-ceiling height and the area and location of the window constant, changing the room depth will cause a change in light intensity. With deeper rooms, the same quantity of incoming light is distributed over a larger area (see Figure 1.28).

Reflectances of Room Surfaces
The reflectance values of room surfaces will greatly impact the performance of a daylit space (see Figure 1.29). The ceiling is the most important surface in reflecting the daylight coming into a space onto the work plane. The next most important surface is the back wall, followed by the side walls, and finally, the floor.

As the designer, keep the ceiling as light as possible and use only the floor for patterns or deep colors. Dark colors on a floor will have the least impact on the daylit space.

Interior Shading Controls
Several types of manual interior control devices can be used to eliminate excessive...
bright spots and also get daylight where it is needed.

Venetian blinds are effective because they can be fixed to block direct-beam sunshine or can be partially closed to reflect in the space while still allowing a view to the outdoors. Blinds offer versatility and tend to increase the ratio of ground-reflected light to direct sky contribution.

Draperies are often used as control devices because they can add texture, color, and flexibility to a space. Fabrics are available in a range of weaves with varying shading coefficients. An appropriate weave pattern can soften the light to necessary levels.

Roller shades of various degrees of opacity can be an effective control device for reducing glare and direct-beam penetration. One benefit of the interior controls is that they can be easily and completely retracted during those times that sunlight and daylight are desirable.

DESIGN OPTIONS

SIDELIGHTING

Sidelighting concepts use the walls of a building as the location of apertures to admit daylight (see Figure 1.30). The apertures can also serve by incorporating view and ventilation as a design dynamic.

Sidelighting provides illumination with a strong directionality due to the diminishing light levels as the distance from the aperture increases. Daylight admitted through wall apertures is ideal for illuminating horizontal surfaces and work planes.

As a disadvantage, sidelighting may cause glare because of the high contrast between the aperture and the surrounding wall surfaces. Proper shading devices, either exterior or interior, can largely mitigate this liability.

Figure 1.30 Sidelighting with direct-beam control. (Detail courtesy of IBI Group, Irvine, California.)

Vertical windows have long been used by designers to introduce natural light, bring in fresh air, and establish a connection with the outdoors. The dimensions, location, and spacing of windows are important variables. A basic understanding of some of the relationships among these factors will help the designer. Direct ample amounts of light where it is desired.

- Larger window areas yield greater amounts of daylight.
- Glazing located high in the wall will allow daylight to penetrate greater distances into a room. The higher the aperture, the deeper the penetration of usable daylight.
- Small window openings placed in an opaque wall often create severe contrast and occupant discomfort.
- As the height of the windowsill increases, the point of maximum illumination moves away from the window.

The contribution of light from the ground and other exterior reflecting surfaces can be a significant component of the total penetration of illumination on clear days.

Spaces can be daylit with windows unilaterally, bilaterally, and multilaterally with varying
effects. Unilaterally lit rooms receive light entering through windows in one wall only. Bilaterally lit spaces are illuminated by light entering through apertures in opposing walls (see Figure 1.31), and multilaterally lit areas receive light entering through fenestration in at least two nonopposing walls.

Clerestories are vertical or near-vertical windows whose sill height is above eye level but below ceiling height (see Figure 1.32). They are therefore not necessarily view apertures and so may easily incorporate glazings that are not transparent.

The principal advantage of clerestories is that the elevated vertical glazings introduce daylight high into a space, often resulting in broader distribution and a reduced likelihood of excessive brightness in the field of vision. In addition, because they open onto the bright part of the sky dome close to the zenith, they can allow brighter and deeper daylight penetration into a building than can a window.

Clerestories provide excellent lighting for horizontal work planes, as well as vertical display surfaces. Daylight entering through a sufficiently high clerestory will typically reach a vertical surface without striking intermediate objects, thus avoiding shadows on these areas (see Figure 1.33). Light admitted through

Figure 1.31 Bilateral daylight contribution.

Figure 1.32 Clerestory aperture.

Figure 1.33 Clerestory aperture detail by Edward Mazria. (From Fuller Moore, Concepts and Practice of Architectural Daylighting, VNR, New York, 1986. Used by permission.)
clerestories also exhibits less variation between maximum and minimum illuminances compared with a window and thus produces relatively even illumination.

The only major drawback to clerestories is that they require tall floor-to-ceiling heights if they are to function properly. Gymnasiums, libraries, galleries, museums, and circulation spaces all are excellent spaces in which to admit natural light through clerestories.

**TOPLIGHTING**

Toplighting concepts allow daylight to penetrate a space from apertures that are located above the ceiling line and usually constitute part of the roof of the building (see Figures 1.34A and 1.34B).

All toplighting concepts provide interior light with distribution patterns and character significantly different from those provided by sidelighting. Lighting effects can vary dramatically, depending on the configuration and placement of roof apertures. Not only can consistent and relatively uniform daylight distribution be accomplished, but dramatic high-intensity “punch” can be introduced to strategic areas as well (see Figure 1.35).

Toplighting often restricts natural light to the upper level of the building. Another drawback of toplighting is that the penetration of direct-beam sunlight into a space usually needs to be carefully controlled to prevent occupant discomfort (see Figure 1.36). Certain spaces such as circulation areas may work well with direct-beam sunlight to add visual interest.

**Skylights** are defined simply as horizontal glazed roof apertures that are parallel or nearly parallel to the roof. Skylighting is an excellent toplighting strategy because large quantities of light can be admitted to all areas of single-story buildings or into the top floor of multistory buildings, with relatively small openings (see Figure 1.37).

The layout and spacing of skylights in a roof determine the light distribution characteristics of the area below the skylights. While maintaining a constant aperture area, the arrangement can vary from a single large skylight to many small skylights distributed uniformly across the roof with varying effects.
Large, widely spaced skylights are usually the most economical to install but may result in uneven light distribution, reduced energy savings, and possible glare problems. Small, closely spaced skylights, on the other hand, will provide more uniform lighting conditions and greater energy savings but may be more costly to install.

The general rule of thumb is to space skylights at 1.0 to 1.5 times the ceiling height. Variations will inevitably occur because skylight placement must also be coordinated with the structural, mechanical, and lighting systems.

**Figure 1.35** Bilateral strategy of Antelope Valley Library. (*Courtesy of Spencer Hoskins Architects.*)

**Figure 1.36** Toplighting through deep light well. (*Illustrated by Moshe Safdie. Courtesy of the Canadian National Gallery.*)

**Figure 1.37** Typical skylight construction detail showing splayed ceiling treatment through plenum.
Diverse glazing options provide opportunities for the designer to select from diffuse light, direct-beam sunlight, or any combination of the two that may be appropriate to a space. Glazing characteristics are discussed in more depth in Chapter 3.

Roof monitors are raised building elements of a roof with vertical or sloped apertures on one or more sides. Although these devices require architectural coordination, proper orientation, and special drainage details, they allow the top floor of a building to benefit from daylight with less heat gain than is normally associated with other strategies.

**Core Daylighting**

Core daylighting refers to a strategy that implements optical systems to light spaces of a building with sunlight that may receive both electric lighting and cooling loads. This is not a new concept because simple forms of this strategy existed in early Egyptian cultures that used mirror strategies to light deep spaces within the tombs of the Pharaohs.

There are generally three elements to core daylighting systems: the light collection system, the light transportation system, and the light distribution system.

**Collection System**

The core daylighting collection system captures daylight and redirects it. Collection systems may be located on the exterior of a building on the roof or at exterior walls. Two types of core daylighting light collection systems exist: active optical systems and passive optical systems.

Active optic systems use a tracking system that follows the sun as it moves across the sky and redirects the direct-beam solar into the interior of a building (see Figure 1.38). The direct-beam radiation that strikes the active mirror or lens is then directed to an input aperture of the light transportation system. This type of system is significantly disadvantaged under partly cloudy or overcast sky conditions because there is very little light input. An advantage of these types of active systems is that the visible radiation collected can be closely controlled and redirected with a high degree of certainty. On the other hand, this system can be a very complex mechanical device with fairly high associated first costs.

Passive optical systems implement fixed elements to view the most favorable or brightest portion of the sky dome and redirect the light into the light transportation system. The positioning of these types of collector systems must be tuned for a specific latitude to assure optimal performance. With no moving parts, this type of system is less costly for both first cost and maintenance-related expenses. A drawback is the reduced control of the directionality of the collected daylight.

**Transportation System**

The core daylighting system moves the collected daylight from the collection system to the light distribution system where the light requirement exists. New materials have been developed to overcome some of the limita-
tions associated with transporting light any significant distance. The most common types of transportation systems are either fiber optic or light ducts lined with a highly reflective material.

**Distribution System**

The core daylighting distribution system receives its light input from the transportation system and distributes light onto a target area or a space. This element of the system then carries light from the transportation system and emits light within the building. The devices used to accomplish this once again include both optical fibers or optical light pipes or light guides.

An example of this type of strategy has been incorporated into the design of a commercial building in Austin, Texas, for the 3M Company, which manufactured many films used in the design (see Figures 1.39 to 1.42).

The daylighting system designed and installed at 3M Company’s Austin facility marks the third generation of the passive optic system pioneered at the Civil and Mineral Engineering (C/ME) building, a joint venture between BRW Architects and 3M, at the University of Minnesota. This system, designed in conjunction with the engineers at 3M to use their spreading film in the collector system, is used to light a five-story, 65-ft-tall, 50,000-ft² atrium connecting multiple office blocks. 3M’s expertise was teamed with CRSS Architects, Inc., Houston, Texas, for the building’s design. One of the major objectives for the Austin Center was to provide an integrated building campus that brought together all functions of the 3M business (laboratory, administrative, marketing, sales, etc.) into one single structure where people could move freely between locations and interact with each other on a daily basis. It was also important that interior offices have windows with access to natural daylight. Thus, the solution incorporated an enclosed atrium, located between the separate buildings, that was equipped with a daylighting system that could provide natural lighting while reducing the building’s energy load.

Three Fresnel panels were used to make up the exterior primary collector and consisted of a daylighting film laminated to polystyrene panels having an acrylic exterior surface. Three similar panels were fabricated for the interior secondary reflector. The film’s Fresnel grooves run horizontally on the primary collectors, spreading the light ± 5 degrees in the north-south direction, whereas the grooves run vertically on the secondary collectors, spreading the light ± 5 degrees in the east-west direction. The primary reflector spreads the light...
10 degrees in the north-south (vertical) direction, and the secondary reflectors spread the light 10 degrees in the east-west (horizontal) direction. With this film orientation, the harsh solar images would not be cast on the atrium floor 65 feet below. The finished panels were mounted on a metal frame fastened to the adjacent roof structure or dormer. The exterior collectors and vertical glazings between the primary and secondary collectors are easily accessible from the building’s roof. The total fenestration of glazed area, consisting of the north-facing vertical windows, is approximately 28% of the atrium’s total floor space. The system also performs well on cloudy days; for the average overcast day, unusually high light levels are produced within the atrium space. Occupants have reportedly said that they feel that the atrium is brighter on these days than the outside appears to be. The 3M system also significantly reduces the solar heat gains that would normally be associated with a glazed atrium daylighting system. This heat reduction results from the fact that the lenses are made of a material that is an excellent reflector of the visible spectrum but is much less reflective of the infrared wavelengths. With this Austin daylighting system, nearly 58% of the infrared radiation is removed from the light entering the space.

ATRIUM

The atrium building finds its origins in the ancient Greek and Roman courtyard house where the courtyard performed as the social center of the house. Today, the atrium behaves in a similar fashion (see Figure 1.43). Typically, the centroidal placement of the atrium allows it to serve as both an element for circu-

Figure 1.41 3M building roof detail.

Figure 1.42 3M building atrium.

Figure 1.43 Atrium of Brown Derby Hotel. (Photograph courtesy of Susan Ryan Colletta, Denver.)
lation and an element for spatial order. An atrium enjoys numerous functions that can effectively provide pleasant and comfortable environments while allowing opportunities for significant energy savings. Recent changes in glazing and system technologies have allowed large-scale atrium spaces to function with more reliability, fewer water leaks, less maintenance, and fewer other related problems displayed in the past.

Just as the ancient Roman and Greek courtyard house benefited from shade, thermal heat storage and transfer, ventilation, and evaporative cooling, the atrium performs similarly. An atrium designed for maximum energy savings and efficiency should incorporate daylighting, ventilation, and passive heating and cooling techniques as design features. Because the atrium is a centroidially located space protected by glazing, it effectively creates a second perimeter zone within a building. Daylight is able to penetrate into the large interior space while the intervening surfaces reflect the light to adjacent spaces on lower floors. Aspect ratios determine the quantity and location of solar radiation on and within the atrium.

### Section Aspect Ratio
The section aspect ratio (SAR) affects daylighting, passive heating, and cooling factors within the atrium. A high SAR effectively reduces or eliminates the amount of solar radiation that will reach the lower portions of the space. However, a high SAR does contribute to passive cooling by thermal convective means. A low SAR is ideal for daylighting, passive heating, and radiative cooling.

The orientation, size, and geometry of the space, size, and placement of apertures, in addition to facade reflection properties, play important roles in the ability of daylight to penetrate into the interior spaces of a building. However, among the numerous issues considered during the design process, climate presents the greatest potential influence. Local climate conditions affect heating, cooling, and daylighting design strategies. In daylighting, design strategies need to address predominant sky conditions to maximize daylight. For example, predominantly cloudy sky conditions will maximize its daylighting potential with a stepped atrium section. In general, an overhead daylighting source enables the most daylight to penetrate the space because the sky dome is brightest at the zenith. Vertically glazed atrium spaces may enhance exterior views, but the quantity of daylight is not ideal under cloudy sky conditions, and the quality can prove to be too severe if fenestration controls are not used. In hot climate zones where solar heat gain is prohibitive, clerestories are effective, especially with exterior fenestration controls.

An atrium design can allow the intervening floors to be open to it. However, this approach brings with it a number of acoustic and fire safety considerations to which the designer must be responsive.

An atrium can also be thermally separated from the rest of the building by transparent or translucent materials. This allows the total amount of glazing area on partition surfaces to be increased because the atrium effectively serves as a buffer zone between the conditioned spaces and the outside environment.