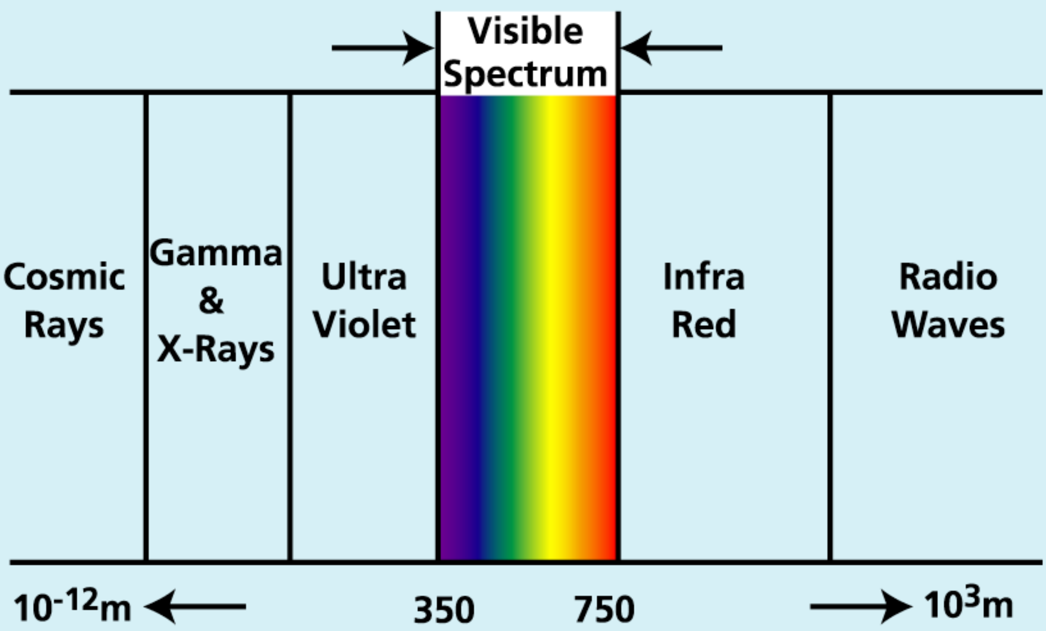
LIGHT

What is Light?

According to the Quantum Theory in Physics, light is a form of electromagnetic radiation (i.e., energy), obeying the laws of wave motion.



DAYLIGHTING

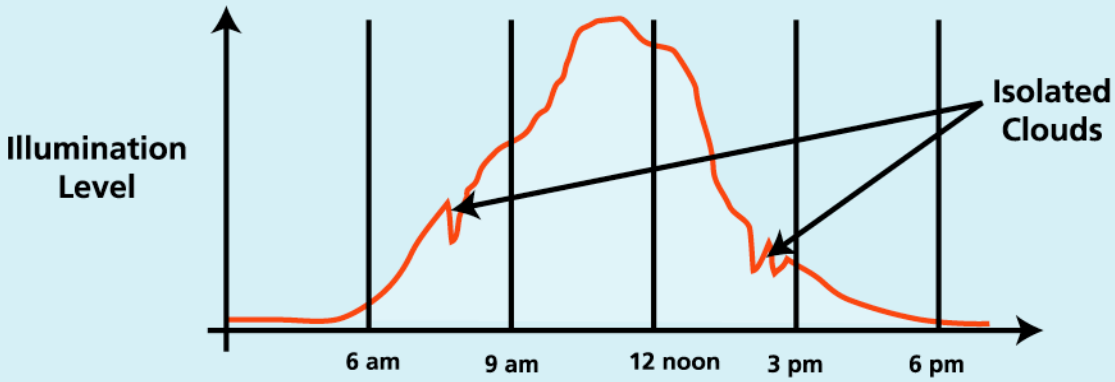
Design Concerns

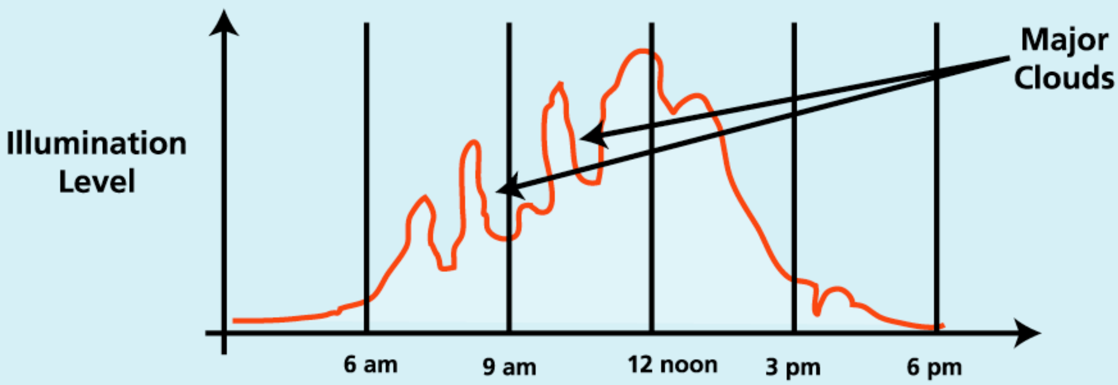
Stability:	Due to the changing relative positions of the sun and the earth the intensity of daylight varies from hour to hour.
Reliability:	The availability of daylight is largely unpredictable due to changing sky conditions (e.g., clouds).
Accessibility:	Structural advances that allow large spans make it difficult to bring daylight to remote areas of deep spaces.
Controllability:	Difficult to separate solar heat from daylight for easterly and westerly window orientations.
Quality:	The brightness of a section of the sky seen through a window can be a source of glare.

DAYLIGHTING

Variability of Daylight

It is a characteristic of daylight illumination that it varies continuously during each day and from day to day.





Light and Color

Color Characteristics

Although light is contained within a narrow band of the electromagnetic spectrum, color cannot be specified by wavelength alone.

A complete color specification requires values for three attributes:

Hue which is specified by the *dominant wavelength*.

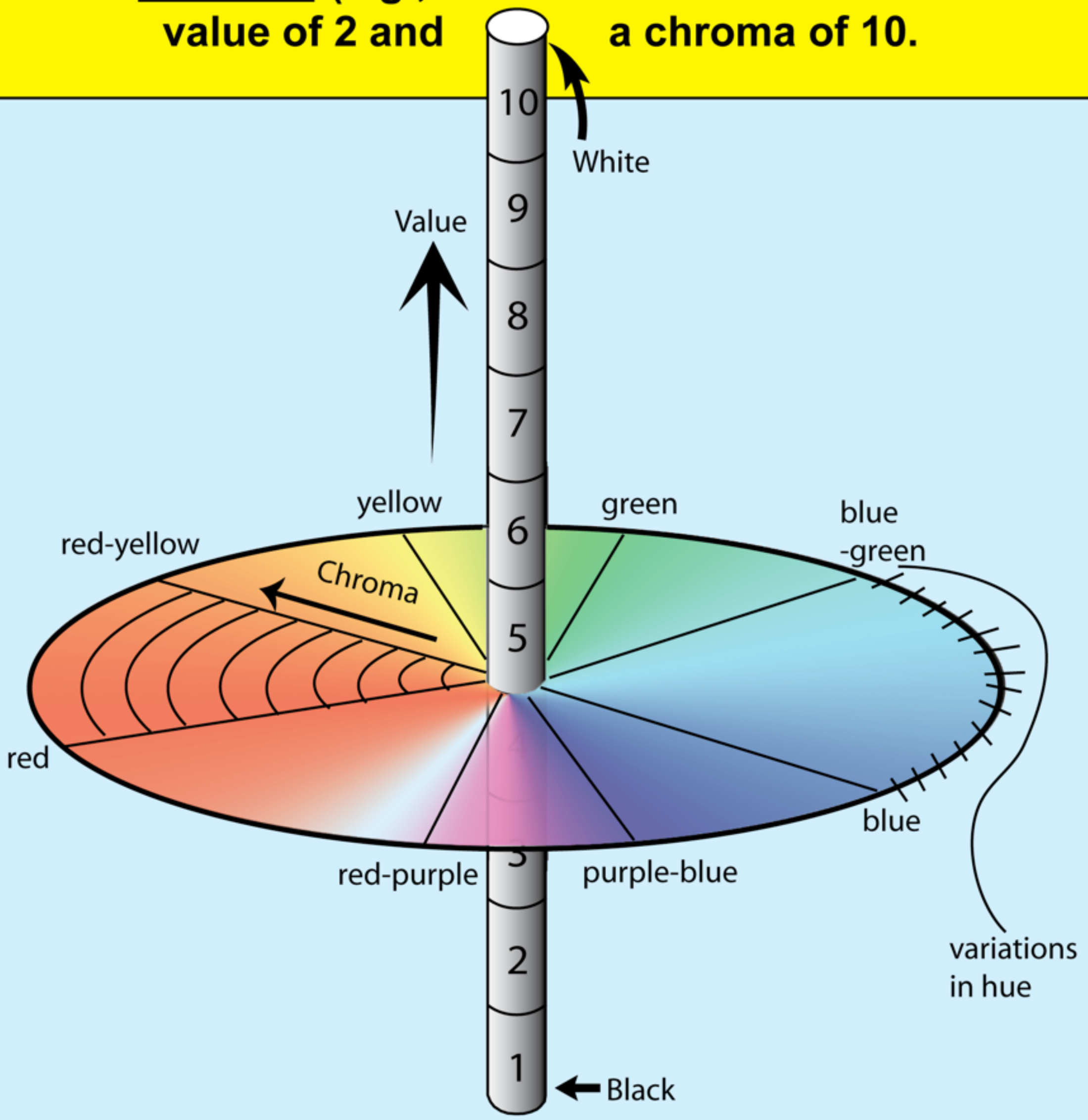
Value which represents the *luminance* or *brightness*.

Chroma which represents the *purity* or degree of *saturation*.

Light and Color

Munsell Color System

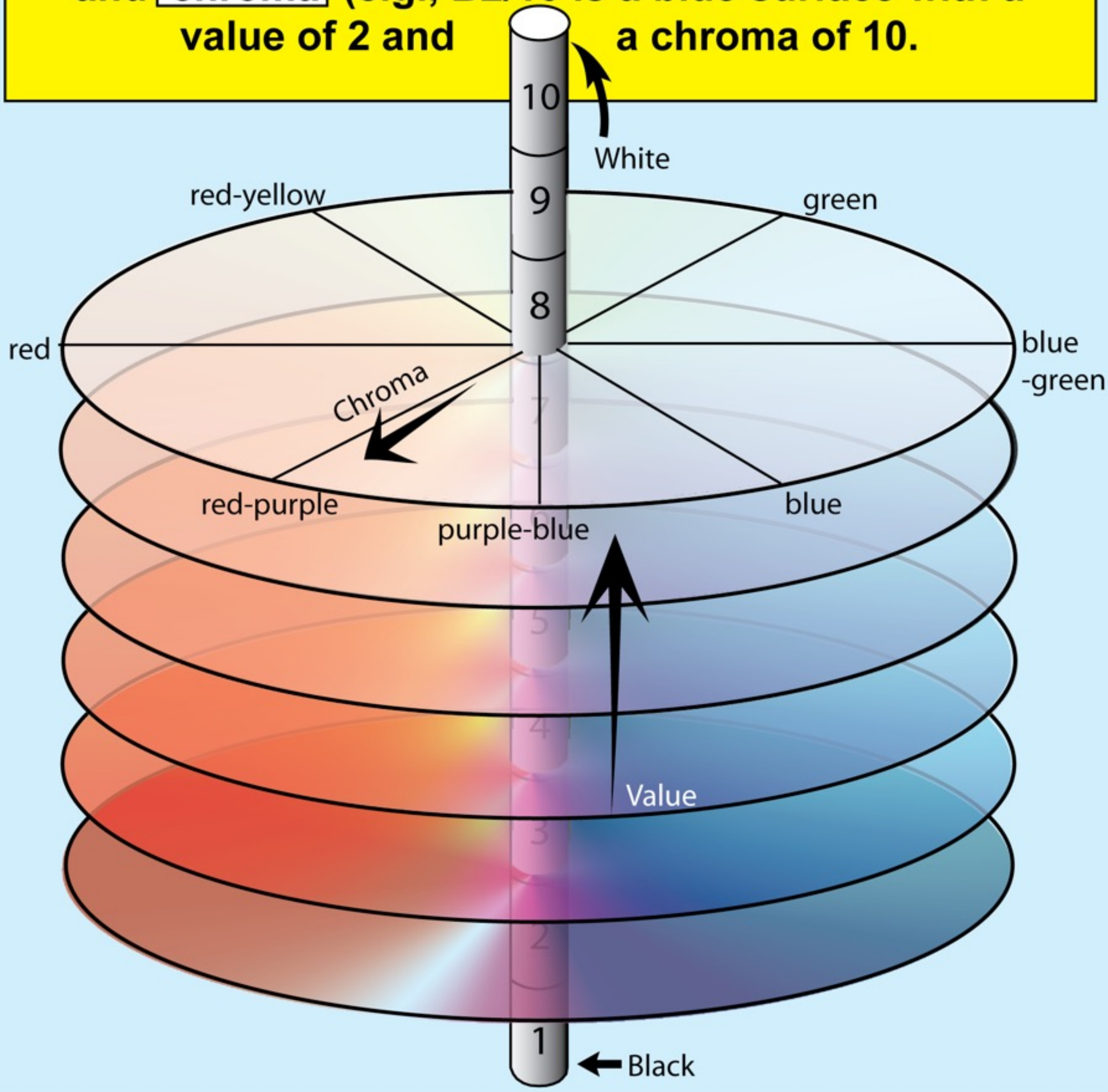
Applies to surfaces only. Allows the color of a surface to be specified in terms of value, hue and chroma (e.g., B2/10 is a blue surface with a value of 2 and a chroma of 10.



Light and Color

Munsell Color System

Applies to surfaces only. Allows the color of a surface to be specified in terms of value, hue and chroma (e.g., B2/10 is a blue surface with a value of 2 and a chroma of 10.



Light and Color

C.I.E. Color Notation System

In 1931 the Commission Internationale l'Eclairage (C.I.E.) established a system of color notation based on the color-matching capabilities of the human eye.

The C.I.E. color system had to take into account two complicating factors:

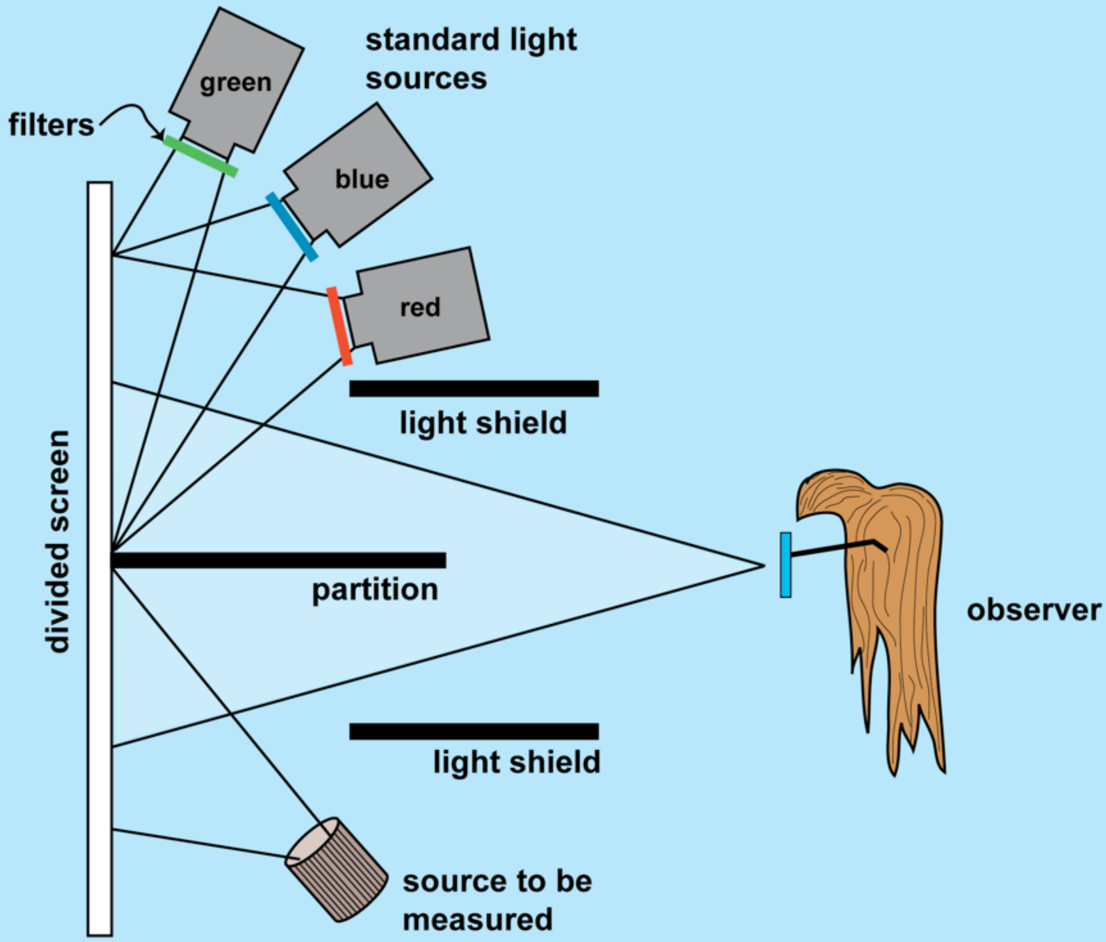
A Any particular color can be produced with several *different spectral compositions*. This phenomenon is referred to as **metamerism**.

B Many more colors can be perceived by the eye than can be produced by the *additive composition* of the three primary colors **red, green and blue**.

Light and Color

Colorimeter

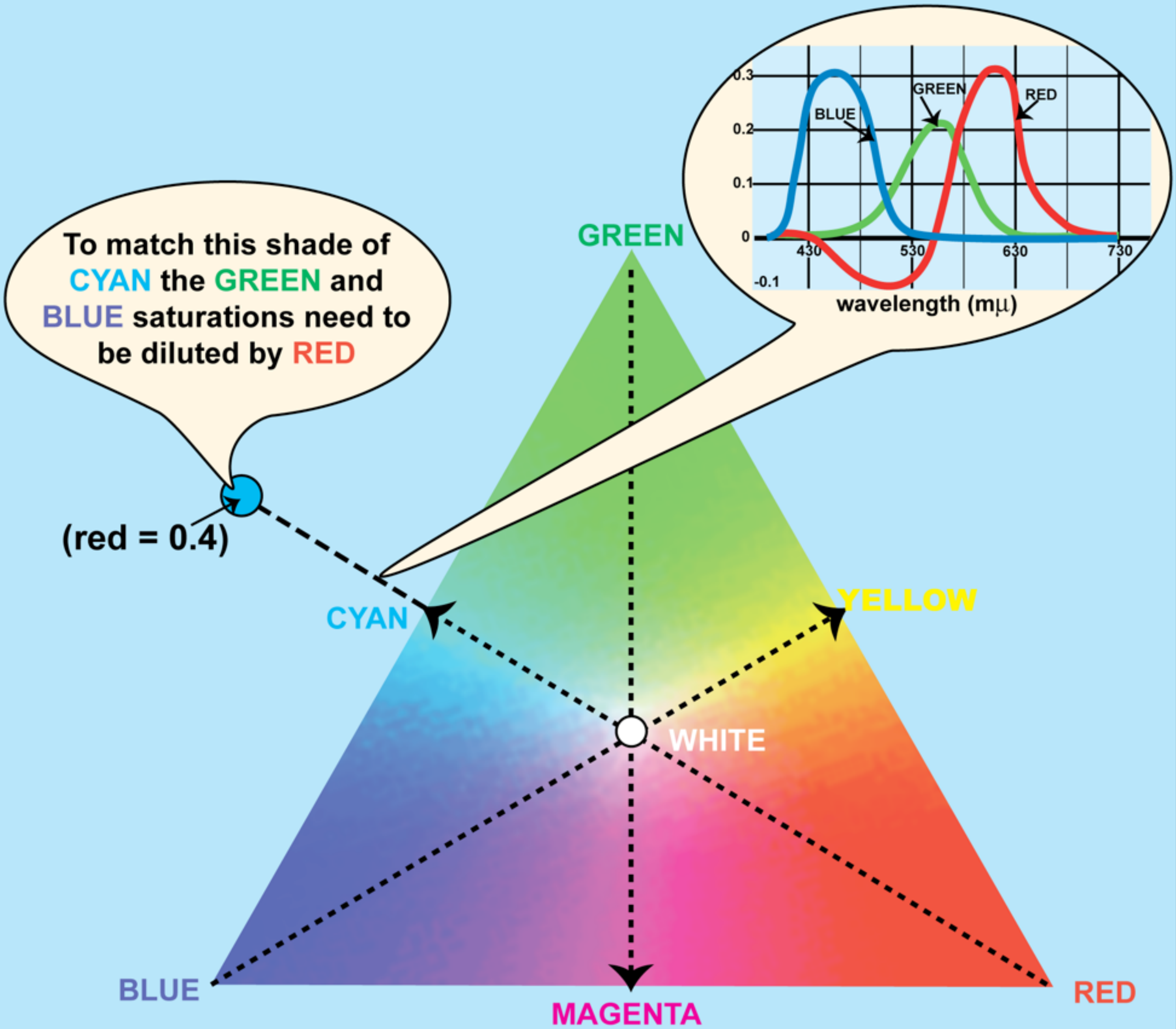
A visual instrument that requires the operator to subjectively adjust three colored light sources (i.e., red, blue and green) until they match the color of the light source to be measured.



Light and Color

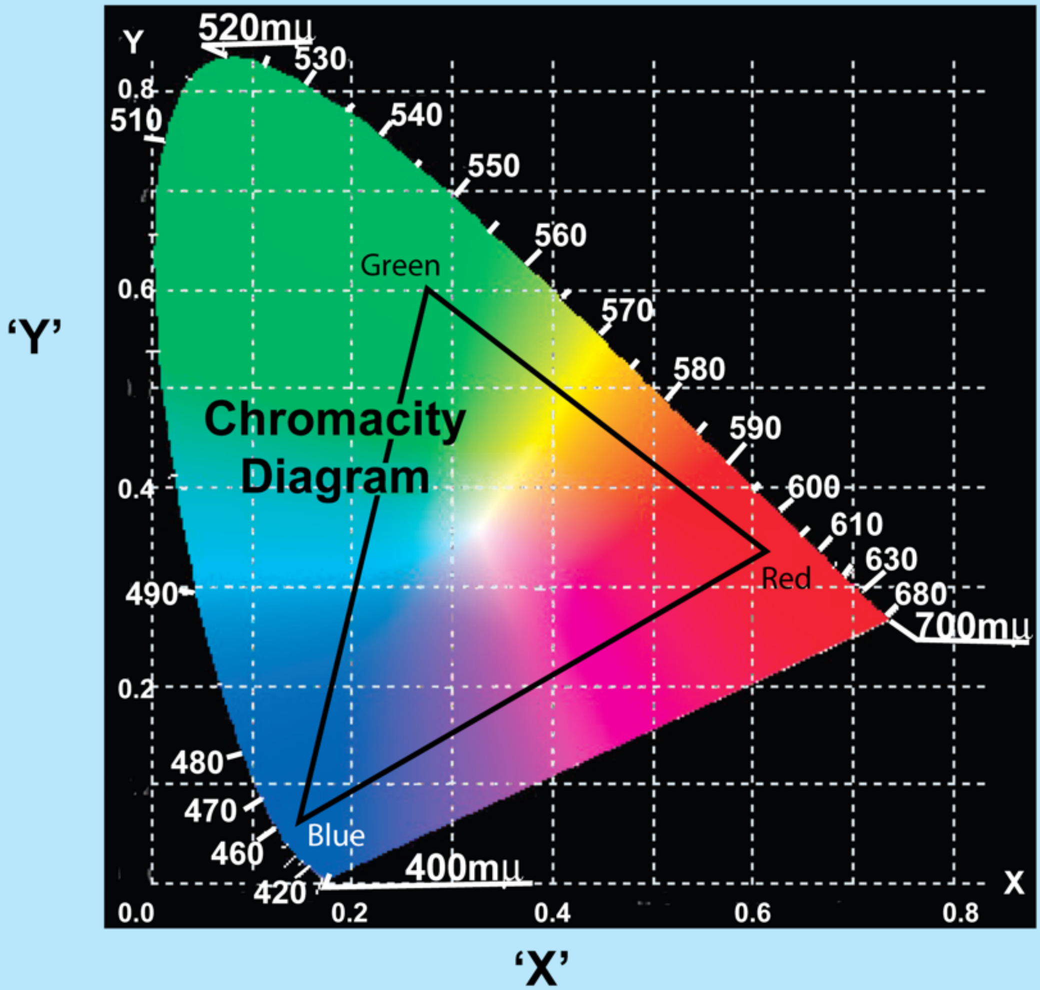
C.I.E. Color Notation

Additive mixing of the three primary colors (i.e., red, green and blue) cannot represent all colors visible to the eye. Therefore, the C.I.E. system defines three super-saturated primary colors that lie outside the bounds of the color triangle.



Light and Color
C.I.E. Color Chart

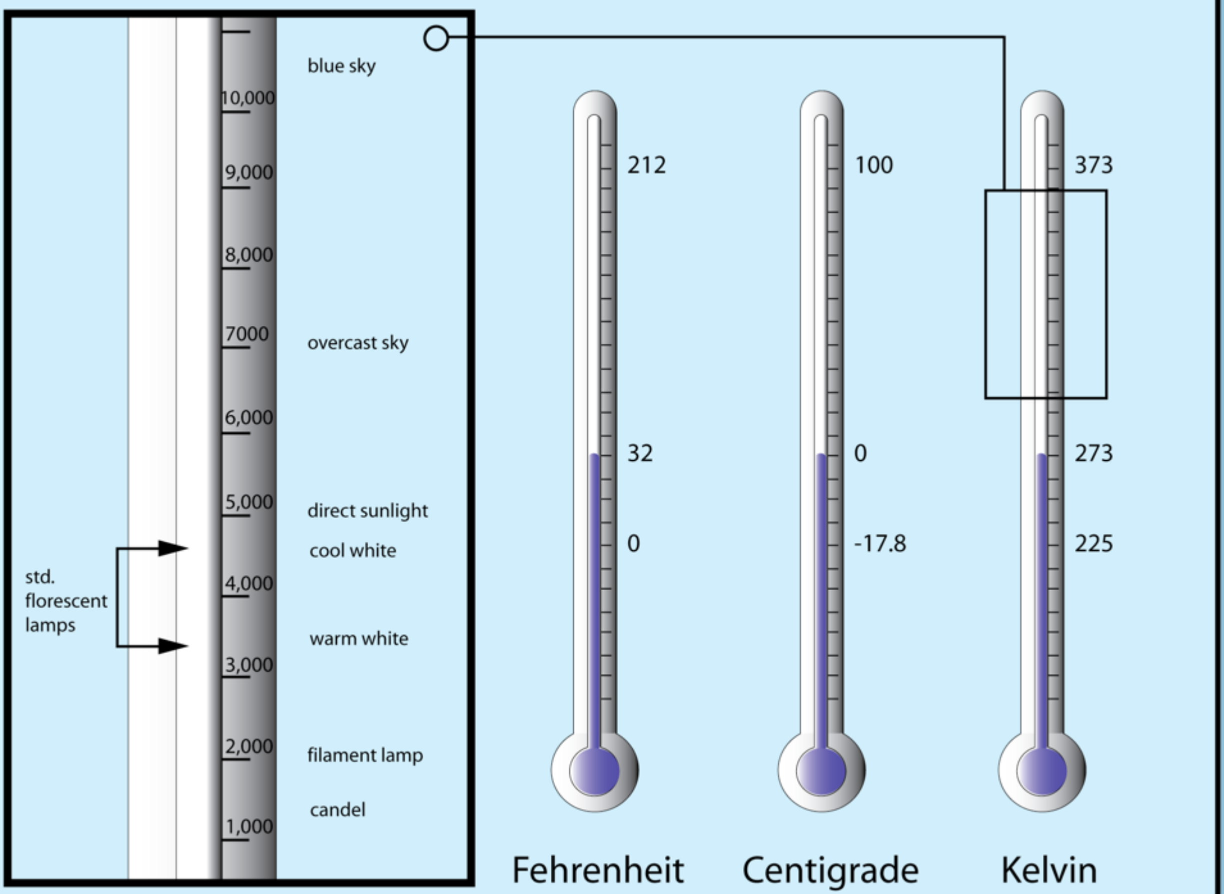
The full range of colors visible to the eye can be represented by the CIE Chromacity Chart in terms of the color coordinates X and Y (i.e., saturation and hue) plus the Z value (i.e., brightness or luminance).



Light and Color

Color Temperature Scale

Color Temperature **is not the operating temperature of a light source, but indicates the spectral distribution of radiation emitted by the source. *A Color Temperature* of 3200 K means that the light source matches the radiation spectrum emitted by a *Black Body* when heated to 3200 K.**

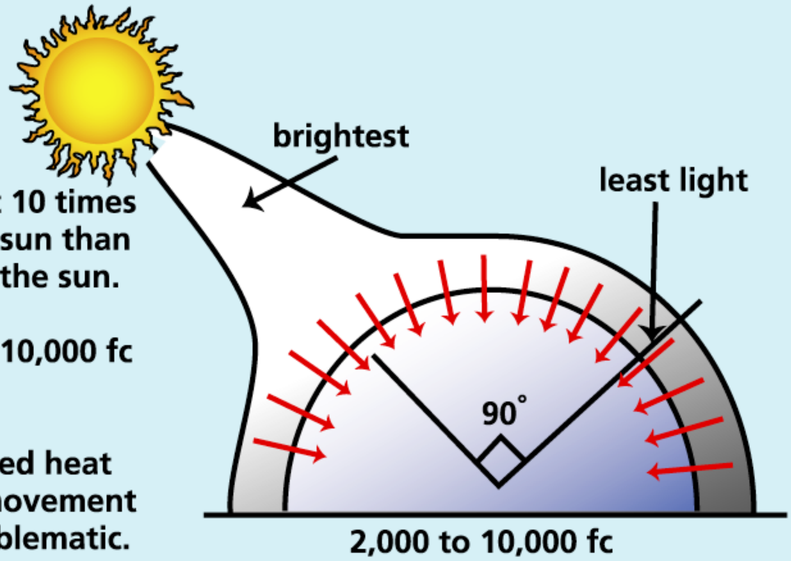


DAYLIGHTING

Sky Conditions

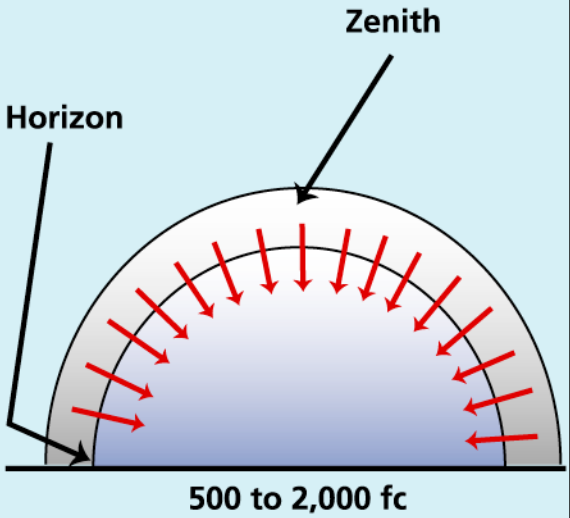
Clear Sky

- Clear Sky is about 10 times brighter near the sun than at 90˚ angle from the sun.
- Provides 2,000 to 10,000 fc on a clear day.
- Brightness, radiated heat and continuous movement of sun can be problematic.



Overcast Sky

- Overcast Sky is about 3 times brighter at zenith than at horizon.
- Provides 500 to 2,000 fc depending on cloud cover
- Mathematically defined as an international standard (C.I.E. Standard Overcast Sky).



DAYLIGHTING

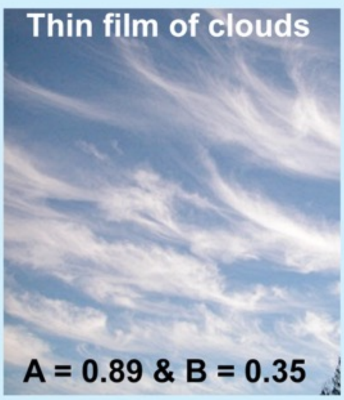
Calculation of Daylight Availability

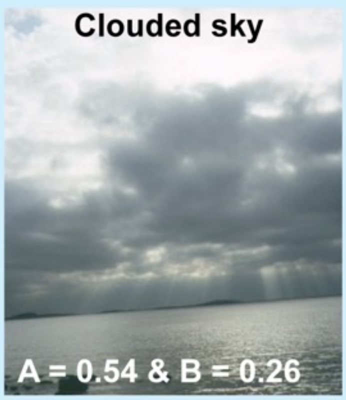
The daylight available on a horizontal surface (E_H) outdoors under a clear sky is contributed by the sun and the sky (acting as a luminous hemisphere).

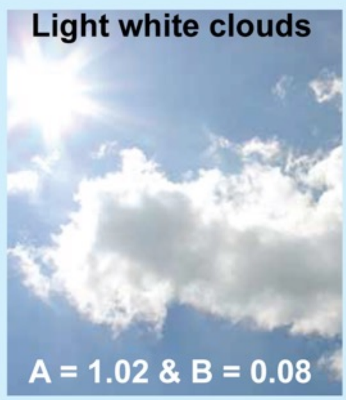
If 'a' is the altitude of the sun and 'm' is the air mass (m = cosec(a)), then:

$$E_H = A\left[1750 \sin(a)^{0.5}\right] + B\left[13200 \sin(a) 10^{-0.1m}\right] \text{ fc}$$

This equation can be adapted to different sky conditions:







DAYLIGHTING

Comparison of Daylight Equations

(1) $E_H = A\left[1750 \sin(a)^{0.5}\right] + B\left[13200 \sin(a) 10^{-0.1m}\right]$ fc

(2) $E_H = 52a$ fc (for: $A = 0.46$ and $B = 0.26$ in equation (1))

(3) $E_H = 30 + \left[1950 \sin(a)\right]$ fc (Krochmann 1963)

Sun Altitude (a)	Clear Sky (Equation (1))	Clouded Sky (Equation (2))	Overcast Sky (Equation (3))
10°	500 fc	530 fc	370fc
20°	750 fc	1,060 fc	700 fc
30°	900 fc	1,590 fc	1,005 fc
40°	1.100 fc	2,120 fc	1,280 fc
50°	1,200 fc	2,640 fc	1,520 fc
60°	1,300 fc	3,180 fc	1,720 fc
70°	1,320 fc	3,710 fc	1,860 fc
80°	1,450 fc	4,240 fc	1,950 fc

DAYLIGHTING

C.I.E. Standard Overcast Sky

The C.I.E. Standard Overcast Sky was adopted by the Commission Internationale de L'Eclairage in 1955.

- The sky luminance distribution from the zenith to the horizon depends on the altitude (a) of the particular patch of sky being viewed, as follows:

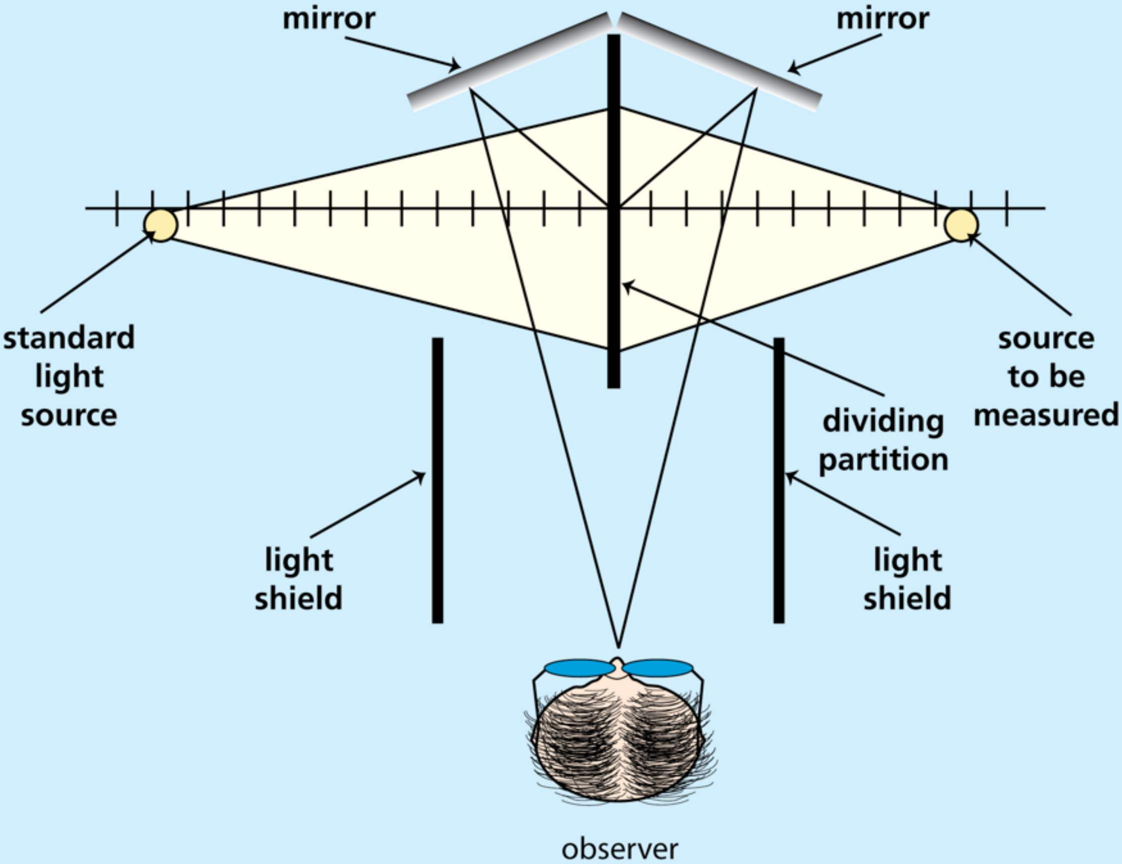
$$\text{Luminance at altitude (a)} = \frac{\left[\text{luminance at zenith}\right] \times \left[1 + 2\,\textit{sin}\ \text{a}\right]}{3} \quad \text{(fL)}$$

- The illumination level provided by the whole overcast sky on a horizontal surface on Earth, is given by:

$$\text{illumination level} = 0.78 \left[\text{luminance at zenith}\right] \quad \text{(fc)}$$

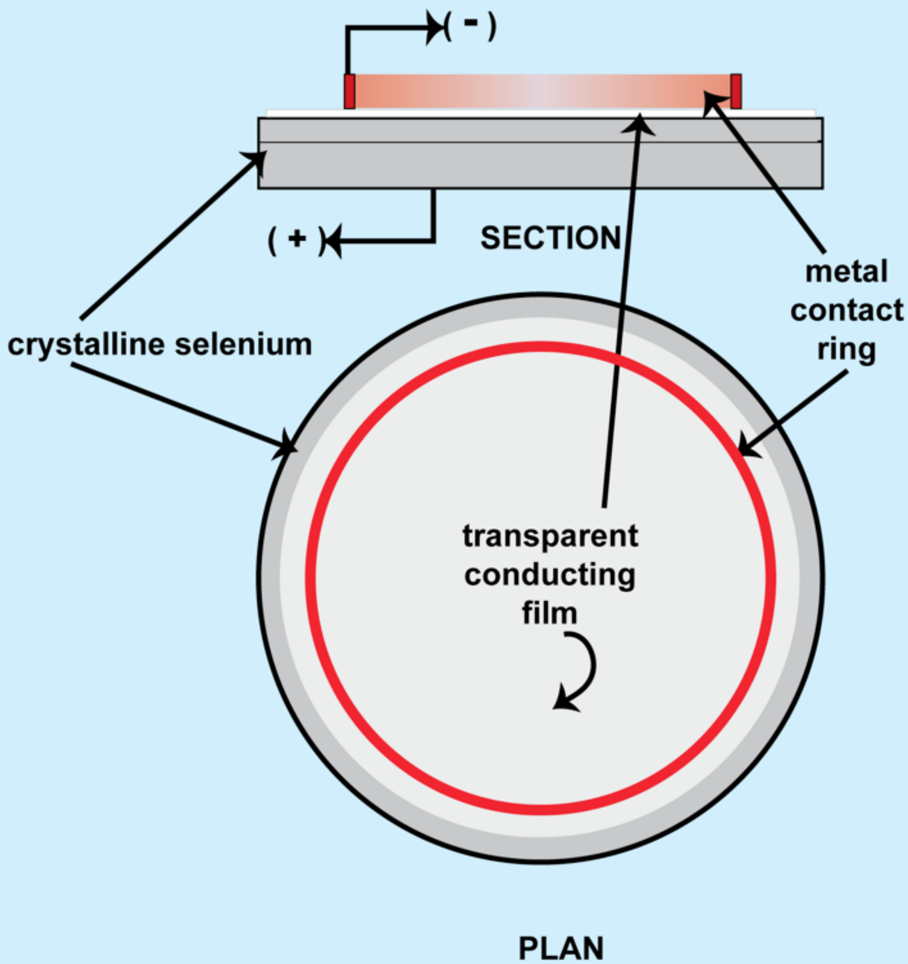
Measurement of Light
Photometer

A **visual instrument** that requires the operator to subjectively adjust a standard light source to match the light source to be measured.



Measurement of Light
Selenium Cell

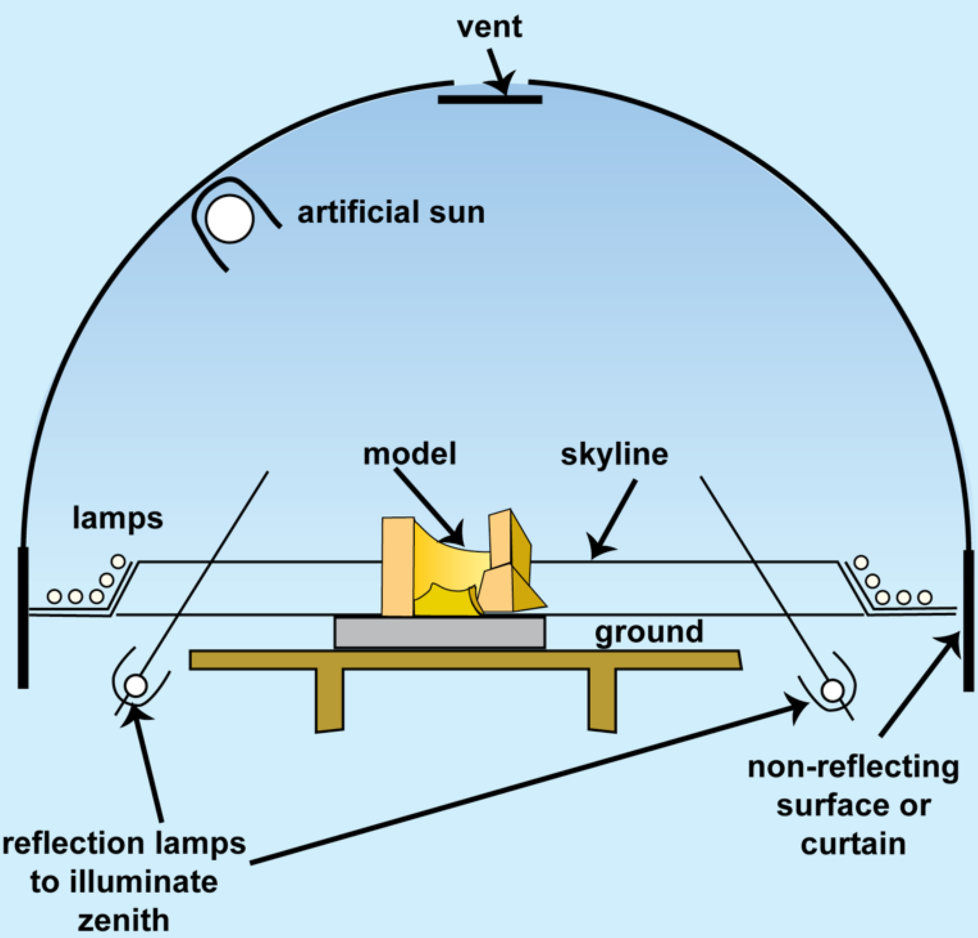
A **photoelectric instrument** that measures the electric current or voltage generated by the light incident on a selenium plate.



Lighting Model Analysis

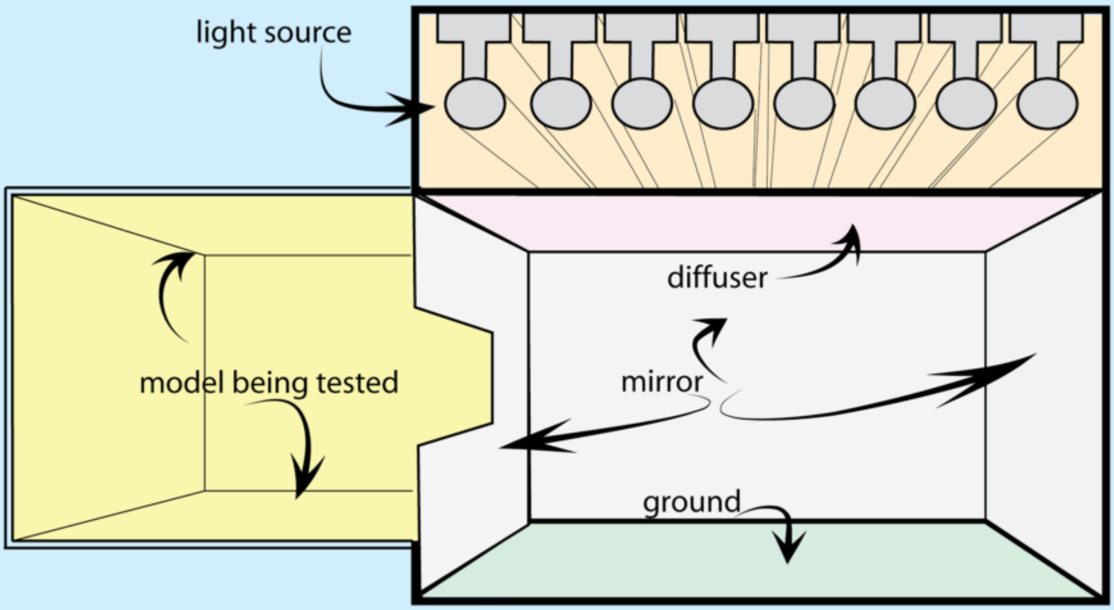
Artificial Sky Dome

Highly reflective internal surface of dome is illuminated by lamps located at the base of the dome. A movable artificial sun can add a significant level of sophistication.



Lighting Model Analysis
Mirror Box Artificial Sky

Internal walls are lined with mirrors to ensure that the horizon is at eye level within the model but at an infinite distance. Illuminated from the top by artificial light sources, the light is diffused by a translucent opal acrylic sheet.



DAYLIGHTING
The Daylight Factor Concept

The Daylight Factor expresses the illumination available on a horizontal surface inside a building as a percentage of the illumination provided by the whole sky on a horizontal surface located outside the building.

$$\text{Daylight Factor} = \frac{100 \left[\begin{array}{c}\text{indoor illumination} \\ \text{on a horizontal surface}\end{array}\right]}{\left[\begin{array}{c}\text{outdoor illumination from whole sky} \\ \text{on a horizontal surface}\end{array}\right]} \ (\%)$$

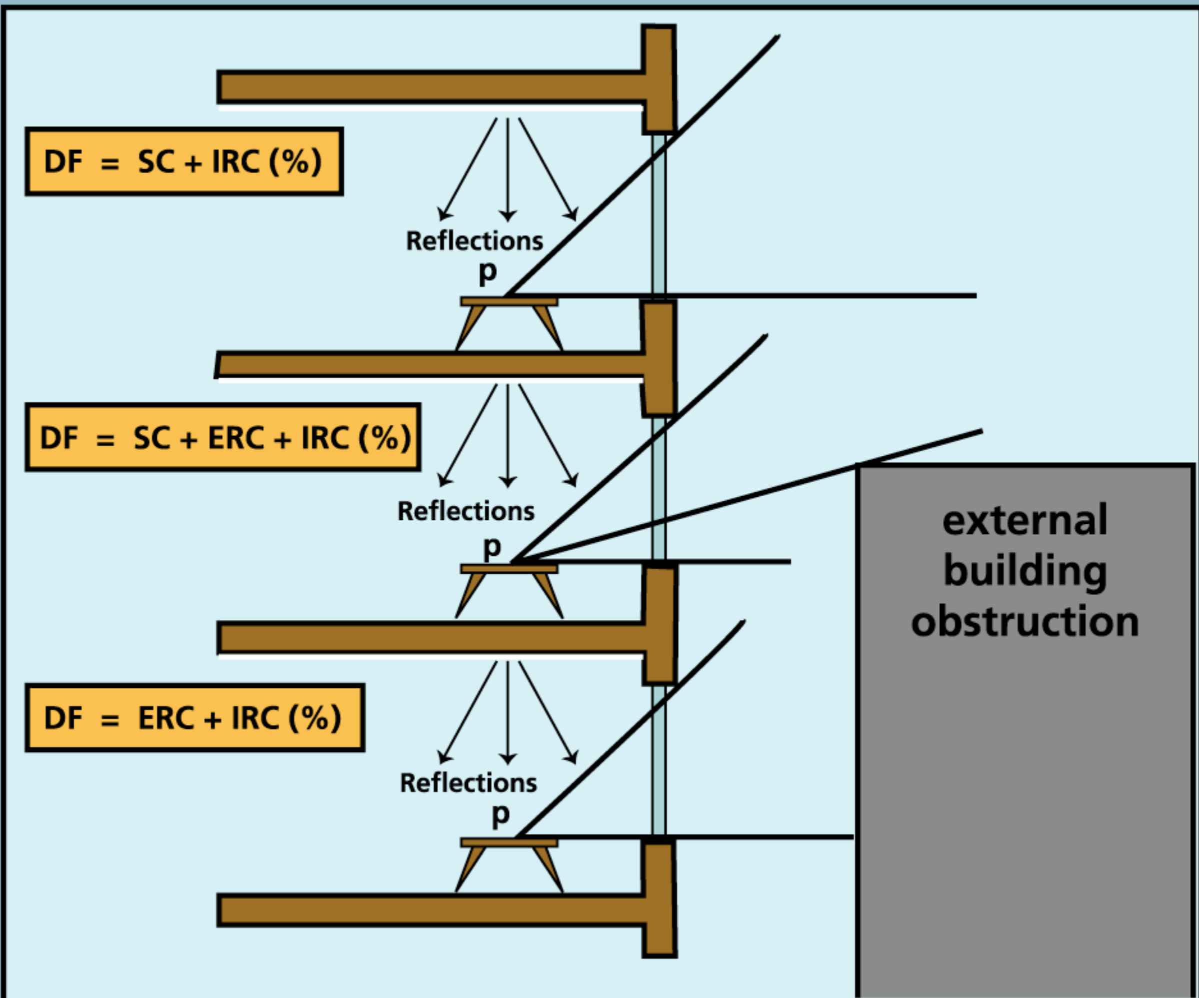
Daylight Factor is useful for ...

- Determining the distribution of daylight from area to area within a building.
- Comparing different window layouts.
- Comparing the availability of daylight in different buildings.
- Comparing the availability of daylight at a particular point at different times.

DAYLIGHTING

Daylight Factor Components

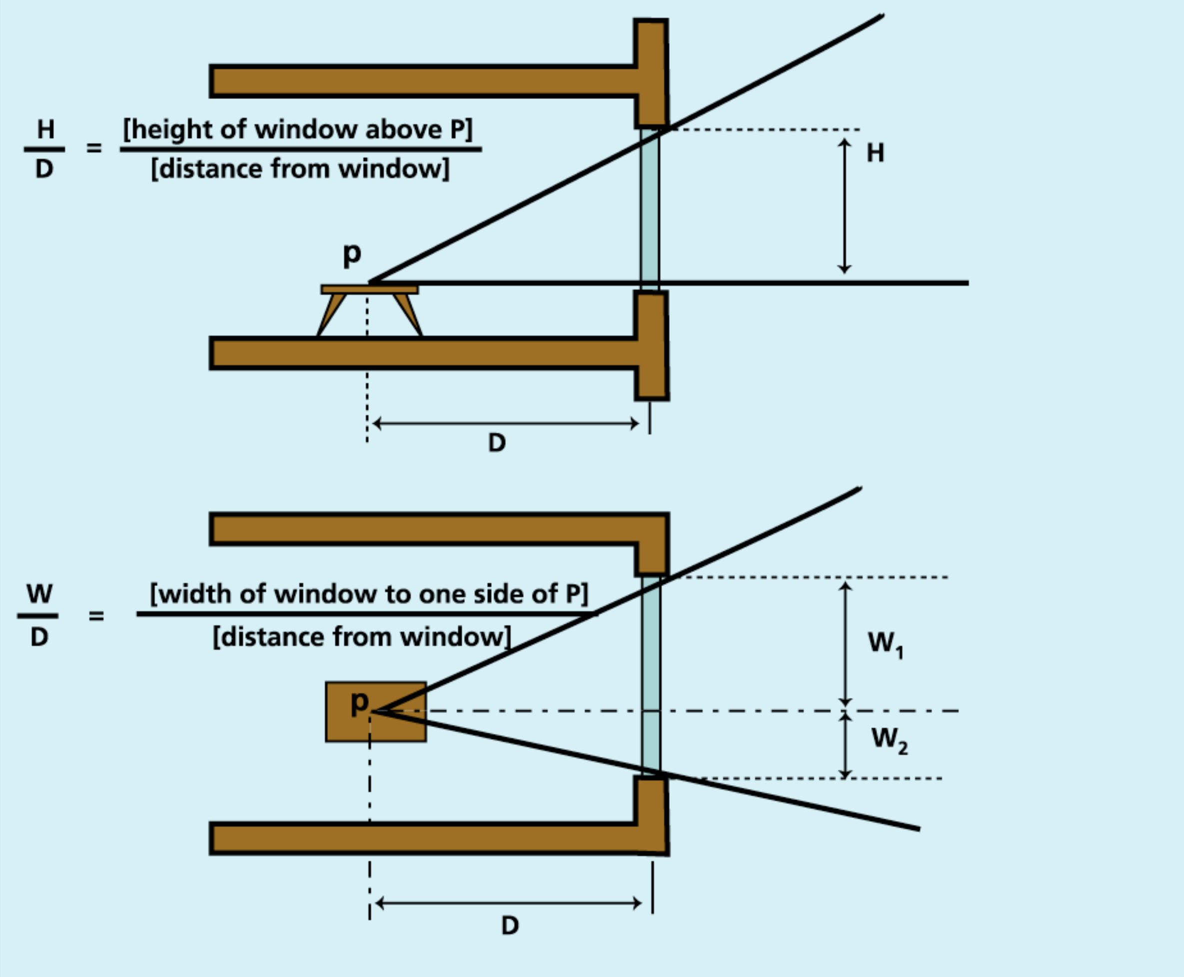
The Daylight Factor (DF) is the sum of the Sky Component (SC) and/or Externally Reflected Component (ERC) and the Internally Reflected Component (IRC).



DAYLIGHTING

Calculation of Sky Component

The British Research Station (B.R.S.) has published simplified Sky Component (SC) tables based on simple geometric relationships.



DAYLIGHTING

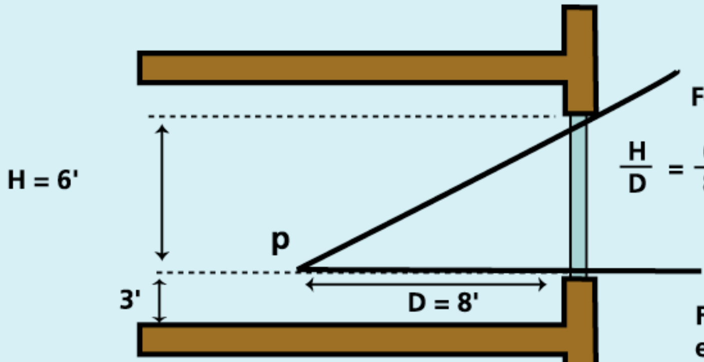
B.R.S. Sky Component Tables

H/D \ W/D	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	angle of obstruction
1.2											50°
1.1							3.70	4.10	4.		48°
1.0						3.00	3.30	3.60	3.80	4.	45°
0.9					2.20	2.60	2.85	3.10	3.25	3.40	42°
0.8				1.60	1.90	2.20	2.40	2.60	2,75	2.90	39°
0.7			0.97	1.30	1.50	1.70	1.90	2.10	2.20	2.30	35°
0.6	0.24	0.39	0.74	0.98	1.15	1.30	1.45	1.60	1.70	1.80	31°
0.5	0.16	0.25	0.52	0.70	0.83	0.97	1.03	1.10	1.20	1.30	27°
0.4	0.10	0.14	0.34	0.45	0.53	0.62	0.68	0.75	0.82	0.89	22°
0.3	0.06	0.06	0.18	0.26	0.30	0.34	0.38	0.42	0.44	0.47	17°
0.2	0.03	0.02	0.09	0.11	0.12	0.14	0.17	0.20	0		11°
0.1	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.			6°

DAYLIGHTING

Sky Component: Case (1)

Case (1): Reference plane at window sill level and reference point (P) on center line of window.

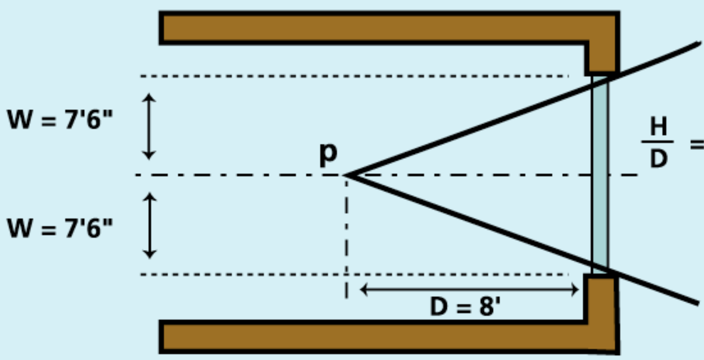


Section

For window on left side of P:

$$\frac{H}{D} = \frac{6}{8} = 0.75 \quad \text{and} \quad \frac{W}{D} = \frac{7.5}{8} = 0.94$$

From the B.R.S. table the equivalent SC is given as 2.5



Plan

For window on right side of P:

$$\frac{H}{D} = \frac{6}{8} = 0.75 \quad \text{and} \quad \frac{W}{D} = \frac{7.5}{8} = 0.94$$

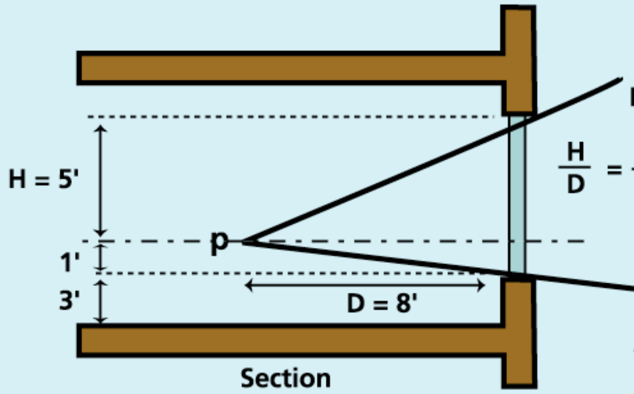
From the B.R.S. table the equivalent S.C. is given as 2.5

Sky Component (SC) = 2.5 + 2.5 = 5%

DAYLIGHTING

Sky Component: Case (2)

Case (2): **Reference plane above sill level and reference point (P) on center line of window.**



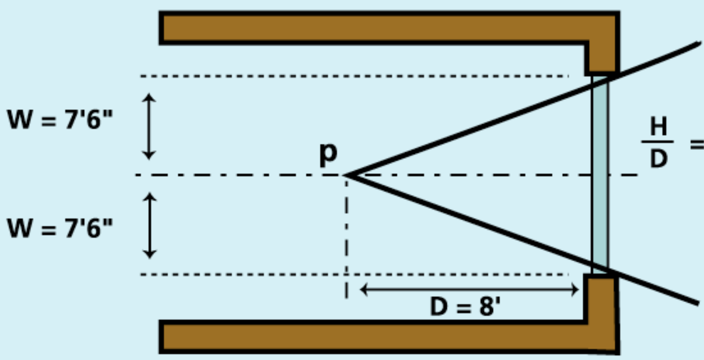
Section

For window on left side of P:

$\frac{H}{D} = \frac{5}{8} = 0.63$ and $\frac{W}{D} = \frac{7.5}{8} = 0.94$

From the B.R.S. table the equivalent SC is given as 1.8

*(PS: The portion of the window below the reference plane is ignored.)



Plan

For window on right side of P:

$\frac{H}{D} = \frac{5}{8} = 0.63$ and $\frac{W}{D} = \frac{7.5}{8} = 0.94$

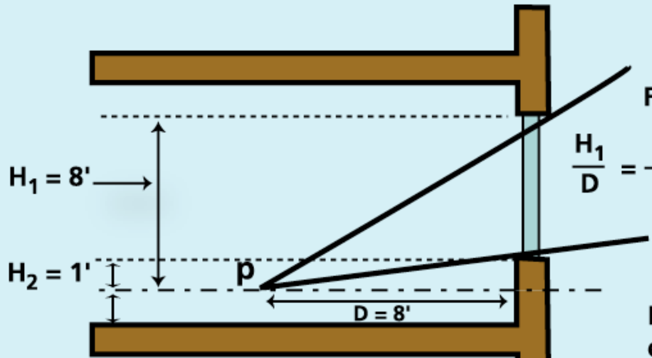
From the B.R.S. table the equivalent S.C. is given as 1.8

Sky Component (SC) = 1.8 + 1.8 = 3.6%

DAYLIGHTING

Sky Component: Case (3)

Case (3): **Reference plane below sill level and reference point (P) on center line of window.**

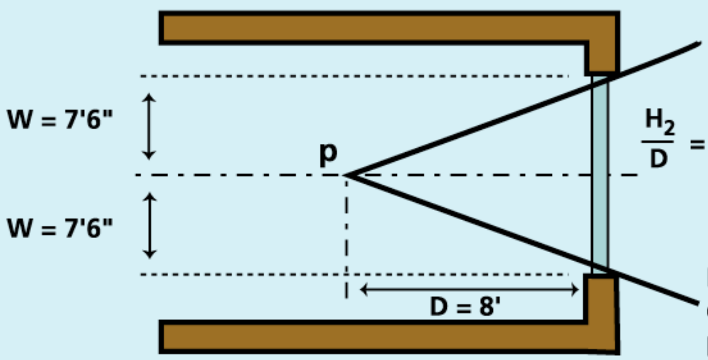


Section

For window on left side of P:

$\frac{H_1}{D} = \frac{8}{8} = 1.00$ and $\frac{W}{D} = \frac{7.5}{8} = 0.94$

From the B.R.S. table the equivalent SC (assuming a full height window above P) is given as 3.9



Plan

For wall portion (below sill) on left side of P:

$\frac{H_2}{D} = \frac{1}{8} = 0.13$ and $\frac{W}{D} = \frac{7.5}{8} = 0.94$

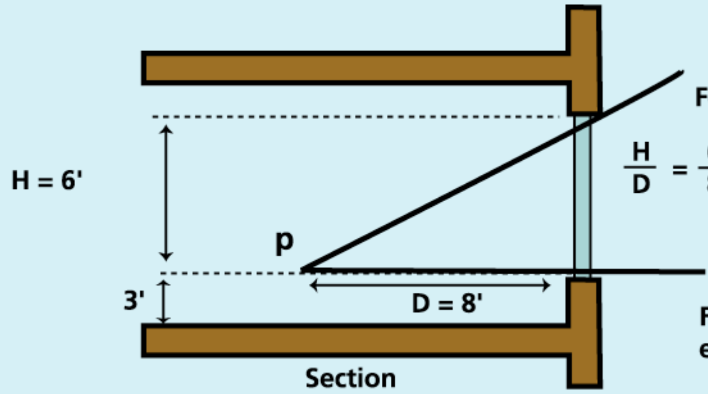
From the B.R.S. table the equivalent S.C. (for the wall portion below P) is given as 0.1

Sky Component (SC) = 3.9 - 0.1 + 3.9 - 0.1 = 7.6%

DAYLIGHTING

Sky Component: Case (4)

Case (4): Reference plane at sill level and reference point (P) not on center line of window.

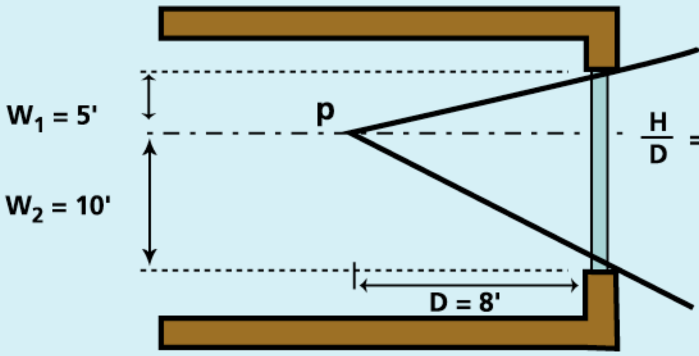


Section

For window on left side of P:

$$\frac{H}{D} = \frac{6}{8} = 0.75 \quad \text{and} \quad \frac{W_1}{D} = \frac{5}{8} = 0.63$$

From the B.R.S. table the equivalent SC is given as 2.0



Plan

For window on right side of P:

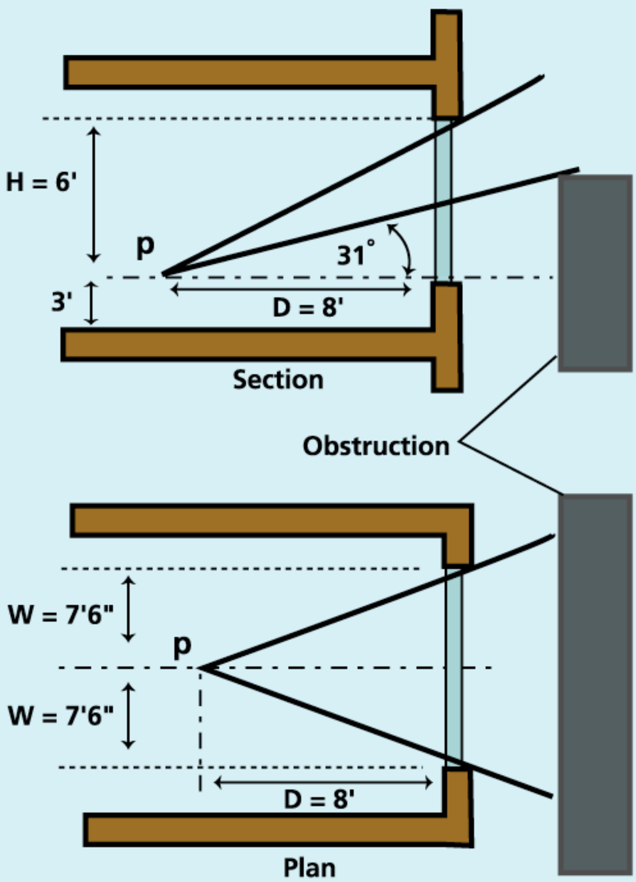
$$\frac{H}{D} = \frac{6}{8} = 0.75 \quad \text{and} \quad \frac{W_2}{D} = \frac{10}{8} = 1.25$$

From the B.R.S. table the equivalent S.C. is given as 2.8

Sky Component (SC) = 2.0 + 2.8 = 4.8%

DAYLIGHTING
Sky Component: Case (5)

Case (5): Reference plane at sill level and reference point (P) on center line of window and external obstruction.



For window on left side of P without obstruction):

$$\frac{H}{D} = \frac{6}{8} = 0.75 \text{ and } \frac{W}{D} = \frac{7.5}{8} = 0.94$$

From the B.R.S. table the equivalent SC is given as 2.5

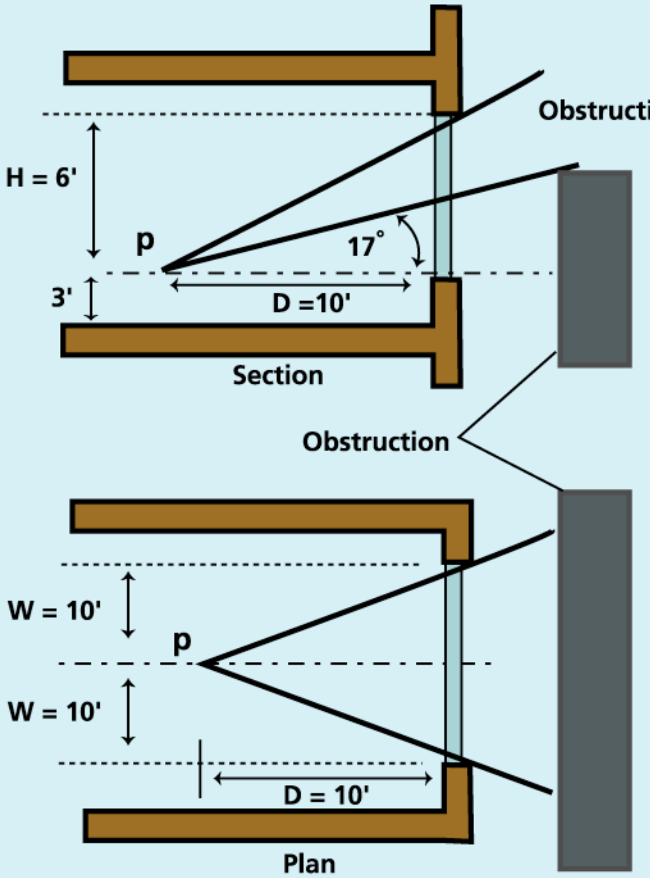
The SC for the portion of the window obstructed is given by the same 'W/D' column and angle of 31° in the last column on the right of the table as 1.7

Since point P is on the center line of the window the table provides the same values for the right side of the window.

Sky Component (SC) = 2.5 - 1.7 + 2.5 - 1.7 = 1.6%

DAYLIGHTING
Externally Reflected Component

ERC: The ERC is calculated as a Sky Component of greatly reduced luminance (about 20%).



For window on left side of P:

Obstruction angle = 17° and $\frac{W}{D} = \frac{10}{10} = 1.00$

From the B.R.S. table the equivalent SC is given as 0.47

Assuming a 20% equivalent sky luminance for the obstructing building the ERC for the left window becomes (0.47 x 0.2) 0.09.

Since point P is on the center line of the window the ERC for the right side of the window is also 0.09.

Externally Reflected Component (ERC) = 0.09 + 0.09 = 0.2%

DAYLIGHTING

Internally Reflected Component

IRC: The calculation of the IRC takes into account that the lower part of a building space normally has darker surface finishes than the upper part.

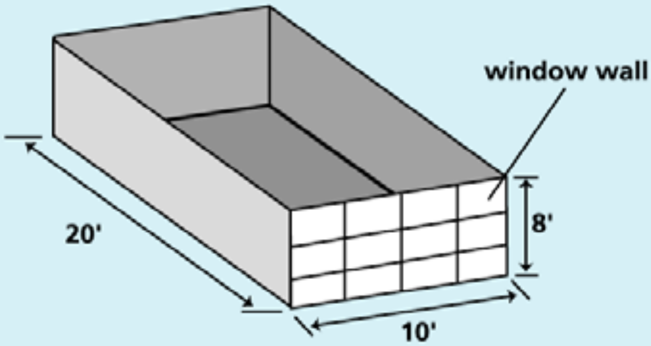
$$\text{IRC (average)} = \frac{0.85\,[\text{total window area}]}{\left[1 - [\text{average surface reflectance}]\right] \times [\text{total surface area}]} \times \left[C\,[\text{average reflectance below mid-height}] + 5\,[\text{average reflectance above mid-height}]\right] (\%)$$

$$\text{IRC (minimum)} = [\text{IRC (average)}] \times \left[[\text{average surface reflectance}] + 0.25\right] (\%)$$

Angle of external obstruction	0°	10°	20°	30°	40°	50°	60°	70°	80°
C value	39	35	31	25	20	14	10	7	5

DAYLIGHTING

IRC Example



Assume 10 FT by 20 FT by 8 FT (height) room with one complete window wall (10 FT by 8 FT (height)). Reflectance: 40% for walls; 80% for ceiling; 20% for floor; and, 10% for window glass.

total surface area $= \left[\begin{matrix}\text{(ceiling)}\\ 10 \times 20\end{matrix}\right] + \left[\begin{matrix}\text{(floor)}\\ 10 \times 20\end{matrix}\right] + \left[\begin{matrix}\text{(short walls)}\\ 2(10 \times 8)\end{matrix}\right] + \left[\begin{matrix}\text{(long walls)}\\ 2(20 \times 8)\end{matrix}\right] = 880\ \text{SF}$

total window area $= (10 \times 8) = 80\ \text{SF}$

average surface reflectance $= \dfrac{(200 \times 0.8) + (200 \times 0.2) + (400 \times 0.4) + (80 \times 0.1)}{880} = 0.42$

average reflectance below mid-height $= \dfrac{(200 \times 0.2) + (200 \times 0.4) + (40 \times 0.1)}{440} = 0.28$

average reflectance above mid-height $= \dfrac{(200 \times 0.8) + (200 \times 0.4) + (40 \times 0.1)}{440} = 0.55$

IRC (average) $= \dfrac{0.85 \times 80}{(1 - 0.42) \times 880} \times \left[(39 \times 0.28) + (5 \times 0.55)\right] = 1.8\%$

IRC (minimum) $= 1.8 \times (0.42 + 0.25) = 1.2\%$

DAYLIGHTING

Daylight Factor Adjustments

The calculated Daylight Factor must be adjusted for glazing, window frames and dirty windows. (The B.R.S. table takes into account the light transmission loss of normal window glass.)

Glass

Glass Type	Factor
Heat Absorbing glass	0.7
Glass blocks	0.9
Wired glass	0.9
Frosted glass`	0.8
Double glazed windows	0.8

Frame

Window Frame Material	Factor
Wood (openable windows)	0.65
Wood (fixed windows)	0.75
Steel window frames	0.85
Aluminum window frames	0.80

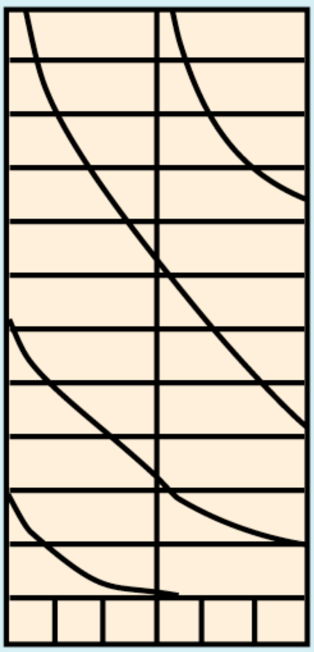
Dirt

Locality	Occupancy	Factor
Rural suburban	clean	0.9
	dirty	0.7
Urban residential	clean	0.8
	dirty	0.6
Industrial area	clean	0.7
	dirty	0.5

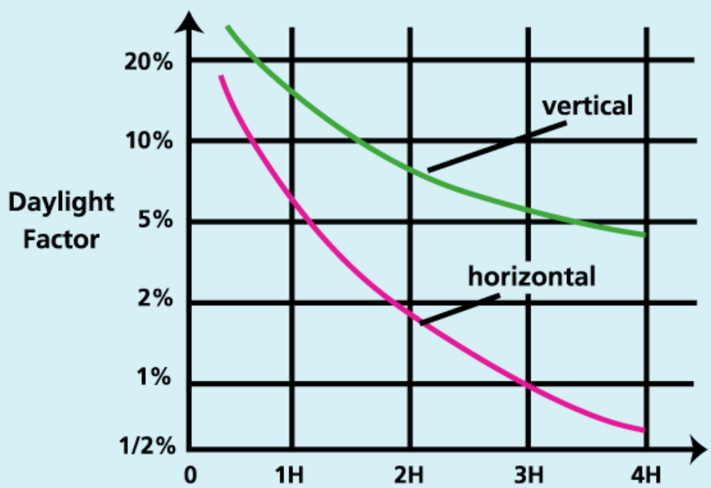
DAYLIGHTING

Daylight Distribution from Side Windows

Daylight penetration through side windows decreases disproportionally with increased distance from the window.



Illumination contours in multi-story building

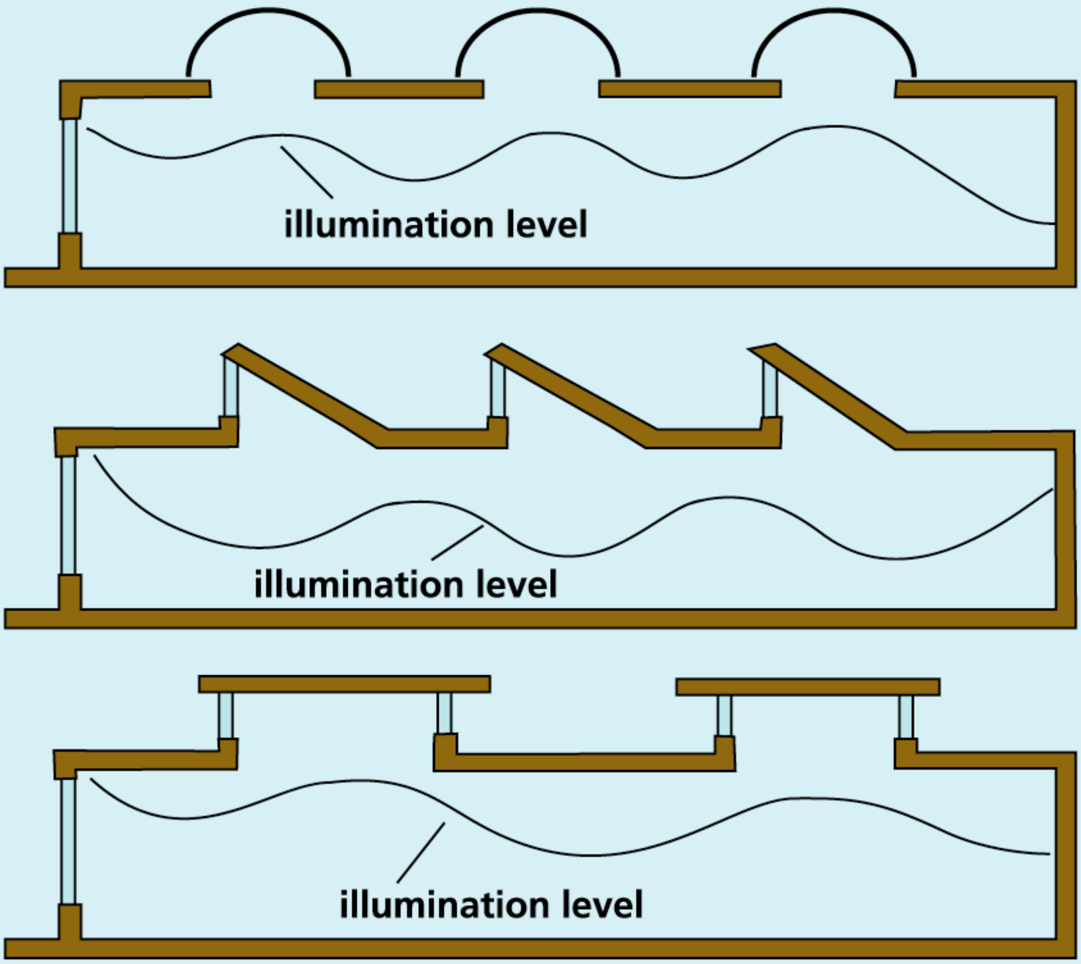


Distance from window in terms of window height (H)

DAYLIGHTING

Daylight Distribution from Roof Lights

While daylight penetration from side windows is normally inadequate in areas more than 15 FT from the window wall, roof openings can provide fairly uniform daylighting over unlimited areas.



DAYLIGHTING

Other Window Strategies