NATURAL LIGHT IN ARCHITECTURAL DESIGN:

ELEMENT AND DETERMINANT

by

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Abstract

Natural Light in Architectural Design: Element and Determinant

Roger Neal Goldstein

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The importance of natural light in our lives cannot be exaggerated. The religious, emotional, physiological, and perceptual effects of daylight upon human behavior have emphasized its unique role in every culture on earth.

In the creation of his shelters, man has always tried to maintain a visual connection with the outside world. The two-way nature of this "window", however, has also allowed the penetration of light into the interiors, enlivening our activities by its dynamics of color, intensity, and direction.

Through an understanding of the unique characteristics of this important architectural "medium", and the historical and cultural precedents for its rational use, the quality of light in the places we design around ourselves will surely enrich our existence.

Thesis Supervisor: Wayne V. Andersen
Title: Professor of the History of Art

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Introduction

Whenever we enter an architectural space, we automatically formulate an unconscious value judgement as to the quality of that space -- "good" or "bad." It is my belief that one of the primary reasons why many "good" places are thought of as such is that the natural light present has specific qualities, both tangible and intangible, that are significant in our perception of these places. In effect, we are attracted by the light, and its ability to determine and change the characteristics of architecture. I have decided to explore the underlying factors that produced these particular qualities of light, especially in interior spaces.

In this age of heightened environmental consciousness, there has been a resurgent interest in natural light as a source of illumination as well as energy for buildings. With light, as with any building material, it is important to understand the design limitations and implications. In this respect, I feel that natural light can be manipulated as effectively and predictably as we use bricks, wood, or concrete. Further, I believe that natural light should be the primary source of interior illumination during the day, supplemented by artificial lighting only when necessary. I have been greatly influenced by the British attitude towards daylighting, which is discussed in greater detail later in this thesis. I believe that there are many architectural precedents which evidence an understanding of the sensitive use of natural light, and that they have not been fully appreciated in this context.

The goals of this thesis are threefold: To understand the inherent characteristics of natural light, and how we perceive them; to learn from the historical precedents; and to suggest a set of general guidelines for designing places, in today's world, with a renewed sensitivity towards natural light.

There has been a range of conceptions concerning this topic; this thesis is but one approach. It is a modern-day set of observations and recommendations, relating to and building upon previous thought. This is not intended to be a complete, detailed design handbook; that may be a future evolution. It is inteded to be a simplified, many-faceted introduction to the subject, and may find particular application, for example, in an early phase of an architectural curriculum.

Most of the literature relevant to the subject of natural light in architecture falls into a few general categories. These include technical daylighting manuals, studies of effects of light (or the lack of it) on people, or historical investigations of architectural elements, such as glass or windows. The problem I found with nearly all of these sources is that nowhere is there a simple, practical explanation of the subject as related to architectural design. It became clear, in the one introductory lighting course I took, and was confirmed by my thesis research, that such an overall study of this nature could be immensely valuable.

This thesis, then, is different from the existing body of written works in that it is intended to be a concise, wide-ranging, practical introduction to natural lighting, with the emphasis on an understanding of the historical, perceptual, psychological, and physical contexts of its use in architectural design. I have tried to uncover the interrelationships among these aspects,

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rather than exploring any one of them in more depth than the others.

Some of my fundamental notions are drawn from a course in Lighting taught at MIT in the Fall of 1974 by Visiting Professor David Moizer. That course tried to deal with both natural and artificial lighting, and stressed mathematical manipulations. It suffered from trying to cover too much, and so my initial research involved re-learning the fundamentals. My research has consisted primarily of reading and digesting any sources that bore a relation to my subject. Daylighting has not been seriously considered in any but technical terms since the mid-century decades; prior to that time, there was a relatively large amount written concerning the value of natural light, in psychological and aesthetic, as well as quantitative terms.

Readings were supplemented by personal observations and photography of architectural examples, especially in the Greater Boston area. In light of my increased knowledge of the subject, I have been able to draw upon my previous travels, both domestic and foreign, to illustrate certain points.

In a larger sense, I have found an explanation for my urge to photograph specific interior spaces: the attraction is simply the quality of light that manifests itself there. This thesis has helped me to find a thread of cohesiveness that ties together several parts of my architectural and visual education.

Natural Light

Light is as much a "material" for building as the stones, bricks, and other components used in construction; for, although there would be no wall without its structural components, the wall has no real existence for us unless it corresponds to a sensual impression, gained with our eyes and substantiated with our minds.

Derek Phillips

1 The Need for Natural Light

Natural light is free and abundant. Its qualities are recognized and varied. Since the beginning of civilization, it has had important positive associations with man's religion, health, and culture.

The need for natural illumination in interiors has been investigated by lighting engineers, physicians, and psychologists for several centuries, and thus had a profound effect on daylighting, the science of natural illumination. Research on the effects of the deprivation of light, the need for view, and effects on biological processes have confirmed the factual bases for this need.

Studies have been conducted on the preferences of office workers and home dwellers for daylight and sunlight. As one might expect, the desire for sunlight is strongest where its duration is most limited. Furthermore, this desire may be proportional in some way to the degree of physical confinement in which a particular activity takes place.[1]

There seems to be a relation between sky and weather conditions, and human emotions. Overcast days, for example, make many people depressed, especially when the cloud cover persists for several days. The long-term version of this sky condition gives rise to what is known as the "winter blues"; a longer period of depression. By contrast, when one discoveres that the overcast sky has broken and the sun has come out, the mood usually changes to opti-

[1]Belinda Lowenhaupt Collins, Windows and People: A Literature Survey (Washington, D.C.: U.S. National Bureau of Standards, 1975), pp. 60-61.

mism and general well-being.

We recognize the characteristics of daylight produced by these two basic sky conditions, and those of different times of day, based on our growing up with an awareness of weather and its implications for clothing, shelter, and activities. Louis Kahn expressed his awareness of this when he stated that "the cloud that passes over gives the room a feeling of association with the person that is in it, knowing that there is life outside of the room ..."[2]

Figure 1.1 The sun is an infinite source of heat and light; the components of its radiations are vital for the maintenance of life.

The increasing amount of time that we spend under artificial illumina-

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[2] Light is the Theme: Louis I. Kahn and the Kimbell Art Museum, comp. Nell E. Johnson (Fort Worth, Texas: Kimbell Art Foundation, 1975), p. 18

tion, especially fluorescent, is biasing our "diet" of light, and may be affecting our mental and physical health. Research conducted in recent years by MIT's Dr. Wurtman has indicated that a lack of certain wavelengths of ultraviolet light (part of sunlight) may have a noticeable effect on human performance.[3] Russian researchers "have insisted upon the inclusion of trace amounts of ultraviolet light in the lighting systems for factories and mines. They claim that a lack of u-v lowers resistance to disease, reduces vitality, and causes the worker to tire more quickly."[4] The study of photobiology, or the effects of illumination on animals and plants, suggests that "it seems reasonable that the light sources to which we expose people should not deviate markedly from the lighting environment under which people evolved in nature."[5]

The need for a view of the outdoors, and how this view is affected by different types of solar (reflecting or absorbing) glasses, has also been investigated. It was found, for example, that office workers whose window walls, 60% of the area of which was glazed with solar reflecting glass (15% transmittance), complained of "the depressing visual effect of the external view due to the reduction in luminance, the need to use artificial light during the daylight hours, and the fact that the glass became a mirror to the room interior when external illumination levels were low."[6] These specially treated, selective transmittance glasses are used for the reduction of solar heat gain and sky glare, but they seem also to have psychological effects that may ulti-

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[3]Collins, p. 69.

[4]Collins, p. 69.

[5]Collins, p. 70.

[6]Collins, p. 66.

mately "cost" more in terms of the emotional and physical well-being of the occupants of the building. (See also Chapter 13, "Glazing Materials.")

The windowless building is a phenomenon of our technological age that may possibly be the nadir of architectural sensitivity to man's psychological needs. With the availability, in the 1950's, of full airconditioning, offices and even schools could be built without windows to disturb their controlled climates. Besides the control imposed on the ventilation and temperature of these interior "climates," the lighing was maintained at a suitable level through the use of extensive artificial illumination.

In spite of their energy-saving, economic "advantages," the entire issue of the health of the occupants of these buildings seems to have been given lower priority than the expedient, technological, controlled solution. With such widespread application of cheap, controllable lighting came a reduced sensistivity towards natural light. James Marston Fitch recognized this situation when he said: "It is characteristic of American illuminating engineering that, historically, it solved the technical and optical aspects of its problem before it solved the physiological; or that once a new source of light were perfected, its use would, for a time at least, obscure its basic subordination to natural light."[7]

Rooms that lack windows, and thus natural light, are usually seen by their occupants as depressing, psychologically numbing, and tension-producing.[8]

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[7]James Marston Fitch, American Building: The Forces That Shaped It (Boston: Houghton Mifflin Co., 1948), p. 245.

[8]Robert Sommer, Tight Spaces: Hard Architecture and How to Humanize It (Englewood Cliffs, N.J.: Prentice-Hall, 1974), p. 116.

There is no contact with or knowledge of the weather or the time of day, and no visual relief. Such a lack of natural light may ultimately have an effect upon human performance, and certainly makes one feel as if he is in a dungeon, with all of its implications.

It should be clear from the preceding discussion that there is reasonable evidence pointing to a necessity for natural light in our offices, schools, houses, and other interior spaces in which we must function with a degree of comfort. This is not a call for all-glass buildings (some of their characteristics are discussed in part III), but a statement of the established human need for daylight.

In those latitudes where daylight is at a premium, such as in Scandinavia, there have been serious attempts to maximize the amount of this daylight that enters buildings, and to do so in very selective ways.

On the other hand, in more tropical latitudes like the Middle East, it is both impractical and uncomfortable to admit a great deal of direct sunlight to interior spaces, but the need for recognition of the existence of the sky is not denied. Ways of letting indirect daylight into the rooms of their buildings, without increasing solar gain, have been developed over the centuries. One such method is the reflector wall, which absorbs the heat of the sun, but reflects the light into the nearby window.

It seems that, in such extremes of latitude, people have become critically aware of their relationship to natural light, out of necessity. It may be that our temperate climate has allowed a range of attitudes and reactions to this issue, rather than a clear commitment to one way of dealing with natural light. If we truly recognize our inherent dependence on the sun, then a

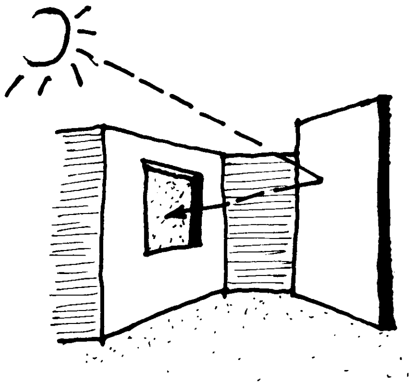

FIGURE 1.2
MIDDLE EASTERN 'REFLECTOR WALL'

considerate attitude with respect to its use seems to be the inevitable result, and can only enrich our lives.

2 The Characteristics of Natural Light

Sunlight and Skylight

The natural light that enters a room from the sky consists of two basic parts. They are (1) direct sunlight (insolation) and (2) diffuse skylight. On a clear, sunny day, the "warmth" of sunlight plus the "coolness" of skylight give correct color rendering. By carefully orienting a window or a roof-light, one can allow for the penetration of both elements of daylight, if so desired. (See also Part III.)

Figure 1.3 Beams of direct sunlight can be magical.

It is reasonable to assume that the sky is brightest in the area nearest the visible sun, which is the southern part of the sky when you are in the northern hemisphere. However, when the sky is uniformly overcast, the horizon is 1/3 as intense as the sky directly overhead, regardless of sun position. This is due to the property of such a sky which makes it act as a complete diffuser. Since one looks through more layers of the atmosphere near the horizon, its brightness is less. What this means is that the northern sky is just as bright as a southern sky on an overcast day.

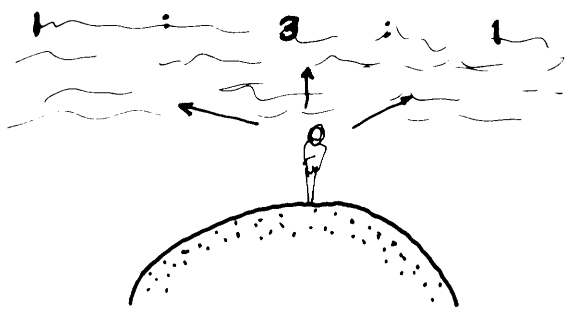

FIGURE 1.4
RELATIVE SKY BRIGHTNESS ON A COMPLETELY OVERCAST DAY

Modelling

One of the most characteristic manifestations of light, produced by a particular directionality, is modelling. Modelling can be described as the revelation of shapes and textures that project pepenticular to the direction of the light. Since we, and all the objects that surround us, are held to the earth by gravity (a force exerted perpenticular to the earth's surface), horizontal illumination tends to produce the optimum modelling effect. Since most windows are on vertical walls, most of the light in our rooms has this horizontal orientation.

Harsh contrasts and shadows are produced when the source of illumination is unilateral (one side). That effect is softened by adding a second source, such as another window, either on another wall or above, which fills in the shadows, and gives a better gradation of tones. If another source is not added, as is usually the case in tower buildings, high reflectances of room finishes will aid in this tonal formation. (See also Part III, on room finishes and their effects.)

Dynamics of Natural Light

Another quality of natural light that distinguishes it from artificial lighting is its dynamic nature. Shifting clouds that momentarily obscure the sun, sudden thunderstorms, the slowly setting sun, all remind us of the uncontrollable, continually changing weather. This characteristic that we all find so pleasant is also what provided constant impetus for the development of controllable, predictable artificial light sources.

It is argued that because of its limited duration (1/2 day), and its variation during the seasons, natural light is not an economically effective

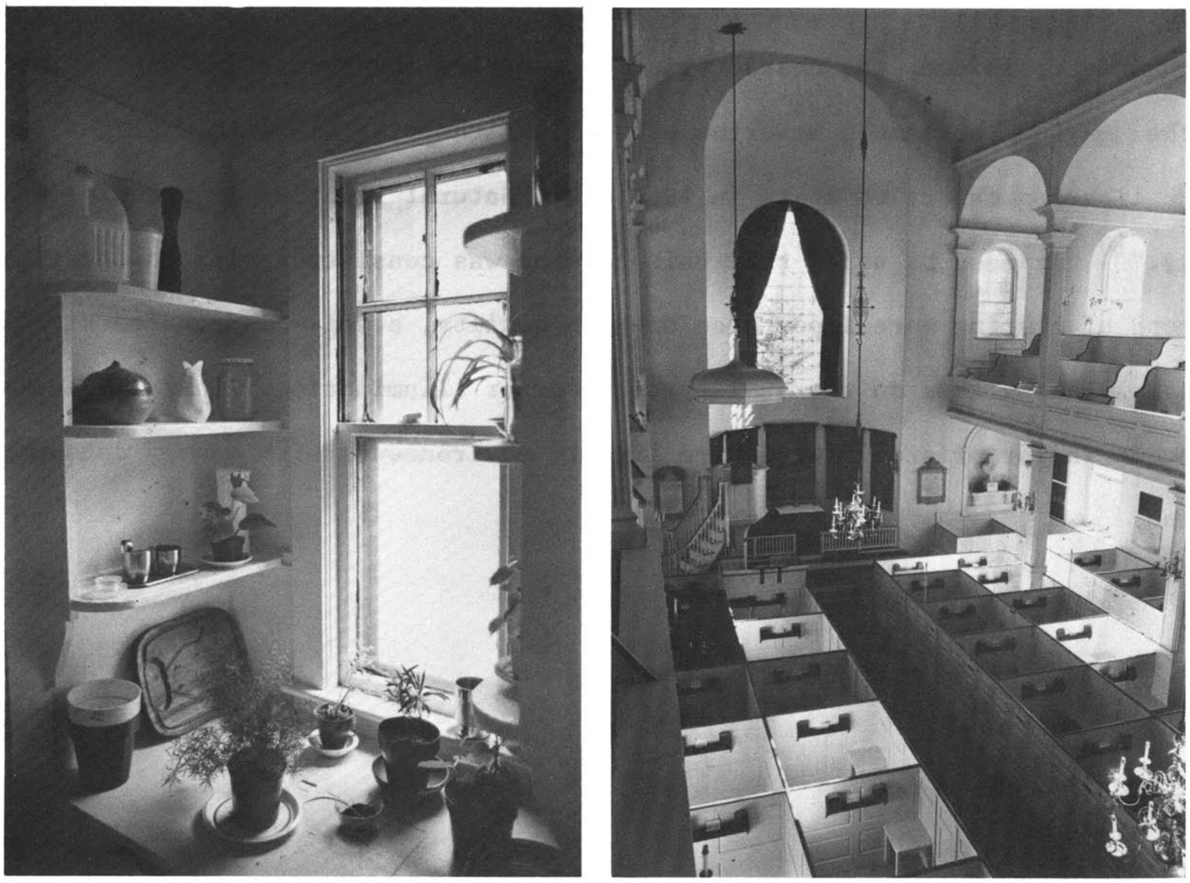

Figure 1.5 (left) Light-colored finishes soften modelling. (right) Boston's Old North Church is animated by the moving sunlight.

light source.[9] These dynamics also prove to be a problem from the point of view of precise rendering of colors; the eye can recognize colors under different kinds of natural illumination, but it is not suitable for precise scientific work involving color.

Of course, we may all agree that its advantages far outweigh its dis-

[9] Derek Phillips, Lighting in Architectural Design (New York: McGraw-Hill, 1964), p. 7.

advantages; indeed, the characteristics that are interpreted as one or the other may be the same! Nevertheless, all of the problems with daylight led one lighting expert to state in 1964 that "Natural lighting is becoming a luxury."[10] It must be noted that this opinion was consistent with the American trend of placing more importance on high quality, evenly-distributed artificial lighting than on the quality of interior illumination. This stance has become inappropriate if we desire livable environments with energy conservation.

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[10] Phillips, p. 13

3 The Perception of Light

Visual Sensitivity and Adaptation

It would be valuable at this point to digress into a brief discussion of the sensitivity of the human eye with respect to color, intensity, and contrast of illumination.

On the inside of the rear of the eyeball is the retina. Its two main components are the rods and the cones. Each of these types of light receptor has a different sensitivity. The rods are more sensitive at lower light levels, but they don't discriminate among colors; their maximum response is to shorter wavelengths of light, or the blue end of the visible spectrum. The cones, on the other hand, are more sensitive to the red end, and account for full color discrimination. They respond primarily at higher light levels.

The concept of adaptation level is useful in this context. Simply stated, it means that one's eye/mind, or perception/interpretation team can acclimatize itself to a given lighting and contrast situation, usually within a range of 100:1, and that brightness constancy will be maintained over this range. Beyond this adaptation level, we automatically limit the brightness range in order to improve perception and discrimination. Commonly-used automatic reflexes are shading with a hand, or moving closer to the object we wish to see. This problem occurs most often in bright places like the ocean beach or a snowy area on a sunny day, or a plaza of light-colored paving material.

An aspect of adaptation level that must not be overlooked is the time and space that is necessary to adapt to a change in brightness level, such as the transition from the daylit outdoors to a dark entry hall. Perception and discrimination of objects in the visual field are impaired for a time ranging from seconds to several minutes, depending on the person's age, the brightness contrasts, and the time of day.

In designing interior spaces, this factor should be kept in mind. One might provide a visual transition between the outside and the inside, in order to facilitate the eye's adaptation to different brightness levels. This space has additional value as a physical transition space, and takes the form of an entry hall, porch, portico, or lobby.

Another common example of a situation requiring such a visual transition is the highway tunnel. During the daytime, the brightness level change as one enters the tunnel is extreme, and one's perception of other cars is dangerously impaired. It would seem logical to increase the artificial illumination of the ends of a tunnel, in order to ease this transition. Experimental installations utilizing this principle are in place throughout this country, and the related research has been extensive.

Contrast/Brightness Constancy

The contrast range of sunlight is greater than that from most artificial sources. In actual relative intensities, in foot-candles, the ratio of direct sunlight to dark shadows on a clear summer day may be on the order of several thousand-to-one! The human eye, however, is able to discriminate between these extremes and everything between just as easily as it does in a room with "flat," low-contrast lighting. It can recognize a white surface or a color in both circumstances, even though a camera would probably not be able to do so. This phenomenon is known as brightness constancy, and can be described more fully as "the effect of interpretation that one perceives things in relation to both their reflecting characteristics and to the incident light so that a white wall at the back of a room, receiving perhaps one-tenth of the illumination of a grey surface near the window, nevertheless looks white and not grey."[11]

As mentioned above, this situation is purely perceptual, and it cannot be photographed. Brightness constancy is a phenomenon that is in effect at all times, whether or not we are aware of it, and its preservation is an important criterion in good daylighting. Furthermore, the fact that humans respond to a wide range of lighting situations through this mechanism is responsible for some difficulty in making useful photometric measurements. A lighting engineer can measure the light and design the lighting in such a way as to be "correct," but he cannot predict how bright it will appear to an observer.

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[11]R.G. Hopkinson, P. Petherbridge, J. Longmore, Daylighting (London: Heinemann, 1966), p. 449.

Gloom

We have all used the term "gloomy" to describe a particular lighting quality in a room, but the mechanisms that produce it are not always understood. It is usually the visible result of any one of several effects of the failure of brightness constancy at reduced illumination levels.

When illumination is reduced:

a) The apparent contrast between greys and whites increases

b) The apparent contrast between greys and blacks decreases.

These two effects combine to create the "white dog effect," because of the ability to discern white objects in underlit situations.

c) Subtle gradations of tone in modelling seem harsher.

d) Warm colors lose their vividness (chroma) sooner than cool colors. That is why a darker room looks colder. This is due to the differing receptivities of rods and cones; the eye is more sensitive to blue (rods) at lower luminances.

All of these effects combine to create what we commonly call "gloom." Probably the largest single factor creating the feeling of gloom, however, is excessive contrast at the window. We will see later how important it is to have tonal grading away from the window, both from the point of view of perception and from the point of lighting quality: i.e., the elimination of glare.

Glare

One of the basic problems inherent in the use of natural illumination is glare. An understanding of its nature will help in identifying its causes and remedies. The avoidance of glare must always be weighed against both the quantity of daylight in the room and the distribution of this light.

Glare is related to the contrast present in one's visual field at a particular moment. It is important to emphasize this qualification because one can avoid a particular glare problem often by turning away from the light source. This reaction does not, however, eliminate the source of the problem.

Figure 1.6 Glare can be created by excessive contrast in the field of view.

The luminance of the sky is the greatest factor in determining glare, and so its reduction from the point of view of the observer will result in the most improvement. Keeping this in mind, as well as the trade-offs among quality, distribution, and glare, it seems only logical that windows designed for good light penetration on dull days will inevitably need some sort of brightness control on bright days. (See Chapters 13 and 14.)

The nature of glare is determined by the type and location of light source and the characteristics of the surfaces that surround a given task. A good example of the relation of "surround brightness" to "task brightness" is given in the differing experiences of viewing headlights at night and during the day. The apparent contrast is greater at night (also due to a lower adaptation level), and the direct view of a headlight is more acutely felt than when the surrounding areas of the visual field are brighter.

The fact that this light source is directly in one's field of view makes it even more disturbing. Similar examples of such orientation are the "window at the end of a corridor" and the tunnel discussed earlier. The presence of such a light source makes it hard to discern details in objects in the view in that direction; in a larger sense, it reduces the ability to see.

In certain cases, however, a light source in one's direct vision has found appropriate application. The most common example is in religious buildings, where the association with the "guiding light" proves to be a more powerful principle for such architectural design than the avoidance of glare. One is drawn to "follow" the light; hence the proverbial "light at the end of the tunnel."

Let's examine these examples in relation to the two basic types of glare: disability and discomfort.

Disability glare is due to the reduction in the sensitivity of the eye to contrast. The most common cause of disability glare is the scattering of light inside the eye, which thereby superimposes the luminosity of the eye upon the image. This is known as "veiling glare," and the most recognizable example of such glare is the same corridor-window situation. Disability glare is also a function of the cloudiness of the interior of the eyeball, which increases with age. This is one reason why older people find it more difficult to drive at night: headlights create more veiling effect.

Discomfort glare can be considered to be an extreme case of disability glare. It is determined by excessive contrast in the visual field, and by the ensuing saturation of the visual response mechanism. If one has ever tried to perceive depth or objects in shade while standing in a snowfield in the sun, one has experienced discomfort glare. The automatic response is to squint, thereby reducing the overall brightness of the visual field, and the contrast present.

The contrast sensitivity curve of the eye has an effect on glare perception. At low light levels, contrast perception is lower than at high levels. In other words, there will be more disability glare from a large window on a dull day (when the interior light levels are lower in proportion to the sky brightness) than on a bright day.

Size of windows has an effect, too, upon glare. With small windows, glare is due mostly to contrast. In fact, small sources in general generate both types of glare (see also "Gloom.") Glare due to large windows, on the other hand, is primarily from the optical saturation of the eye's interior.

The immediate environment of the window, that is, the framing and the

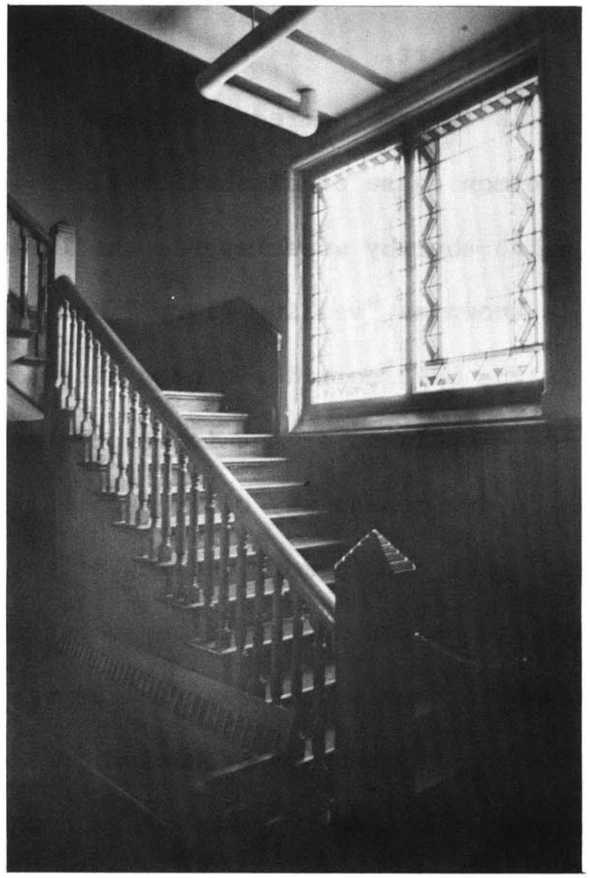

Figure 1.7 Glare can be due to optical saturation of the eye, or even of the camera.

window wall itself, play a major role in the existence and extent of the glare. Dark window bars, mullions, frames, and window wall -- all increase the contrast with the sky, and hence the glare. As we shall see in the second and third sections of this study, there are some very simple remedies for glare, regarding the use of glazing materials, framing design, and surface finishes, all of which have been employed both consciously and intuitively at one time or another throughout the history of windows.

In all of these situations, it must be kept in mind that perceived glare is largely determined by the particular task being performed, and whether its proximity and orientation to the window are changeable. It is important to avoid the creation of potential glare situations in every case, but particularly in places such as factories, offices, and schools, where tasks are often fixed in relation to the view of a window.

The avoidance of glare, and the resulting implications for designing with natural light in a controlled way, have been superseded at various times in the history of architecture, often for reasons related to religious preference. A present-day observer of a "bad" lighting situation in an old church, for example, must be wary of judging it solely as related to today's recommendations for provision of quality daylighting. Clearly, there were different values operative at the time of its construction, regarding window size and location and interior finishes. The religious associations with light and light sources were thus in conflict with what would be suggested today. Indeed, such conflicts were used purposefully to create particular moods in those interiors. As long as an architect is aware of the options to, and consequences of, a design, such decisions can be creative tools for daylighting of interior spaces.

4 The Calculation of Interior Daylight

This chapter is not intended to be a complete, technical guide to daylight calculations, only to explain some of the terminology that is used in most discussions of daylighting.

Illumination refers to light falling on a surface, and is given in units of foot-candles. A foot-candle is the light shed by a standard candle upon a surface exactly one foot away. Luminance refers to light radiating from a source, and is measured in foot-lamberts, equivalent to foot-candles. An important physical principle, which limits the effectiveness of internally-reflected light, is the inverse-square law. It states that, as the distance between a light source and a surface increases by a factor of $\underline{x}$, the light intensity on the surface is reduced by a factor of $\underline{1/x^2}$.

A convention has been adopted with respect to daylight calculations. A completely overcast sky is assumed to have a luminance of 500 ft-L, and is known as a C.I.E. sky, after the international body that sets such standards. Another convention is that direct sunlight is always ignored in these calculations.

In order to design a daylighting configuration, it is necessary to recognize that light reaches a point in a given room from a number of sources, as shown in Figure 1.8.

The daylight factor is simply the proportion of the external illumination that reaches a given point in a room at a particular time. It is given as a percentage ratio: i.e., 2% D.F. means that 2% of the available daylight is reaching the reference point in the room.

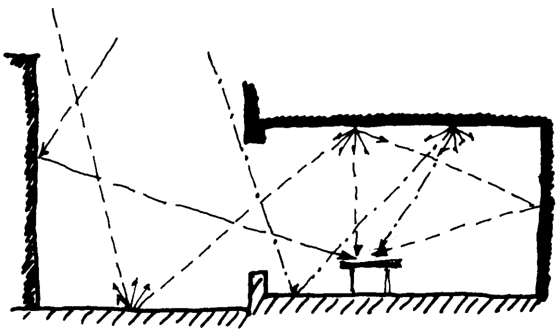

FIGURE 1.8[12]

→ DIRECTLY FROM THE SKY
--→ DIRECT REFLECTION FROM EXTERNAL OBST.
---→ REFLECTION FROM GROUND, CEILING, WALLS
-·-→ REFLECTION FROM FLOOR AND CEILING

The daylight factor is composed of the sky component, or the direct daylight (ignore sunlight), plus the internally reflected component (IRC), plus the externally reflected component (ERC). If the window openings are unglazed, the sky component is called the sky factor. This basically ignores the transmission loss of glass, dirt, and window bars, and the changes of weather.

The ERC is concerned with reflections from objects obstructing one's view of the sky from a given window, such as buildings or foliage, and with reflections from the ground. It is usually a small fraction of the total illumination, except when direct sunlight is bounced off a nearby south-facing wall into a north-facing window, for example.

When the sun is directly overhead, the ground is of greatest value as a reflector. According to the IES Handbook,

> The light reflected from the ground on sunny elevations commonly represents 10-15% of the total daylight reaching a window area. It frequently exceeds this proportion with light, sandy soils, light

[12] Figure from Hopkinson, p. 69.

vegetation, or snow cover. On non-sun exposures, the light reflected from the ground may account for more than half the total light reaching the windows.[13]

This fact can be used intelligently by the architect, as an aid in increasing interior illumination. Callender recommends that "reflecting pavements and similar treatments of the terrain surrounding the building can be particularly effective at distances from 1/2 to two times the height from the ground to the top of the window."[14] This recommendation applies primarily to one- or two-story buildings. Closer than this distance, the window sill usually obstructs such reflections. Further away, the reflections may pass over the roof of the building.

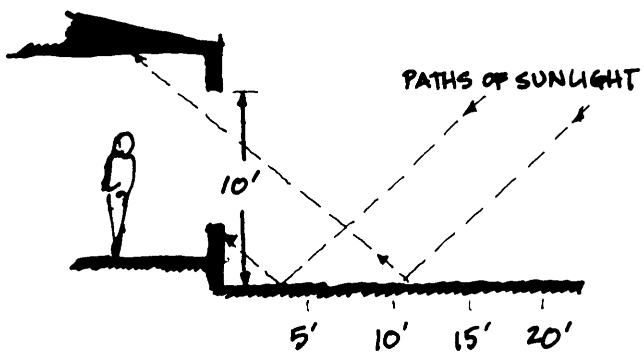

FIGURE 1.9
EXAMPLE:
USEFUL RANGE FOR APPLICATION OF REFLECTIVE TREATMENT

The IRC indicates the importance of exploiting the continuous series of interreflections of daylight in a room whose surfaces have high reflectance factors. These factors are given as percentages: 70% R.F. indicates that a surface of this value reflects 70% of the light incident upon itself. The rest, of course, is absorbed and converted to another form of energy, heat.

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[13] John E. Kaufman, IES Lighting Handbook, 4th ed. (New York: Illuminating Engineering Society, 1966), p. 7-5.

[14] Time-Saver Standards for Architectural Design Data, ed. J.H. Callender, 5th ed. (New York: McGraw Hill, 1974), p. 926.

(See also Chapter 15, "Interior Surface Finishes.")

In daylight calculations, allowances must be made for other factors which reduce or increase the actual amount of light reaching a reference point. These include dirt and maintenance, window area occupied by framing elements, glass transmittance factor, room size, and window size. Each factor is a percentage multiplier less than 1, thus reducing the actual light that reaches the interior.

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The Evolution of Natural Lighting

The history of architecture is the century-old struggle for light, the struggle for the window.

LeCorbusier

5 Early History

The quantity and quality of the daylight that enters a room are determined initially by the window through which it passes. The placement of the window with respect to orientation, proximity to exterior walls, outside obstructions, and sky exposure all have particular effects upon the light as it enters. It would seem valuable, at this point in the discussion of sensitivity to natural light, to investigate the evolution of the window, taking notice of various functions it was called upon to perform, and effects of gradually increasing sophistication in manufacturing techniques and structural systems.

In the early houses that primitive man built, the light came from two directions: From the *top*, via the smoke-hole, and from the *side*, through the doorway. McGrath has suggested that these early light-admitting voids, determined only by necessity, were first steps in an evolutionary process that may have led, directly or indirectly, to the open courtyard house and the window, respectively.

> The development of the inner court may well have been contributed to by the smoke outlet via the light-well, and in this connection it is noteworthy that the classic house consisted of a series of chambers one floor in height grouped round a central court, the external walls surrounding the group having a few small windows but the main lighting being provided by the doors from the chambers to the court, a system which persisted in Mediterranean countries for a considerable time.[1]

The doorway opening seems to have become the standard void-in-the-wall, admitting light from one side of a room. The door itself originally acted as

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[1]Raymond McGrath, A.C. Frost, *Glass in Architecture and Decoration* (London: The Architectural Press, 1937), pp. 86-87.

a filter or barrier in the opening, allowing or prohibiting light, physical access/egress, and penetration of weather. Over time, the half-door, or Dutch door, came into evidence, still providing those three elements, but with more flexibility -- it was now possible to prevent access while still admitting light and air. The vestigial form of this half-door can be seen in the existence of the half-glazed door, which gives one a poor compromise of those three qualities.

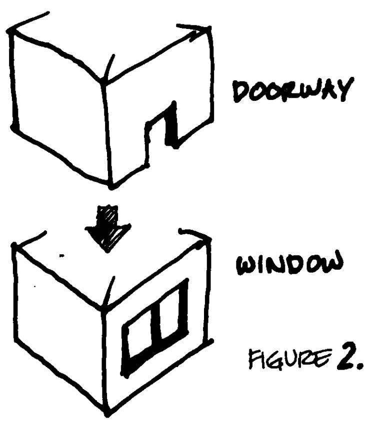

FIGURE 2.1

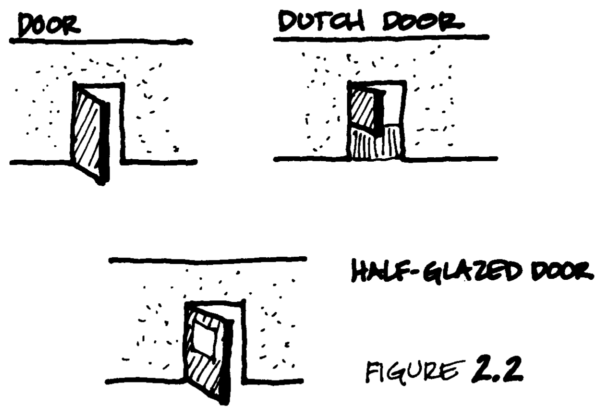

FIGURE 2.2

The word "window" is derived from the Norwegian word vindauga, meaning "wind-eye," and early windows served simply that purpose, to limit the infiltration of weather. The only filters of incoming elements were shutters of various types. It wasn't until the Romans that an attempt was made to use transparent glazing materials to keep out the weather. In the first century A.D., thin sheets of "lapis specularis" (probably talc) were used for glazing, according to references in the writings of Seneca and Pliny.[2] According to evidence from excavations in Pompeii and Herculaneum, it has been determined

[2] John Hix, The Glass House (Cambridge, Mass.: MIT Press, 1974), p. 9.

that some rich Romans had small pieces of real glass for their greenhouses.[3] This primitive glass was apparently cast in a mold consisting of a flat stone, out of which had been carved a shallow depression. The public baths in Pompeii also had windows of plate glass which had been slightly ground on one side to prevent passersby from looking in.

In spite of this evident use of glass as a glazing material, other substances were more commonly employed in Rome. These included linen, shells, alabaster, and sheets of mica. Windows of this time in the Far East were occasionally glazed with mother-of-pearl or tortoise shell. (See Chapter 13 for a contemporary example of a translucent wall material.)

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[3] M.A. Wallace-Dunlop, Glass in the Old World (London: Scribner & Welford, 1882), p. 163.

6 History of English Daylighting

Of all the civilizations of the modern world, the British seem to have been most publicly concerned with natural light. They have done the most research, established the most precise standards and design criteria, and written the greatest number of daylighting manuals. Their concern has included legal statements of man's need for daylight: the principle of "ancient light." A series of parameters defining PSALI, or Permanent Supplementary Artificial Lighting of Interiors, has been developed, further emphasizing their conviction that natural light should be the primary source of interior illumination. In PSALI, daylight is the dominant interior light source up to 40 feet from the window. Beyond this distance, it is used as a supplement to the artificial light, in order to add interest and variety, as well as visual contact with the outside world.

It is in the context of this attitude towards natural light that the history of English daylighting is now discussed.

The stone-casting technique of making glass panes was carried by the Romans to Britain, and was practiced there sporadically for several hundred years. In Roman Britain, window glass was usually 1/8-inch thick, with irregular surfaces, and green or blue in color. This latter characteristic created a feeling of coolness in some interiors, thus aggravating the perceived sensations of the traditionally damp English climate.

By the fifth and sixth centuries A.D., the French had progressed further with glass making that the British. In fact, it became such a lost art in

England that, in 675, the Abbott of Wearmouth sent to France for craftsmen to make glass for his church.[4] There ensued a revival of the art in England which lasted 200 years, only to be forgotten again from the eighth through the thirteenth centuries.

In Norman and Saxon England, windows were no larger than small slits set near the top of the wall, sometimes closed by wooden shutters. The restricted size was determined by the prevalence of violent attacks by rival lords. Glass, even if it had been available, would have been out of the question as a window material.

Needless to say, the diminutive size of Norman windows greatly reduced the quantity of light entering the interiors of the castles. In order to maximize this quantity, window reveals were deeply splayed, thereby reducing glare and expanding the illuminated zone of the room.

FIGURE 2.3
INTERIOR VIEW
NORMAN WINDOW

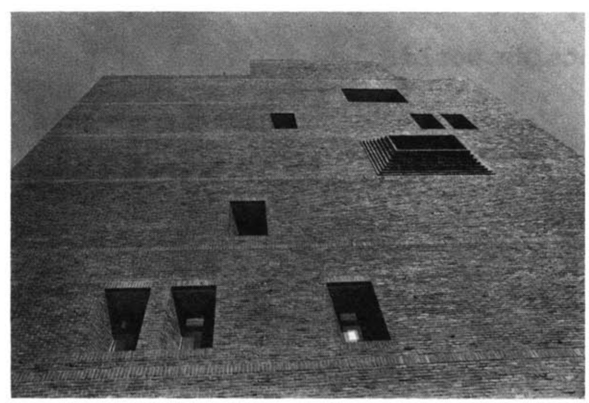

Figure 2.4 These small, deeply splayed windows on Larsen Hall at Harvard are reminiscent of Norman windows, although there is presumably less fear of attack.

[4]Richard Sheppard, Hilton Wright, Building for Daylight (New York: MacMillan, 1948), p. 13.

In walled towns of this era, windows were somewhat larger, obviously because of the reduced need for protection from attack. The inhabitants used oiled linen or parchment strips to seal out the weather. Later they employed ground pieces of horn, set in strips of lead.[5]

It was clear that only those structures that were immune to invading armies were those in which glass could be used as windows. The only buildings that fit this requirement were churches. Since the English had lost the techniques of glass manufacturing, during the eleventh and twelfth centuries most glass in their cathedrals came from France. Every attempt was made to maximize the penetration of the characteristically gentle British daylight into the churches.

The initial use of glass in churches was known as "plate" tracery, and was created by punching holes in plates of stone, and then filling them with small pieces of glass. "Bar" tracery was the next step in the evolution of windows in the eleventh and twelfth century stone churches: members of the window frame were built up of separate pieces. This structure led ultimately to the glazing bar or mullion.

Two external events after the twelfth century had a significant effect on window size and quality in England. First, coal replaced wood in the glass manufacturing process, reducing the cost while improving quality. Secondly, law and order became more widespread in the country, so people were less concerned with protection from attack, and therefore could consider larger windows for their homes and other buildings.

The glass-making industry continued to grow and produce more refined

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[5] Sheppard, p. 14.

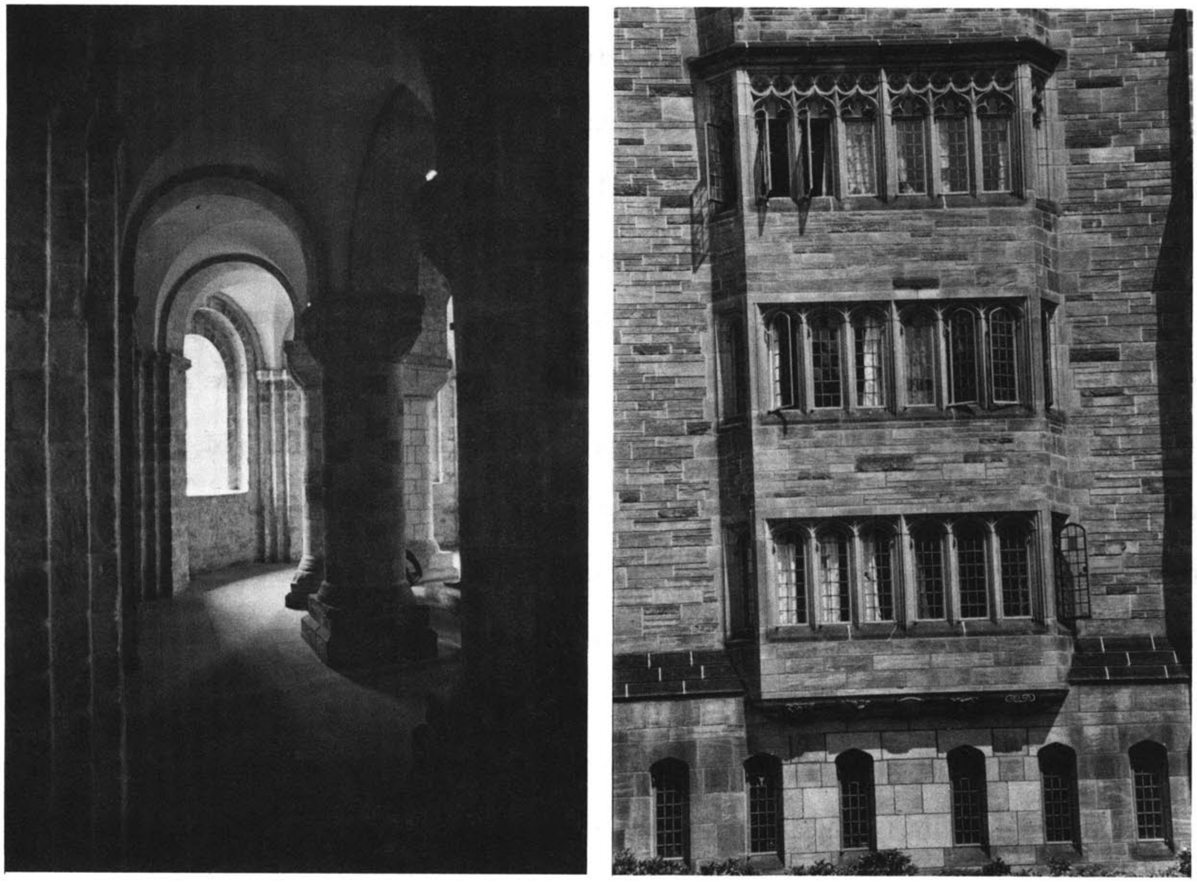

Figure 2.5 (left) The Tower of London's interior demonstrates the "tonal grading" produced by a succession of vaults. (right) This building at Yale, built in the 1930's, has references to old English window design.

products, and cost decreased with higher output, but the size of glass panes remained small. Nevertheless, Gothic churches increased the intricacy of their glazing, and the light thus transmitted to the interior became clearer and less colored due to fewer impurities in the glass. As Charles Winston stated in The Art of Glass Painting (1865):

> As Gothic interiors became, by reason of the increased size and number of their windows, more light, the picture glass-paintings themselves not only contained a less quality of coloured and a greater

> proportion of white and yellow stained glass, but eventually their colours individually became less intense in hue.[6]

The richly colored stained glass we are all familiar with from churches and other religious buildings originally began as painted glass. As glass-making methods improved, the colors were impregnated into the glass through selective use of mineral impurities. Medieval Christianity has been associated[7] with masses of vivid colored glass depicting significant religious scenes. As the political and religious intensity of this period declined, so too did the use of such decorative glass. With the expansion of technological knowledge arising out of the Renaissance came more concern for purity and quantity of natural light in interiors. "The decline of Catholicism and the influence of the Renaissance can be no better illustrated than in this insistence on light at the expense of decoration -- less obscurity but also less brilliance, more reason, it might be said, but less significance."[8]

The Gothic period was the next important phase in the development of glass as a building material. As Gerhard Rosenberg stated in the R.I.B.A. Journal of 18 January 1936, "Without glass, indeed, there could have been no Gothic."[9] The quality of light in Gothic buildings, especially cathedrals, was determined primarily by the available glass, by the intention of the architect to use as much glass as possible, and, hence, the structure thus necessitated.

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[6] McGrath, p. 91.

[7] McGrath, p. 92.

[8] McGrath, p. 92.

[9] McGrath, p. 93.

By using a structural framework consisting of massive masonry piers that provided primary support of the building, the space between these piers could be one huge window. Exterior and interior reveals were splayed in both plan and section, resulting in better spreading of the light. Glass "lights" were made no larger than eight inches square, and so were held together by lead strips, producing the intricacy we recognize. Moldings, also splayed, were needed to keep off the rain because these lead joints leaked badly. They also "captured" more daylight, and reflected it into the interior spaces. The pointed arch from the vaults of the church itself was carried consistently in the window; a gable carried the runoff from the window head. Since the glass was small, and lead-framed, there was a problem of rigidity. As a result, lead glazed panels could not be more than 2'6" square. This finally determined the minimum spacing of the stone mullions that held the tracery together.[10] (See also, Chapter 12, "Window Design -- Framing.")

The perception of these windows was not as a void, as there would have been had the panes been much larger, as is common today. "The beauty of the Gothic window, so far as the exterior is concerned is that it presents a textured surface sufficiently individual to emphasize the window opening and sufficiently patterned to curtain the void."[11]

After the War of the Roses in the late fifteenth century, there was no longer in England the worry of attack, and thus the necessity for fortification was far less pressing. Windows were free to be as large as was desired and practical. Demand for glass continued to grow, and more foreigners, es-

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[10] McGrath, p. 94.

[11] McGrath, p. 95.

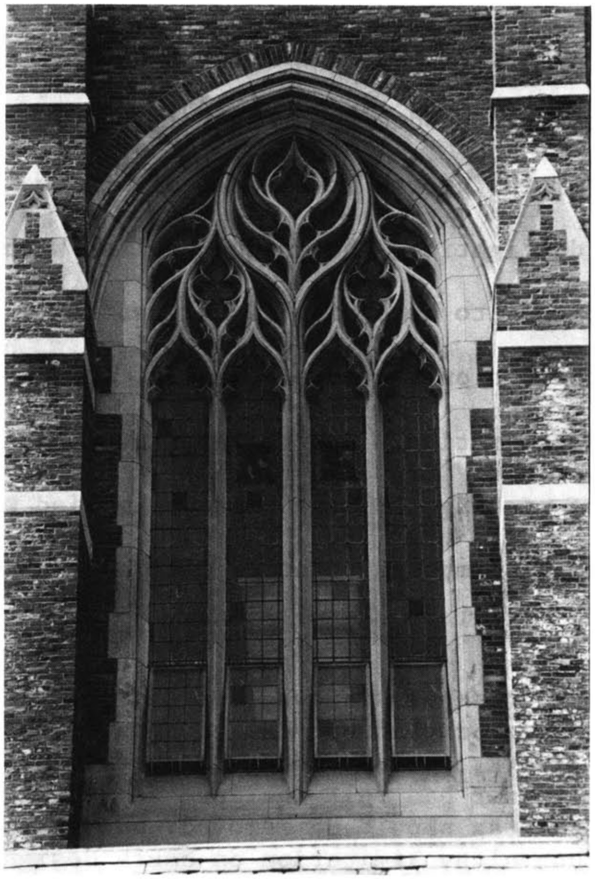

Figure 2.6 A Gothic-style window at Yale shows external splaying of stone elements, which increases interior illumination.

pecially Frenchmen, were brought over to England to impart their skill to the English manufacturers.

It was with the advent of the sliding sash window and the availability of larger panes of glass, that English windows underwent their most significant metamorphosis. Window bars began to shrink. It was no longer necessary for reasons of structure, rigidity, or formality to take up as much as 30% of a window opening with bars. The trend moved towards minimal glazing bars, still separating small panes, but producing greater illumination inside a room.

In the midst of the growth in the use of windows and the corresponding increase in interior daylighting, the unique English Window Tax of 1697 was enacted. This levy proved to be a significant restraint on the trend in progress, and more of a burden on the lower classes, who were already behind the rich in quantity of fenestration. Due to the expense of glass, window size had become a matter of prestige: large windows implied wealth and influence.

The window tax was imposed on homes with more than six windows, and was worth over £5/year.

> This tax checked the use of windows, but did not alter their design. Existing windows were bricked up; new houses were built with depressions in the brickwork, corresponding to the windows that would have been there if the owner had felt inclined to meet the tax, or ready for piercing if the tax should be removed; but it remained until 1851 -- a severe and unhealthy limitation on house design.[12]

It is important to note that the tax was on the <u>number</u> of windows, not on their <u>area</u>. As a result, the English architect found ways of circumventing the law, even within the restrictions it imposed, and thereby advanced the evolution of the window.

> Windows on ground-floor rooms became taller, rising from skirting level and terminating just below the cornice line: ... This deliberate attempt to admit light as near the ceiling as possible on ground-floor rooms suggests that Georgian architects were anxious to make the most use of available daylight.[13]

Georgian architects developed further another aspect of window design that adds to the quality as well as quantity of daylight in a room: the splay-

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[12] Sheppard, p. 31.

[13] Sheppard, p. 31.

ed reveal. As we saw in the example of the Norman window, this device not only further spreads the light entering a room, but it aids in the reduction of sky glare by "grading" the contrast between the window and the adjacent dark wall, and by reducing one's direct view of the sky. The internal shutters often used in darkening the window were integral to the design, folding back into these reveals. (See also Chapter 12, "Window Design -- Framing.")

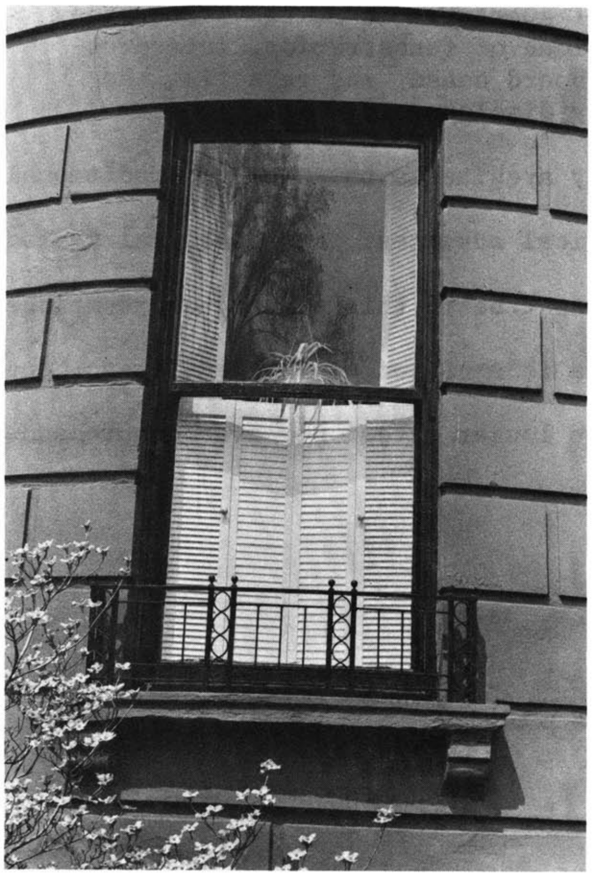

Figure 2.7 (left) These shutters fold back into the reveals of the window. They are also adjustable like venetian blinds. (right) Both types of bays are seen on this facade on Boston's Beacon Hill.

Bay windows had been introduced as early as 1401 in England, and went through several stages of evolution during the ensuing 400 years. During the eighteenth century they became increasingly popular, and were often used in one of two forms: semi-hexagonal (late Victorian) or curved (Regency). (See Chapter 11, "Window Design -- Arrangement.")

The Industrial Revolution of the nineteenth century improved glass quality to the point that, due to increased size, strength, and clarity, mullions became unnecessary:

> This technical achievement provided an opportunity for an entirely new approach to window design; but Victorian architects continued to think of windows as a pattern of apertures in an elevation, they were obsessed by the conventional idea of fenestration, interpreting that term in a purely drawing-board sense, and rejecting the possibilities contemporary industry disclosed.[14]

The Victorians were not the only architects to stick to traditional modes of building in spite of technological advances: the Classical Revivalists did likewise. In fact, the same was true in this country and continues to be the case wherever an earlier style is emulated or revived, even though the raisons d'être for the style are not longer extant nor even comprehended.

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[14] Sheppard, p. 31.

7 Rights to Light

The British were by no means the first people to establish legal definitions and laws pertaining to availability and adequacy of natural light, but their example has been the most contemporary instance of such concern. Their rules derive from Roman law, and were first officially outlined in the Prescription Act of 1832, which stated:

> When a building has enjoyed the access and use of light without interruption for 20 years the right is deemed to be absolute unless the enjoyment was by virtue of a consent or written agreement. Openings in a building to which a prescriptive Right of Light has been acquired or could be established are commonly referred to as 'ancient lights.'[15]

This concept of ancient lights was upheld, argued, and justified in the British courts for over a century. The question of "adequacy" of light, and whether rights had been infringed or not, was determined by the judge, in individual cases. It clearly was a subjective decision and one that was based on broad interpretation of the law. The time span of 20 years was an arbitrary one, chosen simply to be sufficiently long to symbolize "ancient."

In 1922, the first court case arose which led to a more specific definition of adequacy, Semon and Co. vs The Corporation of Bradford. Ultimately, a series of quantitative parameters were put on the aspects of penetration and amount of light entering an interior space. A standard average sky luminance of 500 lumens/sq.ft. was defined, the working plane (reference plane) was set as 2'9" above the floor, and "adequate" light was determined to be .2% sky

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[15] Hopkinson, p. 397.

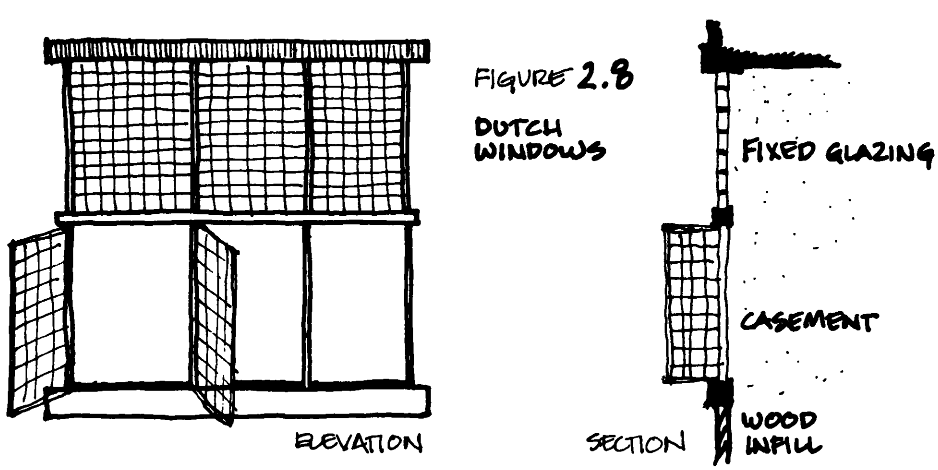
factor. This means that .2% of the available daylight was reaching the particular part of the room that was being photometrically measured. The line joining points in the room of this intensity was known as the "grumble line." This figure was arrived at from the fact that printed material ceases to be read easily below 1 lm/ft^2, equivalent to 1 foot-candle. By comparison, today's recommended minimum daylighting levels are 10 to 50 times this level!

8 Dutch, Venetian, and Japanese Attitudes

As mentioned earlier, the Dutch were sensitive to the issue of natural light, and were responsible for some major design developments in this area. Due to its proximity to the sea, much of Holland's land area was created by reclamation. As cities like Amsterdam grew, the structure found most efficient for housing and occupying the ground area was a tall, narrow rowhouse with a gabled roof. The natural result of such design was that all the daylight in these houses had to come from the gable ends of the building, front and rear. The lower floors were for living purposes only, and had high ceilings, often as much as 14 feet. The upper floors were primarily for the storage of goods.

Early in the history of Dutch windows, glass was used sparingly due to extreme expense. In all cases, however, its use was designed so as to maximize the penetration of natural light.

In the sixteenth century, only the upper half of the windows was glazed; the lower was closed by shutters.



Later, the lower half was glazed with inward-opening casements, but the shutters remained. Often, the upper part also had shutters, which opened inward. All of these light-control devices were combined with heavy drapes and curtains to produce a four-framed window with an almost infinite number of possible configurations. Each time of day, type of weather, and variety of task being performed demanded a particular type of lighting, and this extremely flexible system provided this variety.

Several characteristics of these Dutch windows are of particular importance in this discussion of designing with daylight. First, these windows extended right up to the ceiling, providing even light over the entire room. Second, the windows often stretched from one load-bearing side wall to the other: since the end walls did not support anything but their own weight, this was a very efficient use of structural infill.

The light thus produced/filtered/controlled has particular qualities that are familiar to many of us through the paintings of Vermeer and Rembrandt. One always sees the light playing over the objects and figures in the painting, and senses the source, but the window itself is rarely seen. Each painting has a special kind of light, and it is possible to deduce for each one precisely which combination of open and closed shutters produced that specific illumination pattern.

This "Dutch lighting" was characteristically high on the wall, and, combined with light-colored side walls and ceilings, gave good modelling, as well as reasonable light penetration to the rear of the room.

Houses in Venice also displayed a knowledge of the effect of window placement on interior lighting. One often finds the windows placed directly

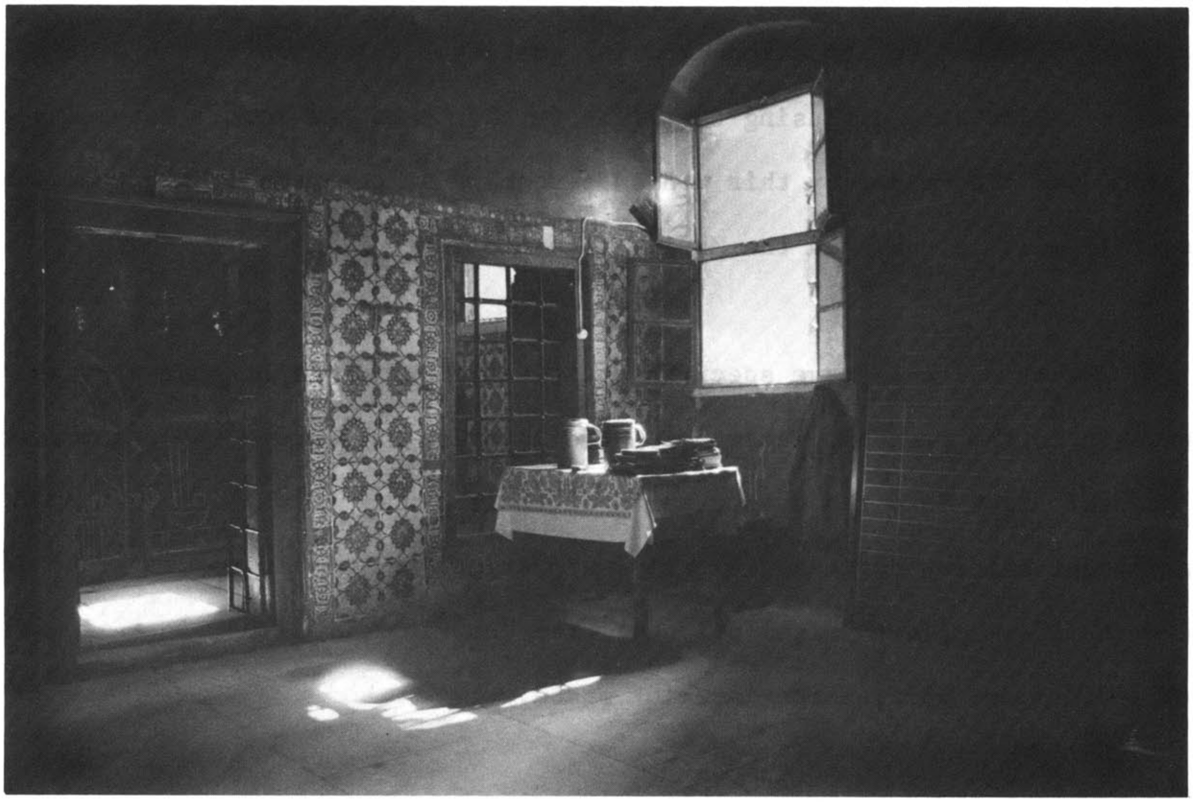


Figure 2.9 This room in Jerusalem is suggestive of Vermeer's use of light, except that the window here is on the right.

against the side walls, with a large blank wall in between. This arrangement is particularly effective for revealing textures of sculpture, wall hangings,

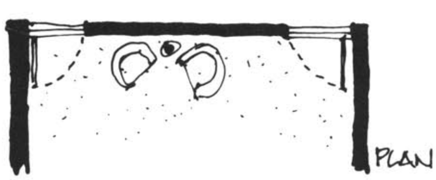


FIGURE 2.10
VENETIAN WINDOWS

and paintings, due to its strong grazing quality. Furthermore, the side walls serve as reflectors, diffusing the light further into the room. Natural ventilation was also aided by this window placement at the ends of the room, and was especially valuable in the Mediterranean climate.

Other cultures have specific attitudes about daylight that provide contrasts to the preceding examples. The Japanese have aided the penetration of natural light into the deeper parts of their houses through the use of translucent sliding screens. Clearly, acoustical privacy is not as important there as is symbolic physical privacy. The "sharing" of light, in this case, both divides and unifies the interior space.

9 History of American Daylighting

In the early years of the American colonies, the use of windows paralleled their use in England. The quality of light that we associate with early Colonial houses was largely dictated by the prevailing styles of architecture in the British Isles, and by the availability of window glass. The first "lights," or panes of glass, came from the mother country in 1638, and were small, diamond-shaped, and low in quality. Much of this early American window glass was blue or purple, and contained many impurities.

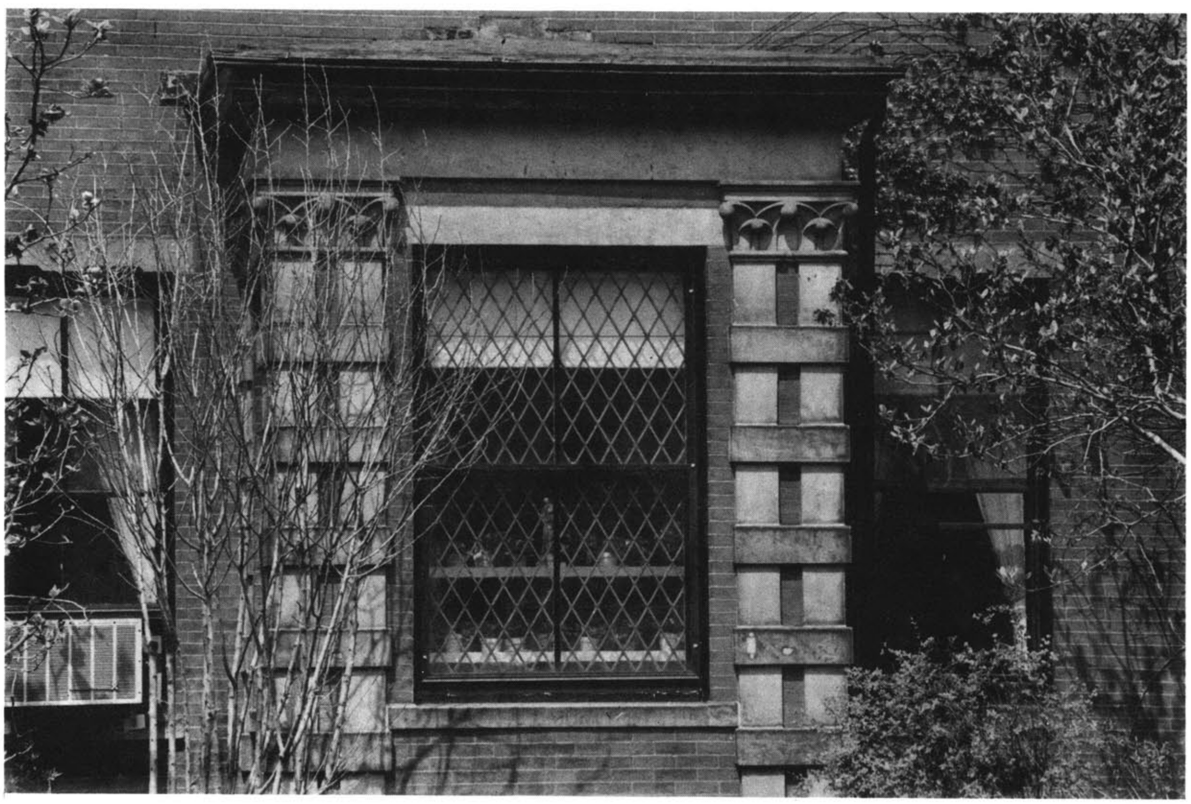


Figure 2.11 Although these are not the original diamond-shaped lights, they refer back to early 17th century windows.

Most colonists used oiled parchment as window closure, and, if they wanted glass (and could afford it), they had to bring it over themselves. Even in 1629, glass windows had not yet reached some of the more remote parts of England, so it is no wonder that immigrants to this country were advised to transport their own glass.[16]

The most common type of window was the hinged casement: these casements were usually grouped in pairs except at the ends of the house. Dormers, when used during the seventeenth century, were present in proportion to the number of rooms on the top floor of the house: in end-chimeny houses, 1 dormer; in central-chimney houses, 2 dormers.

> In central chimney saltboxes, people generally put windows wherever they needed light indoors, without regard for symmetry on the outside. Sash windows had replaced the tiny-paned casements, but only the lower part of the window moved; the upper portion remained fixed.[17]

Whereas window placement in early American homes was based on local need for light, architects of the Georgian and Federal periods were more concerned with regularity and symmetry of the window arrangement.

Most windows of this time were square-headed, and were used singly in building facades. The only exceptions to these square-headed windows, before 1750, were occasional arched windows, placed alone, often over stair landings. Palladian windows then began to appear, marked by a large, arched-head central window, and two smaller side-lights. These disappeared, for the most part, by 1800, and the only use of triple windows was with square-headed central win-

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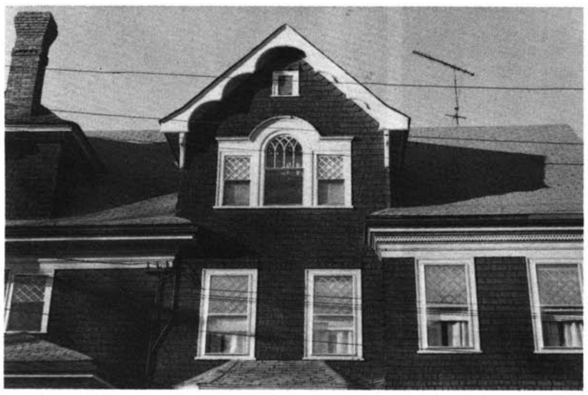
[16]Fiske Kimball, Domestic Architecture of the American Colonies and of the Early Republic (New York: Chas. Scribner's Sons, 1922). p. 27.

[17]Curt Bruce and Jill Grossman, Revelations of New England Architecture (New York: Grossman, 1975), p. 136.



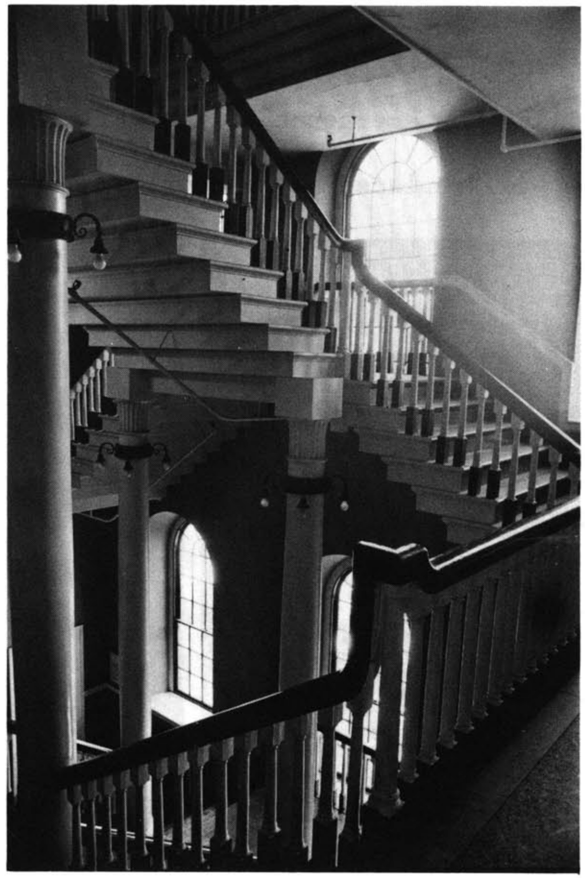


Figure 2.12 (left) A late-19th century Palladian window in Brookline, Massachusetts. Note also the diamond-shaped lights. (right) The windows in Faneuil Hall (1742) take up nearly 50% of the wall area: this is the stairway.

dows. In later years, the Palladian window was revived, as were numerous other architectural features of previous eras.

Another special use of windows that determined a specific quality of light in Colonial interiors was the transom. In the early eighteenth century, rectangular transoms were the rule, providing light for the front hall. After 1757, arched door heads and fanlights (semicircular transoms) cam into common use. By the turn of the century, the rectangular transom was rarely seen, and side-lights were appearing. This evolution can be seen as paralleling the emergence of the Palladian window: the central panel of the window was "replaced" by a door.

Figure 2.13 The evolution of the transom with side-lights; from rectangular to semicircular to elliptical. (Beacon Hill)

In today's domestic architecture, we can see a wide variety of stylistic variations of this manner of lighting the front hall. Even though we have the electric light, it is important to provide some sort of transition of natural light from the outside to the inside of a dwelling. (See also Chapter 3 on "Contrast/Brightness Constancy.")

Although we are accustomed to imagining Colonial interiors as all-white, this was not always the case. Greys, colors, and off-whites were used just as regularly, but the window frames and most trim were almost invariably white, both inside and out. This use of white window frames has been carried to the present day, and can be seen in many "tract" houses. It is likely that this perpetuation of white window frames has been done in the same spirit as such items as shutters (now more likely fixed on the exterior wall of the house, rendering them useless): the knowledge of the original raison d'être for their existence was lost, but the form has been retained, often devoid of meaning.

During this period, frames often protruded from the exterior of masonry structures, complete with all of the standard stylistic characteristics of Greek revival design. As time progressed, and styles changed, the frames moved back to being flush with the wall, and were finally recessed a bit. In this latter case, it is important to note that the exterior masonry reveals remained light in color: this actually increased the amount of light reaching the interior of the room, by reflecting incident daylight through the window. In this sense, they acted like the exterior splays of Gothic windows.

Following the Georgian style in England, shutters on the inside of windows, folding into the jambs, became more common in American domestic architecture. The window sill also underwent some change: "The sill in Colonial windows had been always at some distance from the floor; after 1788, especially in Bulfinch's work, it was frequently dropped to the floor level so that one might pass out to porches and balconies or to the ground."[18] This design increased the amount of daylight incident upon the floor, and thus improved the illumination of the entire room. Most importantly, it altered the visual impression of the scale of the space. (See also Chapter 4, "The Calculation

[18] Kimball, p. 212.

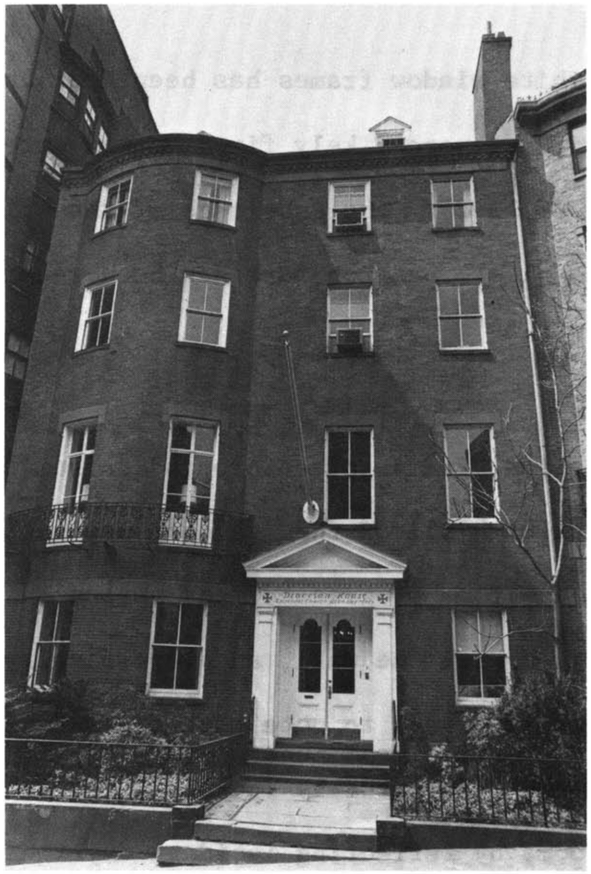


Figure 2.14 White window frames increase interior daylight. Note also the French doors leading to the balcony.

of Interior Daylight.")

Since the Colonial era, glass quality has been vastly improved with respect to its size and consistency, and variety of colors, surface textures and transmittance properties. It has been used for an increasing proportion of exterior wall area, primarily because of advances in structural systems design. It became possible in this century to build a steel-framed building sheathed completely in glass, thus creating completely new visual and cultural conceptions of "window," as well as a host of new problems relating to solar gain, glare, and feelings of exposure. To be sure, there is something magic and crystalline about a glass building, both in its appearance and its reflections. However, it necessitates careful consideration with respect to natural light.

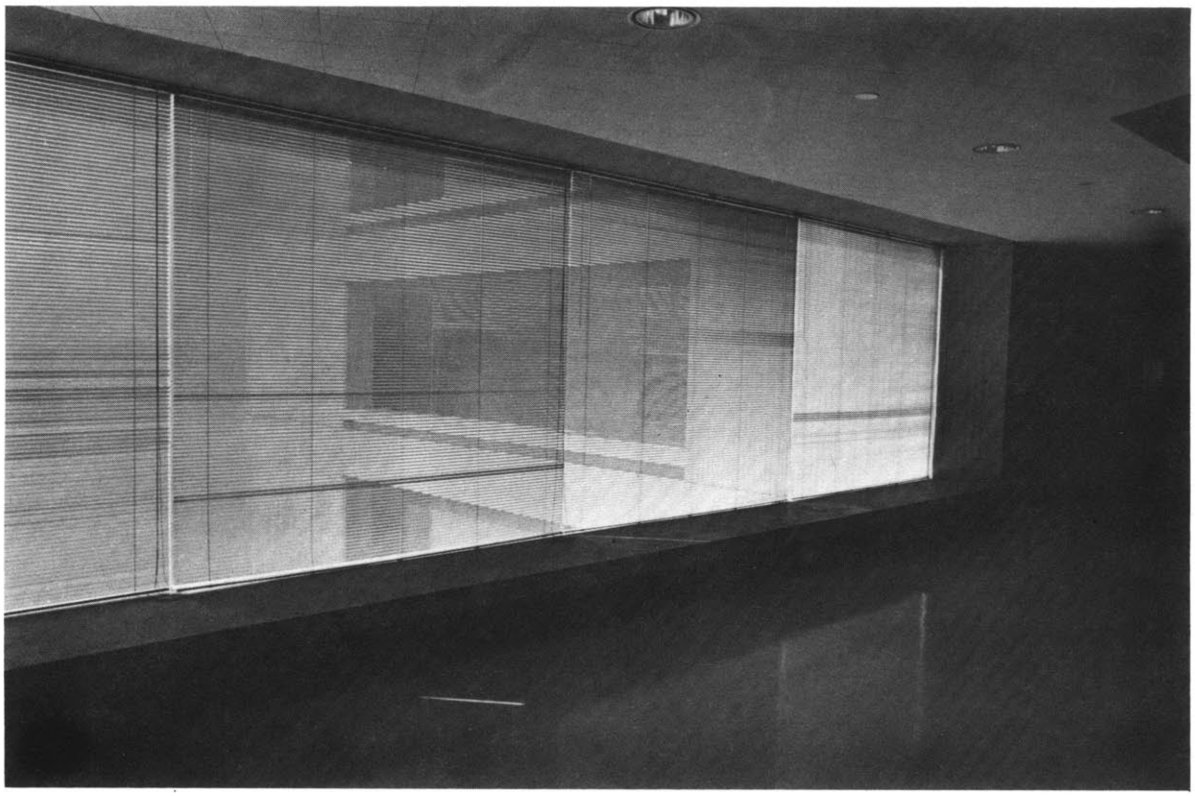


Figure 2.15 Large lights of glass, used widely in modern architecture, increase interior illumination, but demand more attention to sun control, for instance.

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Designing with Natural Light

Let the sun be your decorator.

Frank Lloyd Wright

This section will attempt to synthesize the ideas of the preceding discussion, together with other daylighting principles, into a set of guidelines or rules-of-thumb for accurate, predictable use of natural lighting inside buildings.

One function of windows that will not be discussed here, but which must be considered during the design of a fenestrated space, is ventilation. This issue affects the exposure and arrangement, as well as the operation of windows, and sometimes suggests forms that will necessitate a trade-off with lighting quality.

10 Exposure of the Window

It should be obvious, but the most fundamental part of window design -- its orientation and the corresponding effects -- is often overlooked or ignored. Reasons (such as symmetry, economy, or aesthetics) for such lack of care in window position have been mentioned. When it comes down to the practicality of window arrangement, however, there is no rational justification for the presence of four, or even two identical facades on a building. The sun, after all, shines on three of them at different times of the day, producing different colors and angles of light, not to mention different qualities. As the seasons progress, the solar load on each face changes, as does the penetration of sunlight to the back of the room, related to solar altitude. In our hemisphere, the sun never shines on the north side of a building, so why should the north side look like any other side of that edifice? Let us briefly examine the ramifications of a given exposure on light entering the room from that side. IN ALL OF THE FOLLOWING RECOMMENDATIONS, THE DISCUSSION WILL BE LIMITED TO THE NORTHEAST U.S., AND MORE SPECIFICALLY TO THE BOSTON AREA.

As a general rule, southern skies are brighter than northern skies, providing more diffuse sky light, except on completely overcast days, when the illumination is not dependent on sun position. (See Chapter 1.) "Orientation of the windows in this (southern) direction is in fact often done but the reason is not so much to take advantage of brighter diffuse skies as to allow the occupants of the building the opportunity to receive direct sunlight when it is available."[1]

In terms of direct sunlight, one must take into account that there are, on the average, 100 to 140 days per year when the sky is clear (less than 30% cloud cover) in this part of the country.[2] One may calculate precisely what the probably hours of sunshine are for a given window, day, and time. However, it is more immediately valuable to be aware of the variations present over the course of the year, with respect to solar azimuth and altitude.

For Boston, latitude is 42° North. Figures 3.1 and 3.2 show solar altitudes and azimuths at key points during the year. Because of the sun's lower angle, and thus greater penetration, east and west windows receive the

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[1] Hopkinson, p. 23.

[2] Predicting Daylight as Interior Illumination (Toledo, Ohio: Libbey-Owens-Ford Glass Co., 1965), p. 6.

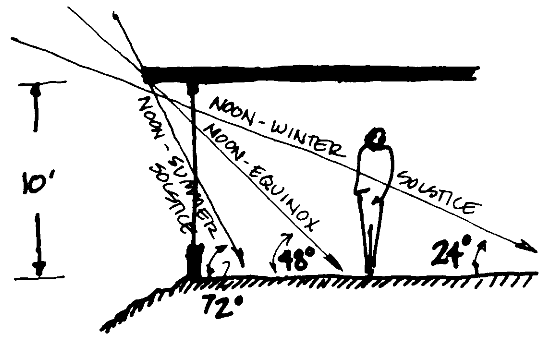

FIGURE 3.1a[3]

SOLAR ALTITUDE FOR LAT. 42°N. (BOSTON)

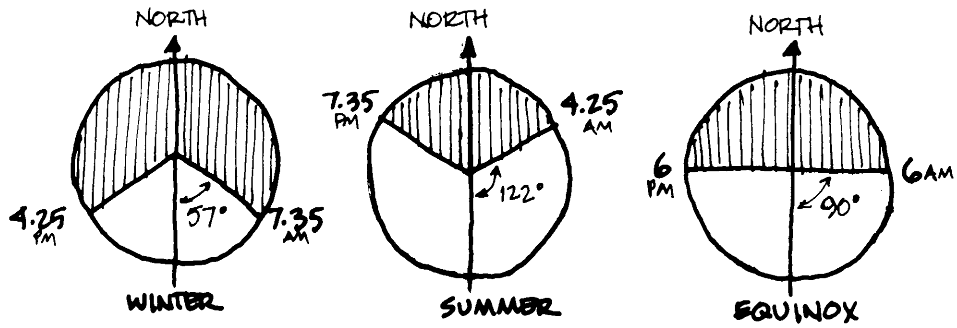

FIGURE 3.1b[4]
SOLAR AZIMUTH

sunlight normal to the glass, and correspondingly higher solar loads, than north and south windows. This leads to the necessity for specific types of shading on east and west and south exposures. (See Chapter 14.)

Clearly, then, if one desires direct sunlight in a particular room at a specific time of day/year, one would never face that window to the north. To maximize solar penetration in the winter, for example, a southeast exposure would suffice, but, of course, the proportionately higher solar load must be taken into account.

The color of the sunlight early and late in the day is also a variable

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[3]Figure from Henry S. Plummer, Built-Light: Analysis and Generation of Associative Natural Light Environments (MIT: M. Arch. thesis, 1975), p. 123.

[4]Figure from Callender, p. 79.

that can be used in a conscious manner. With the late afternoon sun, for instance, one could intensify the warm color of the light by using a "warm" color on the wall opposite a west-facing window, thus flooding the room with reddish light.

Figure 3.2 Late afternoon sunlight floods MIT's Rogers Lobby with warm light.

11 Window Design - Arrangement

In order to achieve good quality daylighting, especially with respect to distribution and ability to perform tasks, several general guidelines can be made:

1. Avoid orienting tasks towards a window whenever possible. Such a direct view will often cause glare, and will reduce the discrimination capabilities of the eye. Examples of this principle, properly articulated, are the MIT Alumni Pool, where the long dimension of the pool is parallel to the win-

Figure 3.3 MIT's Alumni Pool is lighted by a single south-facing glass wall, but the swimmers experience no visual discomfort because they swim parallel to the window.

dow wall, and most school classrooms, where the students' attention is directed at right angles to the window. This recommendation affects space planning and other design decisions.

2. <u>Windows should extend as near to the ceiling as practicable</u>. The area of the window wall near the ceiling is most valuable, both because of the reflections of ground light off the ceiling, and from the greater area of sky seen by the rear of the room. This latter aspect is especially important in overcoming the obstruction of nearby buildings or foliage. A good historical example has already been discussed in the design of Dutch windows of the sixteenth century.

Unilateral Daylighting

This is probably the most common form of window configuration in existence. Unilateral does not mean that there is only one window -- simply that there is one window wall. It is often an unavoidable situation in office or apartment towers, for example: economics and structure give most rooms only one exposure. In fact, the majority of interior spaces in the world are unilaterally lighted.

There are a number of characteristics of the single-side-lit room that should be recognized. First, the directional quality of the light is most evident, especially in modelling. As a further result, shadows are likely to be the most extreme. Second, glare is likely, especially if the window is small in relation to the wall in which it is set. On the other hand, a larger window area results in greater variation in room illumination due to external weather changes, but not necessarily in glare.

Here are some typical unilateral arrangements:

FIGURE 3.4
EXAMPLES OF UNILATERAL LIGHTING SCHEMES

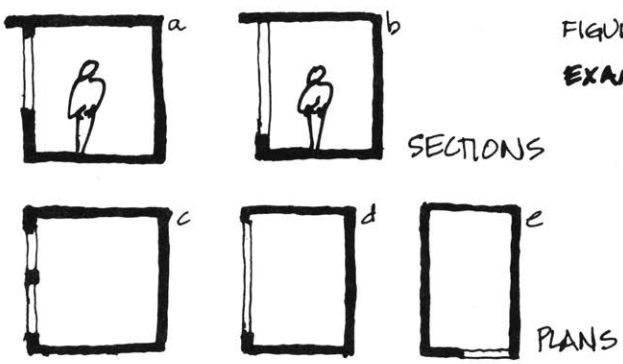

Figure 3.4 A unilaterally-lighted room can have the most extreme contrasts, and can give rise to glare, especially if the windows are small.

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The perception of a wall-to-wall (and floor-to-ceiling) window is quite different from that of a "normal" size window. Whereas the latter can be seen as being an extension of one's eyes, defining a particular view by its limited size, the former loses many of its standard historical "window" qualities: it serves more to separate the inside of the room from the outside. This is particularly true of clear (unobstructed and unveiled) glazing, as is the situation in most office towers these days.

In order to maximize the light that does enter a room lighted by one side only, and thus to produce sufficient quality illumination throughout the room, one could outline the key aspects of room design:

1) The effective depth of the room should be limited to the range of 2 to 2 ½ times the height from floor to window head.[5] Rooms deeper than this will be dark towards the back wall.

2) The ceiling and the wall opposite the window are of great importance in taking full advantage of the incoming daylight, for interreflections and filling-in of shadows. Therefore, these two surfaces would be light colors. (See also Chapter 15, "Interior Surface Finishes.")

3) It is also important that the window wall and the window frame are light colors, although not necessarily white. These will reduce the contrast between the bright window and wall, and thus reduce the glare. A light-colored frame will help distribute more light into the room, as in the Colonial window frame discussed in Part II.

4) If the window area is greater than 1/3 of the floor area, do not use extremely light colors on the other walls, because they will then become sources of discomfort glare. If they are too dark, on the other hand, there

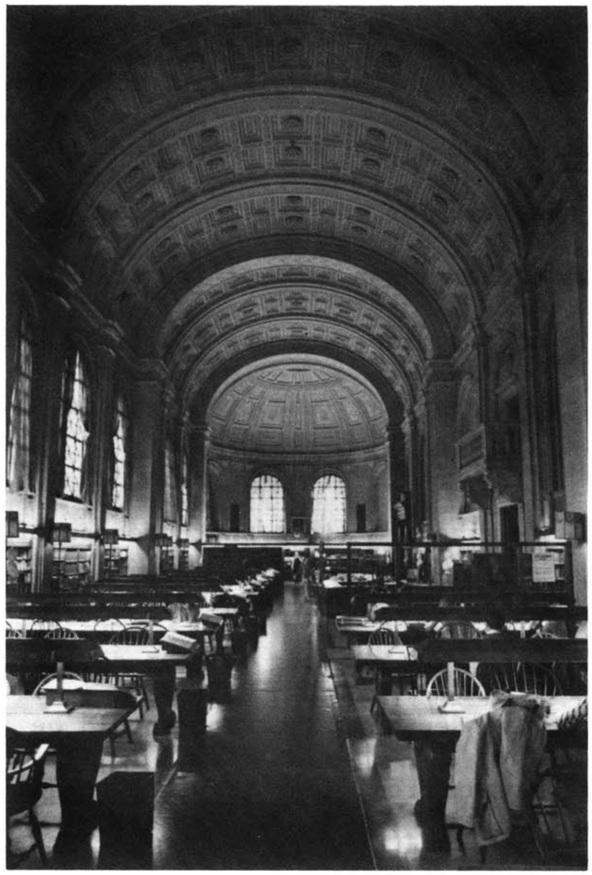

Figure 3.5 Boston Public Library shows the effect of single-side lighting, spread by an arched, light-colored ceiling, at a considerable distance from the floor.

will be contrast problems.[6] (See also Chapter 15, "Interior Surface Finishes.")

Bay windows were developed in England in the 15th century (See Part II.) They were used in American architecture from the eighteenth century onwards, and have become a common part of our vocabulary of window arrangements.

[6]Hopkinson, p. 449.

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It is important to recognize that the original reason for using bay windows on the north side of the street to receive early-morning as well as late afternoon sun, particularly in the summer. The projection of the bay from the outside wall of the building let it "grab" the rising and setting sun, while preventing deep penetration of the summer sun. Bays were used on the <u>north-facing</u> side of Back Bay streets primarily because of zoning, and the desire to be stylistically consistent: they have almost no value with respect to natural light, as it is manipulated by south-facing bays.

Inside the bay, one feels surrounded by light -- the outdoors comes indoors. It gives an illusion of more light to that part of the room. In truth, a bay window actually provides <u>less</u> illumination to the room than would a window the size of the bay opening. The result is that the bay itself is well-lighted, but, due to the obstruction of the corner elements of the bay, and its roof (which acts like a balcony), the room behind the bay actually sees less sky!

Regardless of the actual quantity of light produced by a bay window, it still has great appeal as a design element. In Boston's Back Bay, one sees endless variations on the theme; round, half-round, hexagonal, square, trapezoidal.

Figure 3.6 Bays on Boston's Commonwealth Avenue.

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Multilateral Daylighting

Lighting from more than one side is much more desirable than unilateral, especially with respect to problems of light distribution and glare. If the windows are in adjacent walls, the glare is reduced because the light from one window falls on the other window wall. Room size perceptions are also affected by increasing the number of window walls: the effective depth is doubled if the windows are at opposite ends of the room.

Figure 3.7 Adjacent-wall and opposite-wall daylighting. The latter example is the interior of Faneuil Hall.

Here are some typical multilateral lighting arrangements:

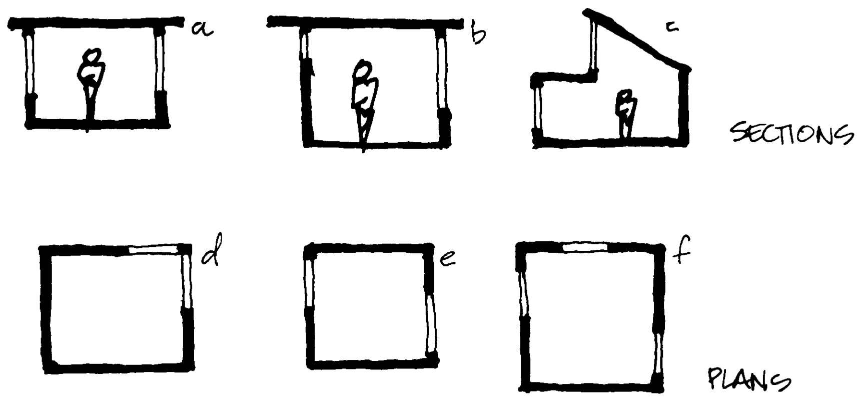

FIGURE 3.8
EXAMPLES OF MULTILATERAL LIGHTING SCHEMES

One way to approach the design of multilaterally lighted rooms is to use the idea of a hierarchy of windows. If one window is the primary source of natural light, the secondary source(s) should be less in the field of view of the room's occupant. Clerestory windows satisfy this requirement.

A specific type of multilateral daylighting is the corner window. It gives one a simultaneous feeling of closeness to the outdoors, and protection, that is similar to the bay window. When used in multiple, as in the preceding illustration, it provides very even lighting of the walls. This design is used to great advantage in Edward D. Stone's Ponce Museum, in Puerto Rico: corners in museums are of insignificant use as exhibition space anyway. In this instance, the lighting design was ideal for natural ventilation as well.

Clerestory Windows

Clerestories can be of great advantage in providing illumination to the back of a room which is otherwise lit only from one side. A clerestory window with the same head height and area as a tall narrow window will provide more illumination on a given reference plane because it sees more sky. It is recommended that the clerestory should be facing the same way as the window, or else illumination will be low near the clerestory. Clerestories of north-facing orientation are often used in studios or similar rooms where only diffuse daylight of nearly consistent intensity is desired.

In order to improve its effectiveness, the sloped ceiling behind the clerestory should be a light color, as should the roof outside the clerestory. This latter strategy increases the externally reflected light, in the same way that the ground reflects light into ground-floor windows. The mounting height of this window affects light distribution; the height of the window itself affects the light quantity.

Time-Saver Standards recommends several general rules with respect to clerestory design, summarized here:[7]

1) The recommended setback is from 1½ to 2 times the side-wall window height. If a sloping clerestory window is used, this can be extended to 2½ times the window height.

This is because the light distribution curve shifts, moving the peak towards the back of the room: a 30° angle from the vertical has been found to be most effective.

2) Recommended room depth from the plane of a clerestory window to the back wall should be 1 to 1½ times the height of the clerestory above the working plane (usually 30"). This rule can be exceeded if the area near

[7] Time-Saver Standards, pp. 933-936.

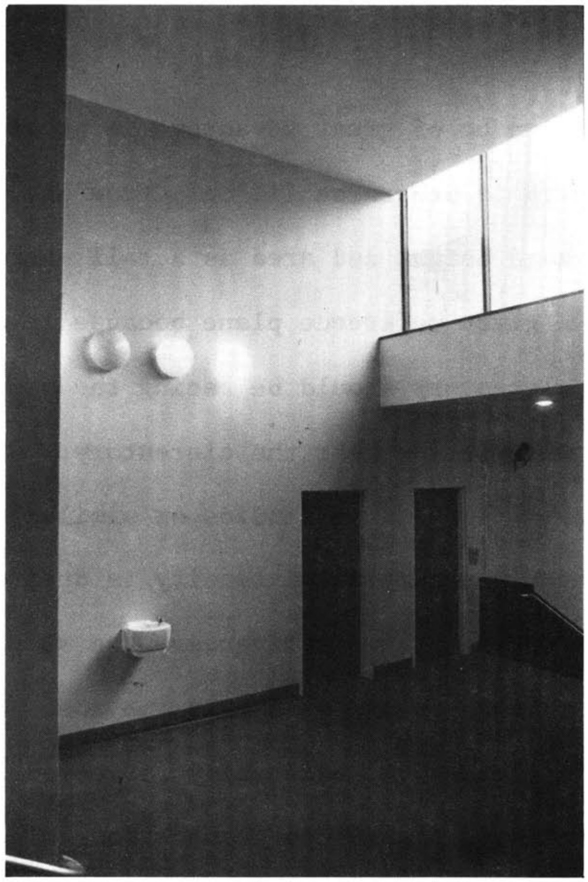

Figure 3.9 The effect of this clerestory window at the MIT Alumni Pool is enhanced by light-colored ceiling and walls.

the back wall is not to be used for critical tasks, because its illumination level will be lower than the rest of the room.

3) When the roof behind a clerestory is sloped, it allows the back of the room to "see more sky," and the resulting increased quantity of illumination can be very important for the brightness distribution there. This does, however, create the necessity, on sun exposures, for some sort of sun control device, either outside the clerestory or just inside.

4) The sill of a clerestory should be sloped downward, for better penetration of light, and for contrast grading.

Rooflighting

Rooflighting (toplighting) has evolved a great deal since the days of the smoke-hole. Some contemporary configurations of rooflights are shown below. Types a, b, c, and d are most commonly found on large factories or warehouses.

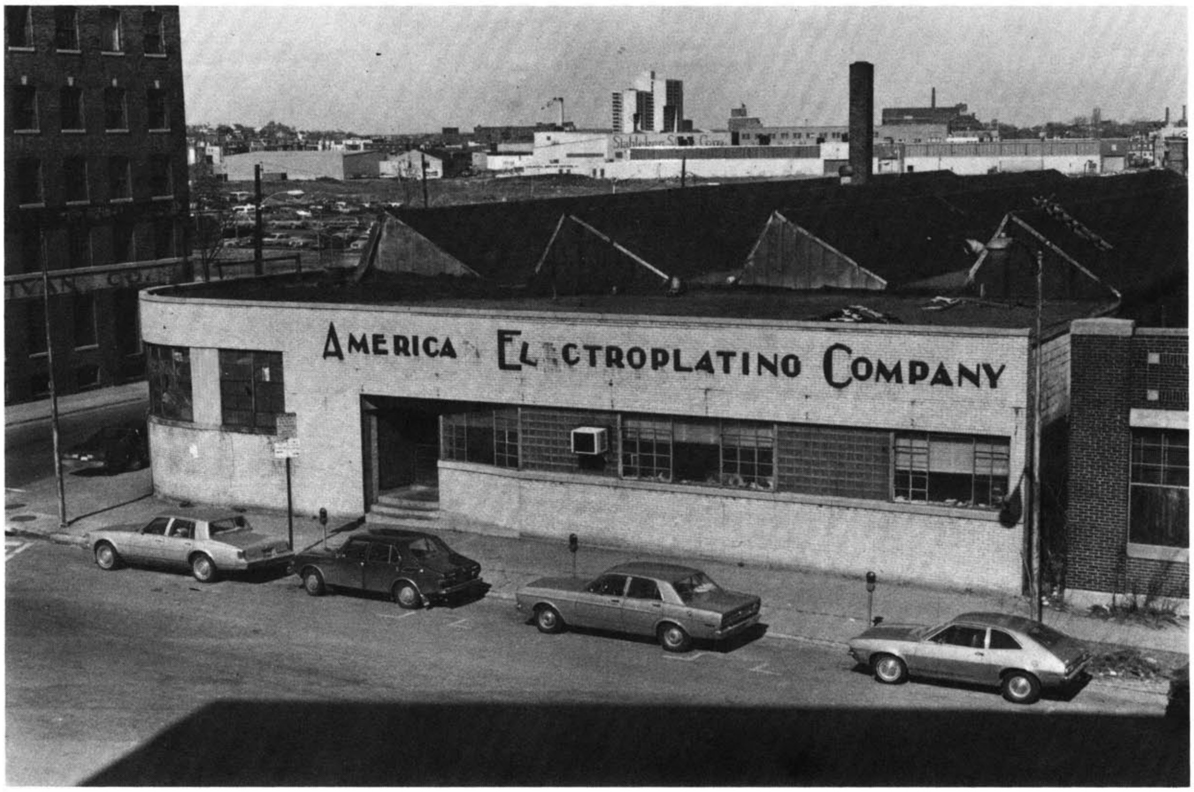

Figure 3.10 Northlights on a Cambridge factory.

One of the more famous contemporary examples of extensive use of skylighting is the S.C. Johnson office, designed by Frank Lloyd Wright, and built in 1936. It represents Wright's appreciation of natural light, and is a superbly successful integration of natural and artificial light.

Assuming that uniform lighting is desired, there are some important differences among the types shown in the illustration. Type a gives uniform sky illumination, but sunlight can be troublesome, as the windows face at least 1 sun exposure. Types c or d give more uniform lighting than the sawtooth (Type b) but sloping the glass increases the amount of daylight reaching the working plane.

There are several rules-of-thumb regarding the use of rooflights, especially Types e and f:

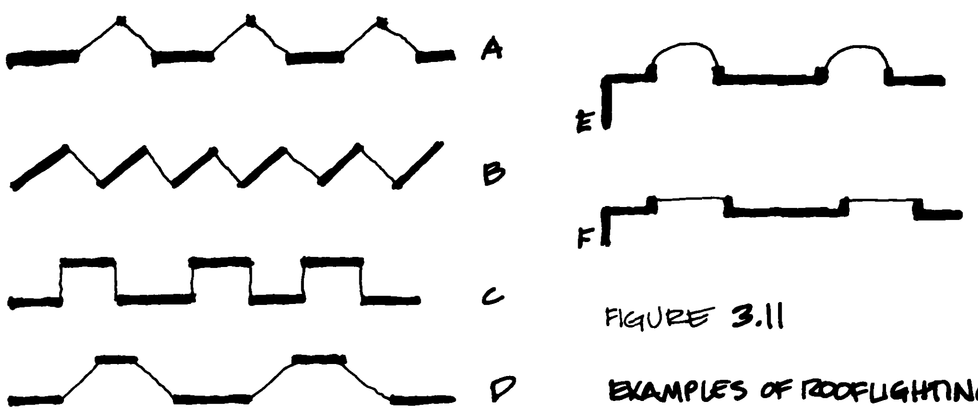

FIGURE 3.11

EXAMPLES OF ROOFLIGHTING

1) The distance between adjacent areas of glazing should not exceed 2 times the height of the rooflights above the working plane.[8]

2) As in any use of sloping or horizontal glass, maintenance becomes a more significant problem, especially accumulation of dirt and snow.

3) The undersides of any roof areas should be light in color in order to maximize the interreflections of the light that enters the room.

4) If possible, avoid orienting tasks such that their line of sight looks towards a roof-light.

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[8] Hopkinson, p. 267.

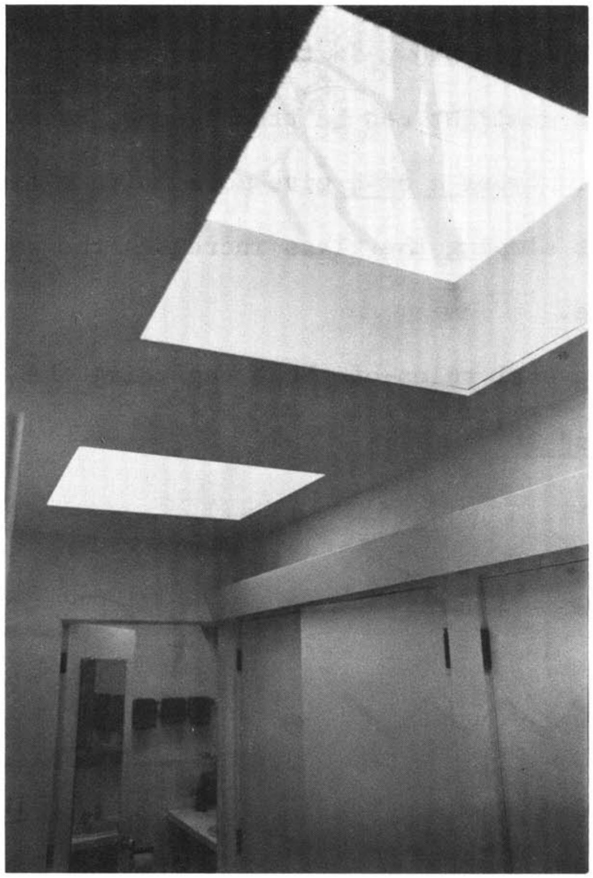

Figure 3.12 Small skylights, clear domes in this example, are appropriate for room-sized spaces. Note the light-colored walls.

Clear glass provides the most light transmittance, but it is not necessarily appropriate for all skylights. Dome-type skylights as well as sheet glass are available in "frosted" versions, increasing the diffused light, and preventing vision through from above.

Glass block has also been used in rooflighting arrangements. Often it is cast in a grid of concrete or steel. This has been more often used in Europe than in America, and usually takes the form of a barrel vault. Its use in this manner, as at MIT, has generally ceased because it cannot be made completely watertight in the horizontal plane.

Rooflighting has been an important part of the design of public and religious buildings for thousands of years. From the Pantheon and the Basilica to H.H. Richardson's Trinity Church in Boston, one can sense the association of the light that comes from above with some spiritual being residing in heaven. In some cases, a roof-light provides this illumination; sometimes a dome or cupola, ringed by windows at its base, is used.

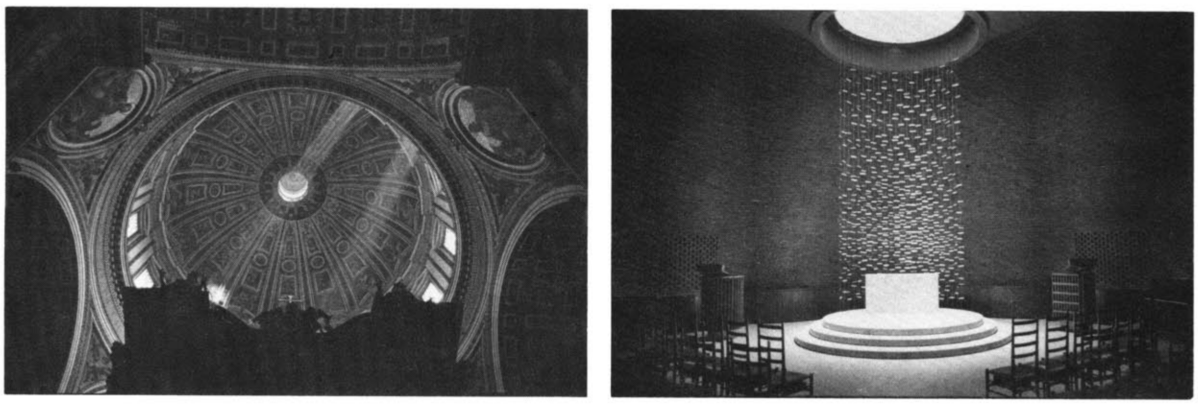

Figure 3.13 Rooflighting in religious buildings. The Basilica and the MIT Chapel both evoke the sense of a supreme force by their uses of light.

In larger places such as the Galleria in Milan, the Crystal Palace, John Portman's hotel lobbies, and even the American (enclosed) shopping mall, the skylight indoor space has provided a unique form of public "theater." It is enlivened by the dynamics of natural light. The human activities of shopping, meeting, watching, and sitting, which always occur in the city streets, are protected from the elements and encouraged to occur no matter what the weather. The constant manifestations of the sky's changing character remind us of our nearness to the outdoors, without altering our behavior in as direct a manner as it does outside the space.

Figure 3.14 London's railway stations and America's shopping malls (Chestnut Hill, Ma., in this photo) exemplify the use of skylighting in public spaces.

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12 Window Design - Framing

Windows have undergone a series of significant evolutions over the course of time, with respect to glass quality and size. Often overlooked or ignored is the corresponding evolution of the design of the window frame itself. As seen in the historical study in Part II, early windows were limited to small panes of glass, and were therefore more complex in their framing. The overall stone structure in Gothic windows, for instance, was large enough to hold up the building, but narrow enough to leave a substantial opening for the glass. The next smaller scale of framing was the tracery actually holding the panes of glass and providing drainage. Last was the leading, separating and making more rigid the glass structure.

Each element of the frame had a specific function, but they all had another layer of intent inherent in their design. They were consciously created so as to modulate the light that filtered through the glass. By splaying the internal reveals of these windows, light distribution was improved. By giving the stonework a 3-dimensional cross-section, a "contrast grading" effect was produced, further reducing glare. These windows had, in effect, both vertical and horizontal louvers, by virtue of the cross-section of their frames. The splaying of the exterior actually captured more light both in-direct and direct, and distributed it better inside. Splayed reveals allowed nearly 100% exposure, and thus maximized efficiency of the windows by eliminating corners of the exterior reveals that caused shadows. The exterior splay actually increased this to more than 100%, by reflection into the interior, and by absorbing the heat of the sunlight, thus reducing solar heat gain.

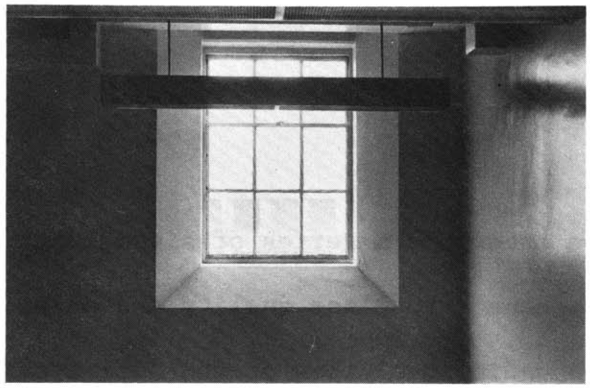

Figure 3.15 Notice the softening effect of a splayed interior reveal. It provides an intermediate level of brightness, and reduces glare.

If we now look at Colonial American window design, we discover another set of characteristics that can be applied to the design of present-day fenestration:

Window frames were generally painted white, both inside and out, and were often highly sculptured or molded. Mullions, even when they shrank in size, retained the "molded" quality. This also contributed to the contrast grading of the incoming light. Georgian windows were deeply set into the wall, with light-colored, splayed reveals.

All of these characteristics of window framing seemed to have developed to fulfill a need, probably because of limitations of structural systems or materials. An early reason for such three-dimensional mullions was to cover up and make weathertight the joints between adjacent pieces of wood.

In all cases, however, these characteristics were of prime importance in the manipulation of natural light: whether this was a matter of

Figure 3.16 "Molded" mullions and muntins also serve to grade the brightness from the window to the wall.

happenstance or intentional design is hard to determine. The fact remains that such characteristics did evolve, and are still relevant to the issue of daylighting of interior spaces.

In recent years, the trend has been to use extensive areas of plate glass, undisturbed by small-scale framing elements like mullions and muntins. This is especially prevalent in office towers and other commercial buildings. One of the reasons for this is simply the availability of such large glass lights. Another is the fact that the initial cost of glass as a building material is almost identical to assemblies of other, more opaque, materials.

A third reason is that such framing elements necessitate much more maintenance time.

About the time that this initial cost equality became the case, everyone seemed to ask: "Why not have an all-glass building, since it now costs the same; after all, the more glass, the better, right?" Besides the psychological problems, solar overload, and glare caused or aggravated by such expanses of glass, there ensued a trend in architecture in which everyone's concept of "window" was altered. With the virtual disappearance of mullions, there was no longer an architectural element present in the observer's view out through a framed opening which provided a visual transition between the interior of the room and the outside world. Small-scale framing elements had performed this function, originally out of necessity, and then were perpetuated like other architectural features, long past the time when such limits as glass size were in effect. The bay window presented still another transition and procession of views.

Let us look at a contemporary trend which illustrates this aspect of window design. It has become standard procedure to rehabilitate the windows of old buildings in the following manner:

a) The old, clear glazed, small-paned, white framed windows are removed, and replaced with
b) bronzed glass, usually fixed sash, in
c) dark metal frames, generally devoid of detail.

We cannot ignore the fact that the windows are often inoperable in order to maintain the building's air conditioning system, and that the glass may be tinted to reduce the solar heat gain. Nevertheless, what has been lost is the marvelous quality of natural light that entered through these windows, which often comprised as much as 50% of the wall area. Once the mullions and the white frames were gone, a large sheet of clear glass would probably have produced glare problems, especially with a dark metal frame. Here was a complete lack of contrast grading, so the correct remedy was used; tinted glass. Needless to say, the special "feeling" of such an old building seems to have been subverted by such a misapplication of modern technology.

A simple experiment was initiated to see whether in fact there are differences between dark and white painted window frames, with respect to glare. A north-facing window with a dark green frame was used, and painted half of it white. The photographic results indicate an increased ability to differentiate the contrast levels of the white window bars, and hence, a reduced perception of glare. To some, the room feels less gloomy (the floor and furniture are dark).

The conclusions from this discussion are several, and can be phrased as recommendations for window framing:

1. Frames should usually be light in color (but not necessarily white), especially for windows that are small in relation to the window wall. Bright colors, i.e. high chroma, should be used rather than dull colors, because the former will suffer less in the contrast with the sky luminance.

2. If possible, windows that are set in opaque reveals in the wall are preferable. The observer's direct view of the sky is thus reduced, without reducing penetration of light into the room. For all-glass walls, the side walls of the room act as the "reveals," and should be treated in similar manner as the reveals of smaller windows. Splaying the reveals, as discussed earlier, and painting them light colors, further reduces glare, by introducing an intermediate brightness between those of the sky and the wall. Recommended

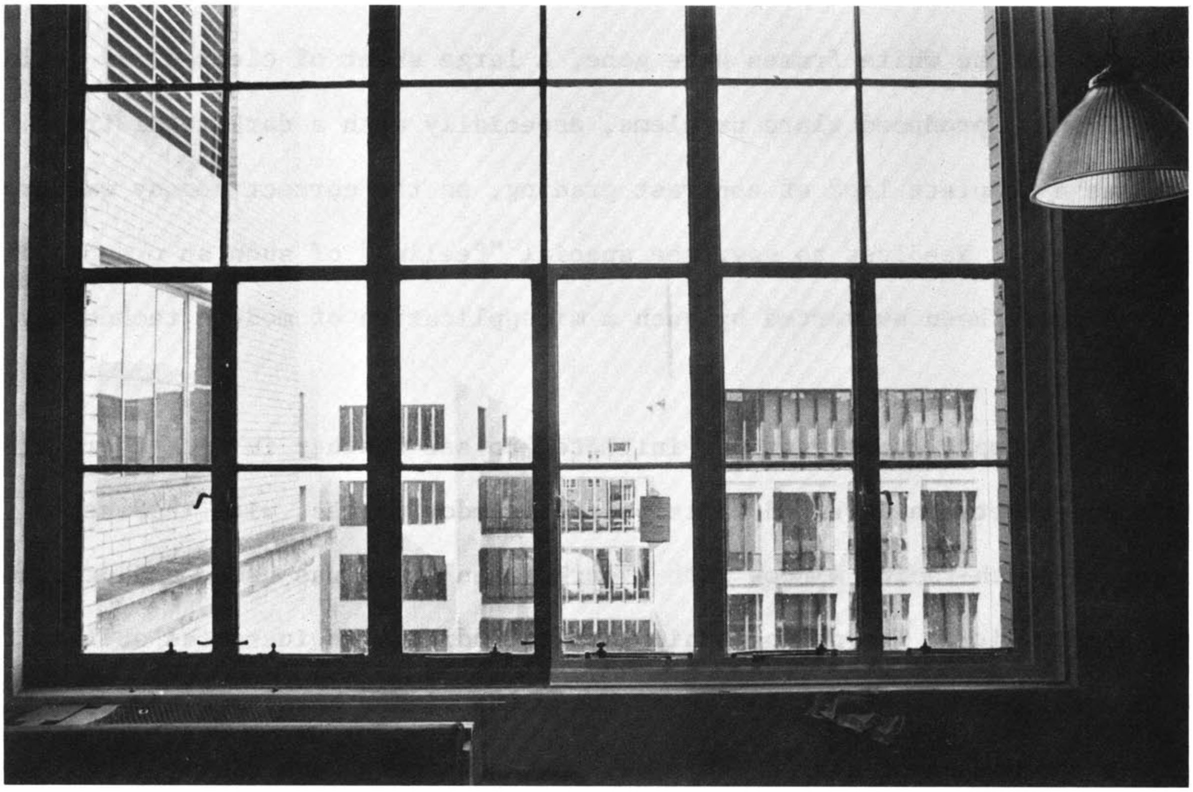

Figure 3.17 The original window frame, on the left, was green. The right-hand half was painted white. Opinion was divided as to the effect on perceived glare; three dimensional shapes of framing are easier to discern in the white half.

parameters for such splays are 9-12" deep, 30^{o} from the normal to the glass, and 60-90% reflectance factors for finishes.[9] (See also Chapter 15, "Interior Surface Finishes.")

The windows of LeCorbusier's church at Ronchamps contain probably the most famous splayed reveals in modern architecture. The windows are carefully oriented to receive light at selected times of day and year, and thus to produce specific direct and indirect lighting effects that intensify the building's religious function. Ronchamps is a prime example of sensitivity to,

[9] Hopkinson, p. 276.

Figure 3.18 Kronborg Castle, in Denmark, contains this great hall, which is lighted bilaterally. All windows are set in deep, splayed, light-colored reveals. Even artwork on the piers can be viewed without difficulty.

and creative design of natural lighting.

13 Glazing Materials

As was discussed in Part II, "glazing" materials have not always been transparent -- in fact, they have not always been glass. As mentioned before, alabaster, mica, oiled linen and shell were used by the Romans; American colonists used parchment and oiled paper before they had glass. Today, although our primary materials are glass of one sort or another, other products, such as acrylic, are employed commonly (Translucent marble was used on the walls of Yale's Beinecke Rare Book Library as Pentelic marble was used to roof the Parthenon.) In this chapter, however, we will only discuss the basic types of glass products currently available to the architect, and their applications.

There are four primary types of glazing materials:

a) Transparent
b) Diffusing
c) Directionally transmitting
d) Selectively transmitting, including directionally selective and spectrally selective.

Transmittance factors indicate the proportion of incoming light that is allowed to pass through a specific type of glazing material. The rest of the light is reflected or absorbed in varying proportions.

Transparent glass is clearly the most common type of glazing material in use today. It is available with varying degrees of strength, breakage resistance, and thickness. It is most often used as a single thickness, or as double glass with an air space between. This latter has much more thermal insulating capability than single glass, without significantly reducing

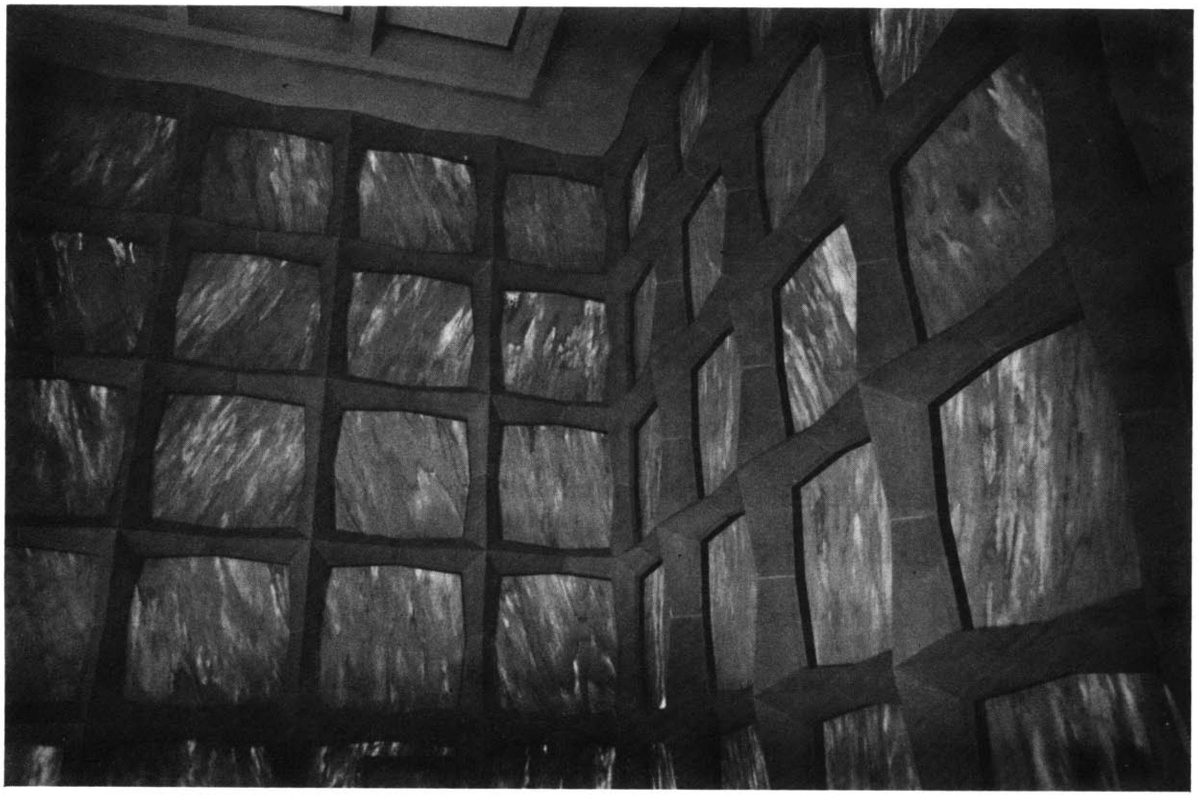

Figure 3.19 Yale's Beinecke Rare Book Library is faced with translucent Vermont marble. This view from the interior shows the dimness of the light that penetrates the marble.

FIGURE 3.20

TRANSMITTANCE DATA[10]

Polished Plate/Float Window Glass	80-90%
Sheet Window Glass	85-91
Heat-Absorbing Plate	70-80
Heat-Absorbing Sheet	70-85
Tinted Polished Plate	40-50
Reflective	23-30
Figured	70-90
Corrugated	80-85
Glass Block	60-80
Clear Plastic Sheet	80-92
White Translucent Plastic	10-80
Double Glazed--2 Lights Clear Glass	77
Double Glazed--Tinted and Clear	37-45%

[10]Figure from Callender, p. 925.

transmittance of light.

Diffusing glass does simply what its name implies; non-selective diffusion of transmitted light. The term "frosted" can be applied to these materials. As the diffusion level increases, transmittance decreases. On sun exposures, brightness controls are often needed. The various types of patterned, hammered, and textured glass can be thought of as diffusers.

Directionally transmitting materials produce a controlled change in the direction of transmitted light by refraction. There are two basic varieties, the most common types being prismatic and "maximum" glass.

Prismatic glass has one smooth face (the outside one) and one surface made up of parallel prisms, which refract the light in a certain direction according to the angle of incidence of the light, and the angle of the prism.

Prismatic glass is available in three angles, each of which is specifically designed for a particular angle of incidence. Here are some diagrams illustrating its use:

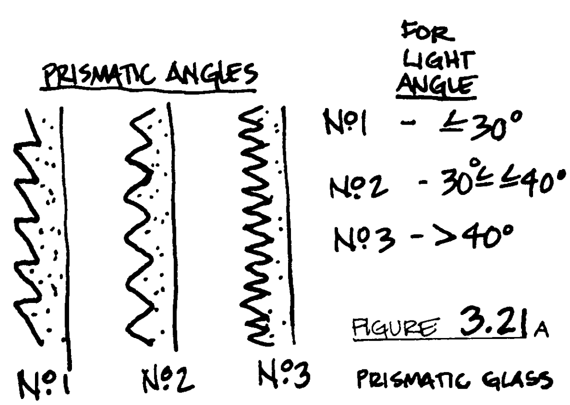

FIGURE 3.21 A
PRISMATIC GLASS

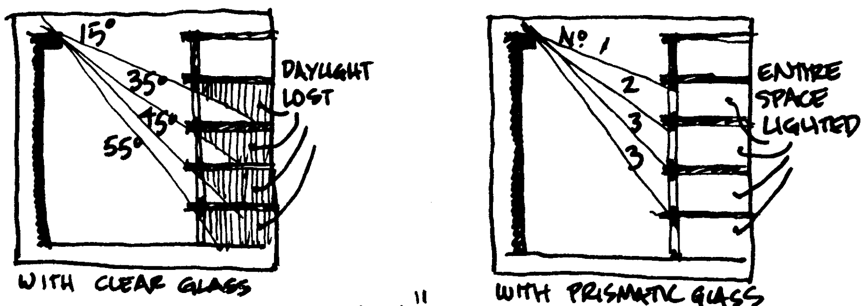

FIGURE 3.21B[11]

The most obvious application of prismatic glass is to counteract the effect of a high obstruction such as a tall building, which blocks out one's view of the sky. It must be installed with prisms running horizontally on the inside of the window. Note also that it is translucent, and that transmittance is less than that of clear glass.

One possible application in an obstructed-sky situation might be to use prismatic glass for the upper half or third of the window, and clear glass for the lower part. That will take advantage of the sky seen by the upper part, and direct that light to the back of the room, while the lower part will still allow the view outward.

Maximum Glass is simply a type of prismatic glass that is most

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[11] Figure from John Gloag, The Place of Glass in Building (London: George Allen and Unwin, Ltd., 1943), p. 72.

applicable to angles of obstruction less than 30° and greater than 40°. It is also a rolled glass, whose inside surface has paralleled prisms that refract the light horizontally after it passes through the glass. Its outer surface is fluted at right angles to the prisms, in order to give better lateral diffusion.

Maximum glass also comes in different angles:

Angle A: for obstructions in which the angle of elevation from the window is less than 30°.

Angle B: for angles of obstruction more than 40°.

An example for application of Angle B is a basement or room whose windows open into an open light well or courtyard.

The fourth type of glazing material is selective transmitting. There are two subgroups under this heading:

a) Directionally selective materials such as prismatic glass block. They reject most of the light from the direction of the greatest sunlight, and admit more diffuse light from the rest of the visible sky.

b) Spectrally selective materials such as tinted glass, heat-absorbing, and heat-reflecting glasses. These characteristics are available in combinations, producing the wide range of solar-bronze, mirrored, and thermal glasses in use today. Note that those types of glass that are most effective in reducing interior solar gain also severely reduce the brightness of the exterior view.

Tinted glass must be used with an understanding of its effect on light quantity and quality. Grey glass came into common use to reduce sky brightness, and thus glare, but it tends (for most observers) to make the room gloomy

(See also Chapter 3.) For this reason, most tinted glass is slightly bronzed, to create a "warmer" feeling in the room.

There are a number of psychological effects of solar glasses, some of which have already been discussed, such as the depressing effect of the decreased luminance of the sky. There seems to be greater advantage in better initial design of a building, with respect to orientation, external sun controls, and window design, than in automatically resorting to the use of tinted glass.

The implications for natural lighting, of a particular building type, are relevant to this design issue. For example, towers automatically produce a predominance of unilaterally-lighted rooms, except at the corners. Clerestories and skylights are virtually out of the question. Clearly, the sides of the building with sun exposure will need sun controls, preferably external to the building. (See Chapter 14.) Whereas, in the example of J.L. Sert's Peabody Terrace housing for Harvard University, where manually operated louvers are provided, such a scheme is entirely inappropriate for an office building. (See Figure 3.27)

Where the function of a building, such as an office, requires the attention of the occupants for more time during the day than does a home, manual controls are precluded. Furthermore, if an office tower must be used, economics and codes will probably severely limit the depth of any surfaces which project from the building.

All of these factors, together with ability and necessity for full climate control, led glass manufacturers to develop the above-mentioned spectrally selective types of glass, as the most appropriate forms of glazing. This was based on the decision (for whatever reasons) to adopt a steel-framed

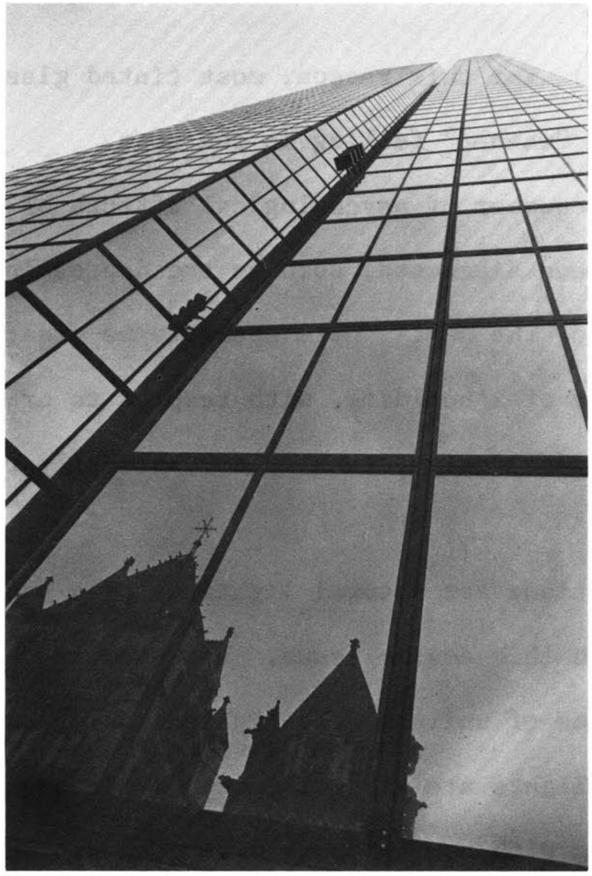

Figure 3.22 The John Hancock office building in Boston is sheathed in solar-reflecting glass. Its reflections are spectacular, but the effects of such glass upon a building's occupants are still being studied.

skyscraper form, which, in this decade, has often meant floor-to-ceiling windows. Maybe this decision is a misplaced priority: more than light and view are sacrificed in this instance.

In 1914, Bruno Taut designed a pavilion for the Glass Industry at the Cologne exhibition. It was completely glazed, and had a staircase made entirely of glass block; risers, treads, and even the walls!

Glass block is a special kind of glazing material that was introduced commercially in this country in the 1930's, and was used initially for walls, partitions, and skylights, as well as decoration. Block continued to be used for exterior walls of staircases during the middle decades of this century.

Glass block is available in almost as many varieties as is sheet glass; clear, frosted one side, prismatic. It is made of 2 pieces of glass for the faces, and roughened glass for the edges. It is evacuated and sealed at high temperatures for rigidity and strength. It is particularly valuable from the point of view of conducted heat gain/loss; approximately 1/2 to 1/3 that of single glazing. Radiant heat gain is 1/3 that of single glazing. Its sound reduction characteristics are equivalent to a 4" concrete wall -- an average reduction of 40 decibels.

Figure 3.23 Glass block, clear and diffusing.

Glass block has found more use in recent years as a decorative medium, and less as an integral architectural material. In terms of light transmittance, block is significantly less than clear glass, but it does provide degrees of both privacy and translucence which few other wall materials, alone or in combination, can provide. It has nearly the structural strength of brick, with the transparency of glass. Due to code limitations, however, it is more applicable as infill than as load-bearing walls.

One use of glass block in conjunction with clear glass, which was often used in American school construction in the late 1940's and early 1950's, is shown by Figure 3.24:

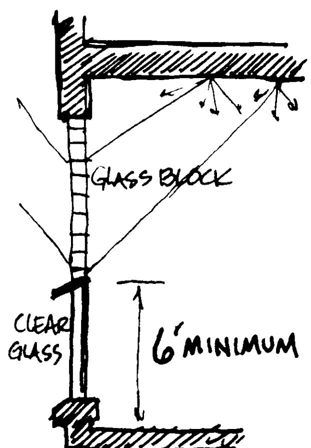

FIGURE 3.24[12]

Its major drawbacks were that a clear view of the sky was prevented, and that the blocks were often sources of glare, due to their diffusing nature.

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[12] Figure from William J. McGuiness and Benjamin Stein, Mechanical and Electrical Equipment for Buildings, 5th ed. (New York: John Wiley and Sons, 1971), p. 708.

Glass as a Paving Material?

Many of us are familiar with the little round glass inserts in some city sidewalks, but few think of them as architectural materials. Pavement lights, or cellar lights, originated as deck-lights for sailing ships. They were invented in 1808 in England, and, when inserted into the ship's deck, allowed the sailors below decks to see their sails! Later, they were used to admit light to city cellars, in the form of a large circular slab of cast glass.

By the end of the nineteenth century, these pavement lights were framed in metal, to increase their strength and resistance to breakage. They were plagued with problems such as leaks and dropping through the sidewalk, but, today, they can support anything, even trucks.

Around 1900, two American professors invented the prismatic cellar-light, which became the standard for city use. Here is a typical cross-section:

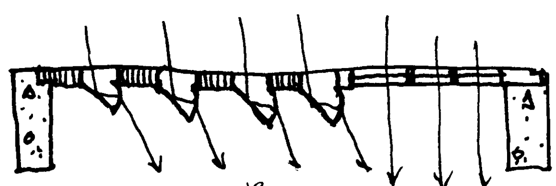

FIGURE 3.25[13]

Although the problem of maintenance, especially cleaning, is a major factor limiting their application, I feel that these paving elements could

13 Figure from McGrath, p. 180

have wider use in modern architecture. Entire ground floors could be paved with them, allowing some amount of daylight to penetrate to an otherwise dark basement, for example.

14 Daylight Control Devices

All exposuresof a building that receive some direct sun should be provided with some method of daylight control. The three primary types of control are interior, exterior, and glazing materials. The latter was just discussed in Chapter 13, and includes tinted glass, light-directing glass and other selective transmitting materials.

On the following page is a representative sampling of commonly employed daylight control devices.

Exterior Controls

Exterior controls are more effective in reducing solar gain because the heat thus deflected will be carried away by external air movements. Once the sunlight gets into and through the glass, a large portion will be converted to internal heat gain instantaneously.

Horizontal shading by balconies or overhangs is particularly effective on southern exposures due to the sun's higher altitude. This kind of shading device is less valuable on the eastern and western exposures. Overhangs, in addition to controlling insolation, do not interfere with ventilation, and may provide outdoor shaded corridors in some climates. It is recommended that the underside of overhangs be painted a highly reflective light color, to take advantage of reflections of ground light.

On the east and west sides, vertical louvers or fins are effective in reducing or preventing insolation, while increasing diffuse and reflected daylight. If employed in combination with horizontal shades, the "egg-crate" effect is created.

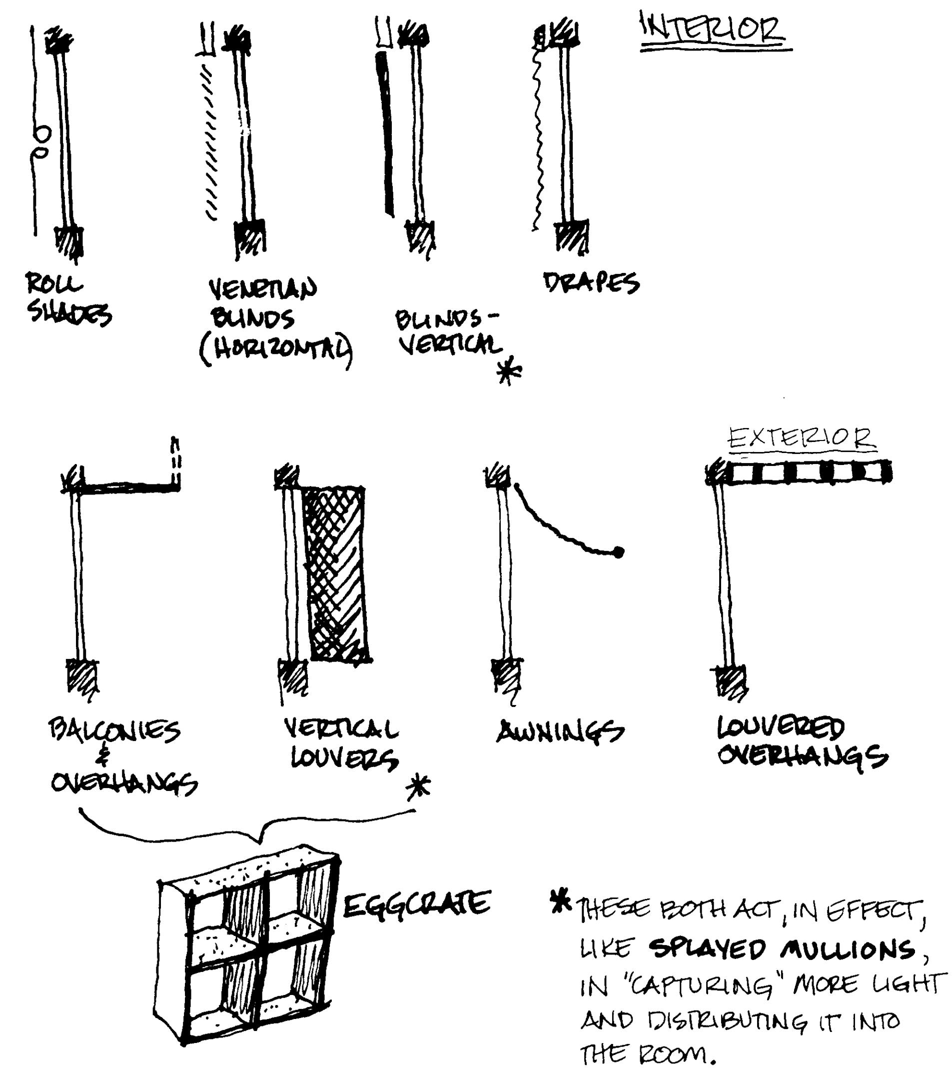

FIGURE **3.26** (after McGuinness)

In this climate, the eggcrate design seems a bit extreme. The prevention of insolation that is called for in more equatorial latitudes, and which necessitates an eggcrate, is not of such high priority in this climate. It must be remembered that the total amount of direct daylight reaching the interior is drastically reduced by an eggcrate.

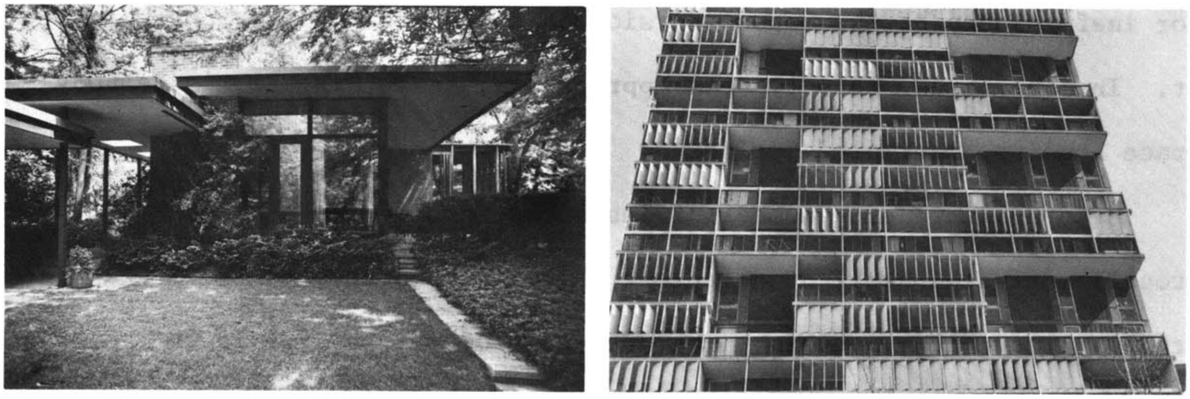

Figure 3.27 (left) Overhangs on this residence are longest on the south and east sides, and are white underneath. (right) Jose Luis Sert's housing for Harvard, showing vertical, manually operated louvers on the western facade.

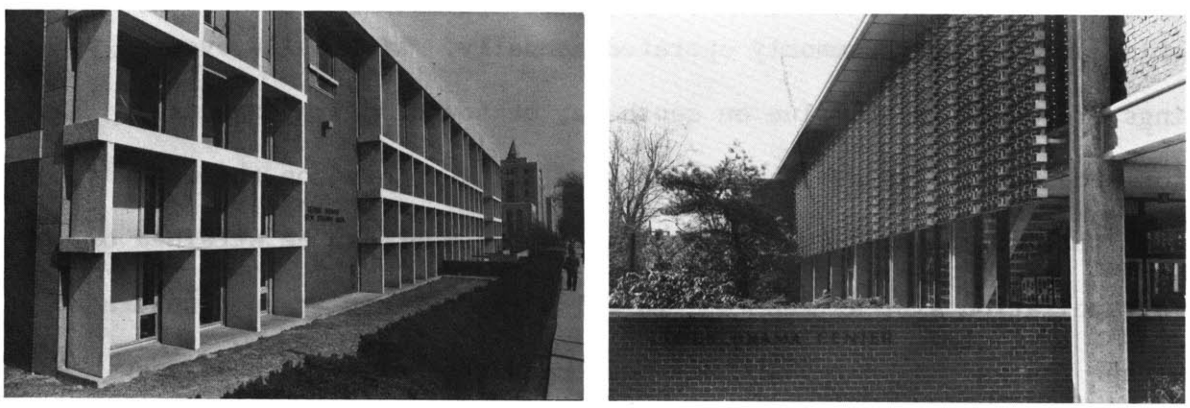

Figure 3.28 (left) This eggcrate faces south; it is on Boston University's Student Union (also Sert). (right) Sunscreens can also be decorative. On the Loeb Drama Center at Harvard, this screen was repeated on three facades, including the north!

Movable versions of all of the above-mentioned devices are available, and can provide the utmost in manipulation and control of sunlight. The major inefficiency of the manual version is the necessity for constant adjustment. In some cases, this type is appropriate, as in J.L. Sert's Peabody Terrace housing, mentioned earlier.

In an increasing number of instances, control is achieved by a photocell-activated sunlight detector, which is connected to the mechanical system that moves the louvers. The advantage of this system is that precise control of interior illumination can be maintained, especially if the supplemental artificial lighting is also part of this system.

Awnings are a common sight to most of us, particularly on storefronts. They used to be ubiquitous throughout this country, before air conditioning was available. They are usually made of canvas, aluminum, or plastic, and are most commonly operated manually. Like solid overhangs, awnings are of the most value on southern, or southeastern exposures. Their performance can be improved by making them light-colored on the outside, to reflect more of the sun's rays. Further improvement can be attained by leaving a ventilation slot at the top, to allow the hot air trapped underneath to escape instead of increasing the heat conducted through the window.

One variation on the solid overhang is the louvered overhang. When used over south-facing windows, it blocks direct sunlight, but allows more to reach the ground, and thence the interior, by reflection, than does a solid overhang. It might be possible to design a louvered overhang for the north side of a building that will increase the brightness of the rooms on that side, if so desired. It catches some sunlight, and bounces it into the north-facing windows (at a sacrifice in the area of sky seen by the window):

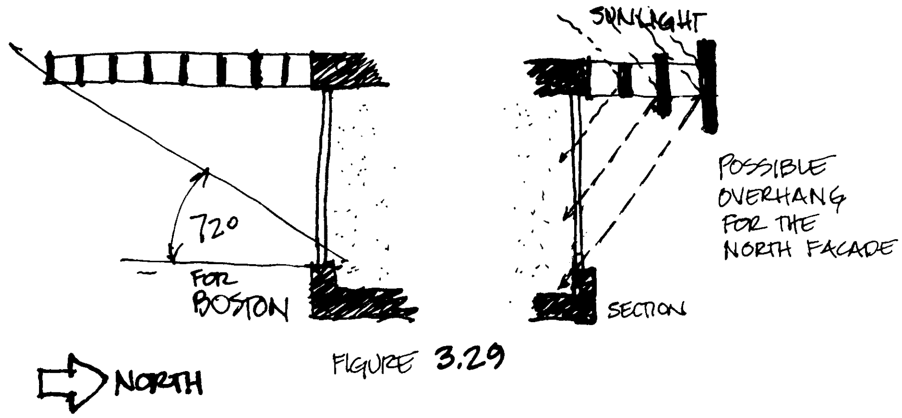

FIGURE 3.29

Seasonally variable daylight controls do exist in the form of vegetation. If properly placed, deciduous trees can provide shade in the warm months and let sunlight through during the fall and winter. They thus reduce sky glare when it is at its maximum, and, seasonally, permit increased solar penetration when the solar altitude is lowest.

Interior Controls

Of the four types of interior daylight controls shown in Figure 3.17, venetian blinds are the most effective and flexible. According to a L.O.F. booklet, " . . . they enable the greatest use of illumination from the sky and they admit more ground light while blocking out direct sunlight. Each slat is a reflector which throws light up to the ceiling."[15] They can be used on any exposure of a building to control daylight, but are most effective on southern exposures.

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[15] Predicting Daylight, p. 12.

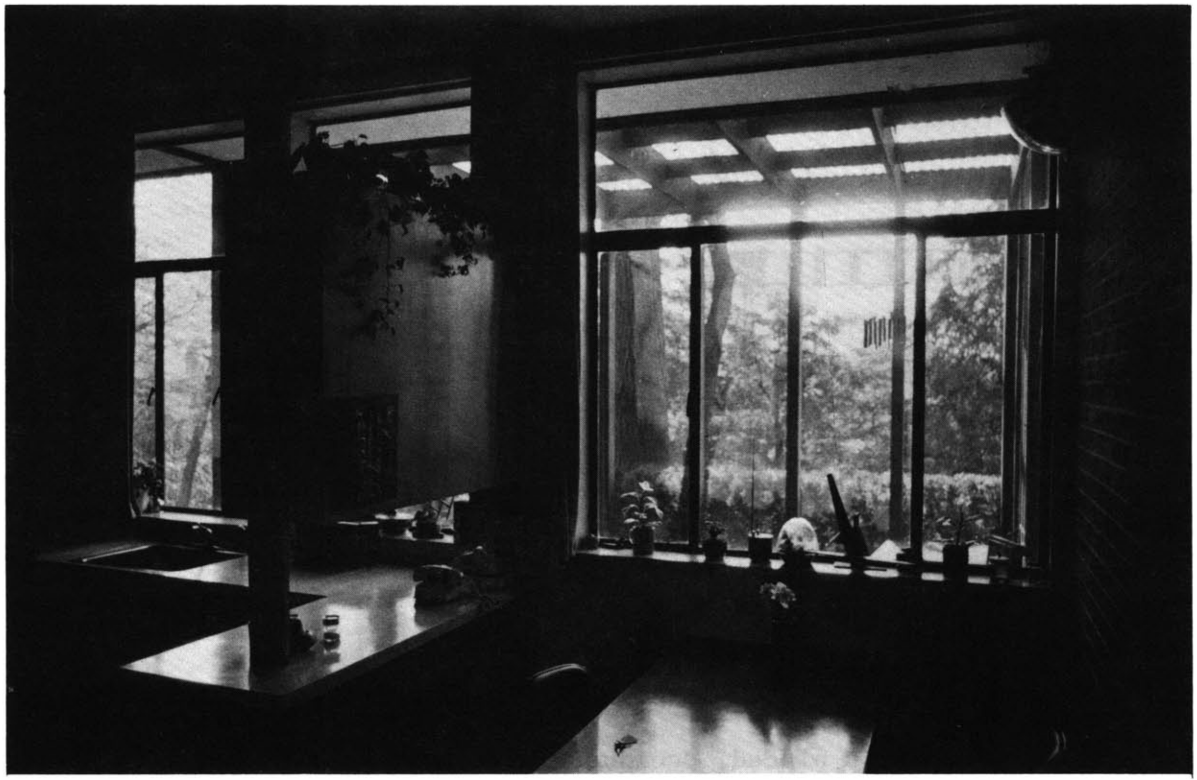


Figure 3.30 This kitchen faces southeast: the deciduous trees shade it in summer, while allowing winter sunlight to get through.

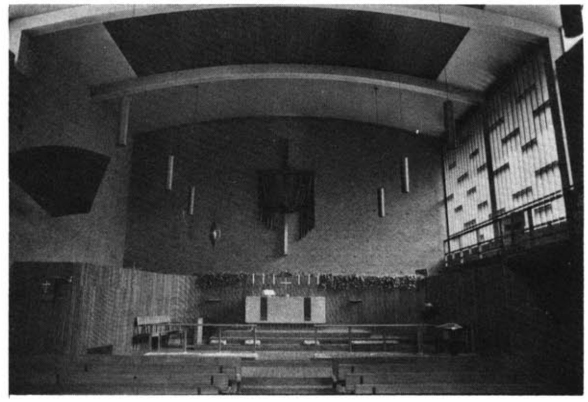
Vertical blinds are less common. Their advantage is that they throw more light on the walls, in much the same way as splayed reveals, thus increasing surround brightness. They seem to be more effective on east and west exposures: they are similar in this respect to vertical external louvers. Vertical blinds can be considered as the modern analogue to the mullion; breaking up the large, single-light, area of glass.

Drapes and curtains are particularly useful for reducing the light level of a room in a substantial, less subtly variable way. Drapes are heavier and usually more opaque than curtains. If their interior face is of a light color, they can reduce glare by contrast grading, even as they frame the

Figure 3.31 The effects of venetian blinds and vertical blinds.

window.

When using light-colored curtains, the daylight coming through is usually diffused, and can thus become a glare source itself. They are better used in conjunction with another type of control such as shades or blinds, because of their inherent inflexibility with respect to adaptation to changing light levels.

<u>Figure 3.32</u> (left) Curtains diffuse sunlight over the entire room. (right) Interior louvers that shield a south-facing window reduce the direct view of the sky, and throw diffuse light onto the walls of the First Lutheran Church of Boston, designed by Pietro Belluschi.

Interior daylight controls serve the additional purpose of providing varying degrees of privacy from the outside world. In most cases, the greater the privacy desired, the more opaque or obscuring is the device used, and the greater is the reduction in interior illumination. At those times that privacy is most desired, however, the desire for daylight is not as important.

15 Interior Surface Finishes

Light is reflected from a surface in one of several ways. Specular reflections are those in which the light leaving the surface has the same angle as did the incoming light.

Diffuse reflections are those in which the light leaves the surface in a multitude of directions. Matte surfaces give complete diffuse reflections; mirrors give specular reflections. (Figure 3.33)

In both kinds of reflection, some of the radiant energy we see as light is lost, and transformed into heat. The darker the color, the less is reflected, and the more is absorbed and converted; that is why dark colors heat up so quickly in the sun. All reflectance factors are, therefore, less than 1, and are expressed as percentages. A light color might be 80% R.F., while a dark color's factor might be 5%. The extreme low end of the scale is probably black velvet, which seems to "drink up" light, due to its enormously large number of interstices, creating a large surface area. It is nearly the perfect absorber.

Surface finishes in the interior of a room are especially important with respect to the quality of light. Special areas of the room, such as the window framing elements, the window wall, and light control devices, have already been discussed as they relate to color and reflections. The importance of the ground reflections outside a window was mentioned. Let us now examine the recommendations for interior surfaces.

In the context of the preceding discussion of the reflectance mechanism, it is useful to understand schematically how different kinds of paint reflect light.

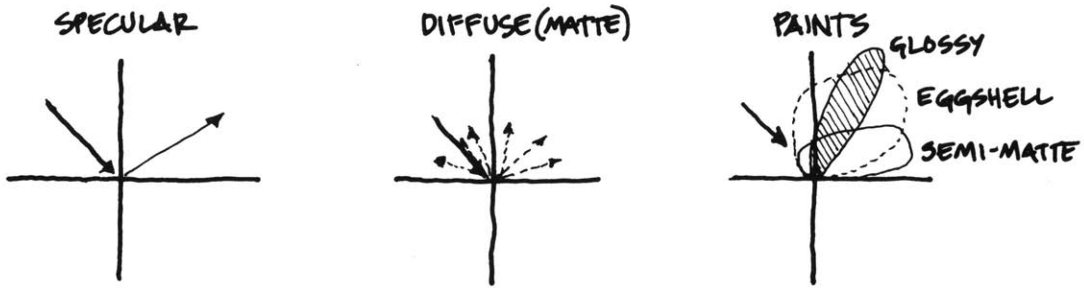


FIGURE 3.33 SCHEMATICS OF REFLECTION

One of the simplest ways to judge the reflectance of a specific color is to determine where it lies on the Munsell color scale. Its value, or degree of lightness or darkness, is "V". White is V=10; black is V=0. It is similar to a photographic grey scale.

Reflectance is roughly equivalent to V(V-1). Therefore, a Munsell value of 9 is equal to a reflectance factor of 72%; a value of 5= reflectance factor 20%.

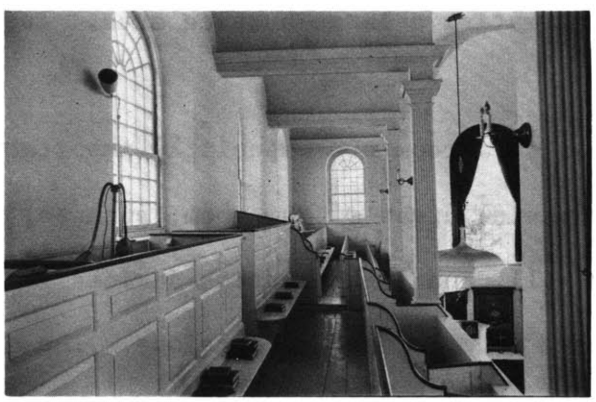


Figure 3.34 Old North Church and Faneuil Hall. Notice how well-lighted is the floor due to the light colors of the ceiling and window frames.

Referring now to the chapter on Daylight Calculations, we note that one element of daylight factor in a room is the Internally Reflected Component. It is largely determined by the reflectances of the walls, floor, ceiling, and even the furniture. Following are some of the recommended reflectance values for these surfaces, which, when used together with such window design as was recommended earlier, will help create good brightness distribution and modelling.

RECOMMENDED REFLECTANCES[16]:

CEILING	70 %
WALLS	40-60%
FLOOR	20-40 %
FURNITURE	20-30%

There are several particular qualifications that accompany these suggestions. The back wall of a single side-lit room contributes markedly to the local brightness, giving an impression of brightness to the entire room. The window wall should also be light-colored, to reduce contrast with the window.

On sunny days, some room surfaces can become too bright, and thus act as glare sources themselves. This is especially true if they are white, or very near white. As a result, the following recommendation is made:

If the window area with side lighting is greater than 1/3 of the

[16] These values are taken from a course in Daylighting taught at MIT in 1974. They are based on British codes.

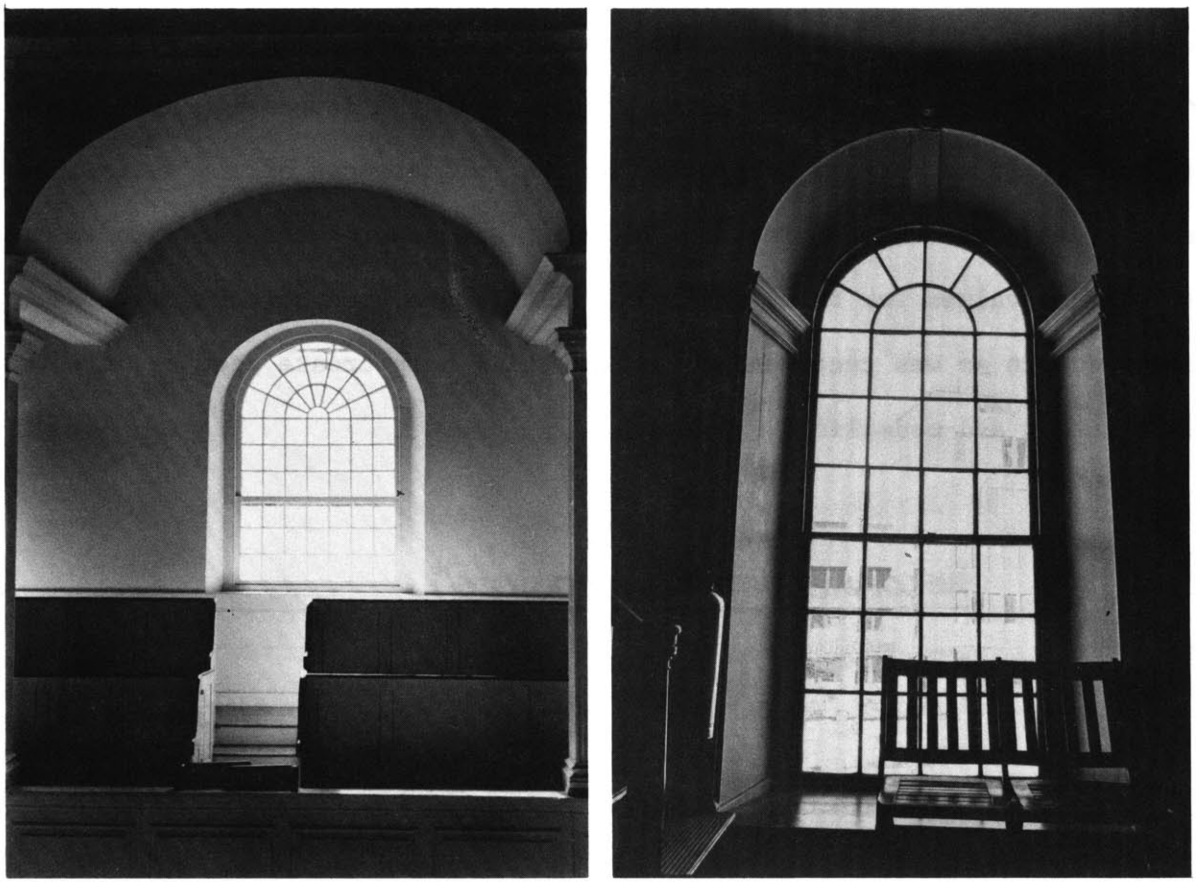


Figure 3.35 Old North Church and Faneuil Hall. Both have deep, splayed reveals, but the walls of the latter are a medium gray, rather than the former's white. Notice also the glow on the window wall, produced by reflections from the rear of the pews.

floor area, white should be avoided, and the average reflectances kept down to 30-50%, with wall reflectances not exceeding 65%.[17] If, however, solar absorbing or reflecting glass is used, these levels can be exceeded, in proportion to the reduction in brightness of the window caused by the lower transmittance of those glasses.

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[17] Hopkinson, p. 449.

The Future

The use of natural light in architectural design has evolved through a progression of changing priorities. These prime determinants have included, at one time or another, religious reasons, desire for clarity of light, desire for precisely controlled light, and even apparent disregard for its presence or implications. The attitude expanded upon in the foregoing thesis is aimed at developing a renewed respect for, and understanding of, natural light.

The design guidelines presented herein can be considered to be a modelling technique, basing the prediction of interior qualities of daylight upon recognizable examples and basic principles. A fundamental question this technique raises is the issue of evaluation: how does one measure the intangible "feel" of a daylighted space? The quantities of light can be calculated, but they are of little use in a subjective analysis -- each person will formulate a different judgement.

And what of the future? Our technological progress will undoubtedly allow us to develop more precise and flexible methods and materials for filtering, controlling, and modifying natural light. New developments in glasses and coatings, such as those that respond automatically to changing exterior light levels, will help change our perspectives on natural light. Continued research in the field of photobiology will probably reinforce the belief that natural light is essential for the survival of all life on earth.

Energy conservation is potentially the most critical and far-ranging field in today's society, and will assume more significance in the coming years. It is important to note that many of the recommendations made in this thesis are consistent with energy-conscious attitudes. In other words, it may not be necessary to sacrifice the qualities of natural light in order to save energy! All these aspects will lead to increasing opportunities and expanding possibilities for dealing with light, and will require correspondingly more advanced evaluation techniques.

There is, however, the possibility that new developments will be applied publicly before their consequences are known. If the past is any indication, the effects of such advances upon living organisms may be overlooked, and "discovered" years later. It can only be hoped that the lessons of the past centuries have been learned, and that these new technologies will be applied in a conscious, humane manner, which will ultimately lead to the improvement of our environment, through a more sensitive use of natural light.

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