4.401/4.464 Environmental Technologies in Buildings

- Daylit area
- Partially-daylit area
- Non-daylit area
- Glazing
Lighting Module

- Light and Human Vision
- Daylighting Design Principles
- Daylight Simulations & Metrics
- Visual Comfort
- Electric Lighting
Weekly Reading And Tutorials

Chapter 2: Designing for Daylight
Chapter 5: Massing Studies
What is daylighting?
Daylighting is the act of lighting the interior and/or exterior of a building with natural daylight.
Brief History of Daylighting

- Default solution until the 1940s.

- 1\textsuperscript{st} renaissance during the 1970s primarily to save energy.

- 2\textsuperscript{nd} renaissance since 2000, light as element of more healthy and productive work spaces.

MIT Chapel by Eero Saarinen, 1955 (Photo courtesy of Freshwater2006 on Flickr. License: CC BY-NC)
# Five Daylighting Definitions

1. The interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment

2. The replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting

3. The use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting)

4. Dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape

5. The use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity
What do your peers think?

Survey of 177 design practitioners

## Five Daylighting Definitions

**Architectural definition:** The interplay of natural light and building form to provide a visually stimulating, healthful, and productive interior environment.

**Lighting Energy Savings definition:** The replacement of indoor electric illumination needs by daylight, resulting in reduced annual energy consumption for lighting.

**Building Energy Consumption definition:** The use of fenestration systems and responsive electric lighting controls to reduce overall building energy requirements (heating, cooling, lighting).

**Load Management definition:** Dynamic control of fenestration and lighting to manage and control building peak electric demand and load shape.

**Cost definition:** The use of daylighting strategies to minimize operating costs and maximize output, sales, or productivity.
How would you define a well daylit space?
Doe Library at UC Berkeley 1911, Architecture: Émile Bénard. Photo courtesy of Mark Pritchard on Flickr. License: CC BY-NC-SA.
Daylight from several orientations

Public domain photo by Abby Rowe, National Park Service, courtesy of Harry S. Truman Library.

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Contrast

Church of Light, 1989, architecture Tadao Ando. Photo courtesy of Naoya Fujii on Flickr. License: CC BY-NC.
Existential Quality

Drawing courtesy of Jeff Niemasz. Used by permission.
Passing of Time

- Lightshelf to reduce contrast at ground level
- White walls are a canvas for daylight

Museu d'Art Contemporani de Barcelona by Richard Meier. Photo © MACBA. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/.
Hidden Openings

Thermal Baths, Vals, Peter Zumthor.
(Photo courtesy of Marco Pozzo on Flickr. License: CC BY-NC-SA.)
Adding Color

- Indirect, reflected daylight, the back side of the illuminated wall is yellow
- Daylight = architectural concept
Light and Darkness

Treasury of Atreus in Mycenae, Greece, 1250 BC. (Photo courtesy of Richard on Flickr. License: CC BY-NC-SA)

https://www.amazon.com/Praise-Shadows-Junichiro-Tanizaki/dp/0918172020/ref=nosim/mitopencourse-20
Dramatic Proportions

- Redwood forest near Humboldt, California (Photo courtesy of Jeff Myers on Flickr. License: CC BY-NC.)
- Basilica di Sagrada Familia, Gaudi, 1882, Barcelona, Spain. (Photo courtesy of Melissa Delzio on Flickr. License: CC BY-NC.)
Framework for High-Performance Façade Analysis

Visual Comfort

Occupant Behavior Controls

Daylight Availability

Manual Control

Photo courtesy of Kristin Roach on Flickr. License: CC BY-NC-SA.
Automated Controls

Rolex Center, Lausanne, Switzerland, Architecture Sanaa
Architectural Control

New York Public Library, Architecture Carrère and Hastings
Adaptive Control

Rolex Center, Lausanne, Switzerland, Architecture Sanaa
Framework for High-Performance Façade Analysis

Visual Comfort

Occupant Behavior Controls

Daylight Availability

Energy

Metrics
Summer 2007 - Daylighting Metrics Study: “The degree of agreement between the experts was surprising given that the same individuals tend to frequently disagree when it comes to the development of quantitative performance metrics of imaginary daylit spaces.” In contrast, daylight factor predictions are much more divergent.
The reference office represents a south-facing sidelit office located in Boston. The office is not obstructed by neighboring buildings.

The large room depth of 8.2 m, which corresponds to nearly 3.5 times the floor to ceiling height, was consciously chosen to be rather large so that the effect of different daylighting strategies remains visible for all variants.
You may think of the reference office as one of several identical spaces in a building.
Dashboard
Reference Office

Located in Boston

Daylight availability
45% of the space is daylit

Spatial daylight autonomy

- sDA\text{\textsubscript{total}}[50%]

Visual comfort
View outside: 66% of the time
Glare: 9% of occupied hours

Daylight glare probability

- Intolerable
- Perceptible
- Disturbing
- Imperceptible

Blinds status (view)

- Blinds closed
- Blinds open

Energy
Energy Use Intensity = 81 kWh/m²
Renewable energy = n.a.
Carbon emissions = 31 kg CO₂e/m²

Monthly EUI [kWh/m²]

- Lighting 6.0 kWh/m²
- Equipment 14.6 kWh/m²
- Heating 57.6 kWh/m²
- Cooling 3.1 kWh/m²
Design Tools
Daylighting Design Tools

What kind of daylight prediction tools do you use to estimate or calculate daylighting during (a) schematic design and (b) design development?

- Experience
- Computer Simulation
- Rules of Thumb
- Design Guidelines
- Manufacturer Information
- Scale Model Measurements

Proportion of participants that use the tool [%]
Toward a Fruitful Relationship between Simulations, Rules of Thumb, and Physical Model Testing
Daylight Availability Studies
Framework for High-Performance Buildings

Visual Comfort

Occupant Behavior Controls

Daylight Availability

Energy
What is the relationship between daylight availability and building massing, i.e. how much of a building can be daylit depending on its overall shape and surrounding context?
What is the Daylit Area?

- How can we determine the daylit area in a space?
- We will be looking at three related approaches.

- Daylit area
- Non-daylit area
- Glazing
(1) Based on Daylight Autonomy

300 lux Isocontours on a Clear Summer Day

noon
9 AM
3 PM
6 AM
6 PM

300 lux Isocontours at Noon

clear sky in winter

clear sky in summer
overcast sky in summer

overcast sky in winter
Daylight autonomy (DA) is a daylight availability metric that corresponds to the percentage of the occupied time when the target illuminance at a point in a space is met by daylight.
(1) Based on Daylight Autonomy

Daylight Autonomy Contours in Boston

50% = DA_{300lux}[50%]
Daylight autonomy is climate-dependent but not too much. It has been adopted by the IESNA LM-83 which now in turn is being used by LEED v3.0.
Varying Daylight Autonomy Distributions across 186 sites in North America

186 sites representing 74% of the US and 63% of the Canadian population.
Varying Daylight Autonomy Distributions across the 186 Sites for a South-facing Office

Daylight autonomy 450lux [%]

Distance to façade in multiples of window head height
Varying Daylight Autonomy Distributions across the 186 Sites for a South-Facing Office
DA300lux[50] for varying façade orientations
Significance of Internal Partitions

Distance to façade in multiples of window head height

When you are close to a window, what are the most important surface properties that determine the daylight near you?
Sensor “sees” a lot of sky

- Visual light transmittance of the window
**Visual Transmittance** $(\tau)$: Fraction of incident visible radiation that reaches the interior.
How would you measure this?
Measuring direct normal visual transmittance

Interior, $E_{in} = 6,940$ lux

Exterior, $E_{ex} = 10,740$ lux

$\tau_{vis} = \frac{E_{in}}{E_{ex}} = 0.65$
<table>
<thead>
<tr>
<th>Glazing unit</th>
<th>Visual light transmittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single pane</td>
<td>0.881</td>
</tr>
<tr>
<td>Double pane</td>
<td>0.811</td>
</tr>
<tr>
<td>Double pane with argon filling</td>
<td>0.811</td>
</tr>
<tr>
<td>Double pane with argon filling and low-e coating on surface 3</td>
<td>0.749</td>
</tr>
<tr>
<td>Double pane with argon filling and low-e coating on surface 2</td>
<td>0.749</td>
</tr>
<tr>
<td>Double pane with argon filling and low-e coating on surface 2 and 3</td>
<td>0.629</td>
</tr>
</tbody>
</table>
When you are deeper in a sidelit space, what are the three most important surfaces that determine how deep daylight enters a building?
Sensor mainly "sees" ground-reflected daylight

- Outside ground reflectance
- Visual light transmittance of the window
- Ceiling reflectance
DA300lux[50%] isocontours

Ground reflectance
\[ I = \begin{cases} P_{\text{incident}} x P_{\text{specular}} & \text{if } \theta = \theta' \\ 0 & \text{otherwise} \end{cases} \]

\[ I = P x P_{\text{diffuse}} x \cos(\theta) \]
How would you measure this?
Illuminance, $E = 1120$lux

Luminance, $L = 158.4$cd/m$^2$

$\rho = \frac{L \times \pi}{E} = 44\%$
Surface reflectance value:
H Yellow, Row 2, Daylight D65
45
\( \rho = 45\% \)
<table>
<thead>
<tr>
<th>Surface Description</th>
<th>Diffuse Reflectance [%]</th>
<th>Specular Reflectance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generic interior floor</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Generic interior wall</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Generic ceiling</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>High reflectance ceiling</td>
<td>90</td>
<td>-</td>
</tr>
<tr>
<td>Generic façade finish</td>
<td>44</td>
<td>-</td>
</tr>
<tr>
<td>Generic exterior ground</td>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>Aluminum, brushed</td>
<td>40</td>
<td>17</td>
</tr>
<tr>
<td>Brick</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>White board</td>
<td>0.69</td>
<td>9</td>
</tr>
</tbody>
</table>
OK, that’s what the computer tells us. How well do daylight autonomy (and other daylight availability metrics) relate to occupant assessments of spaces?
“A key architectural concept is to divide the floor plan of a building or space into a ‘daylit’ and a ‘non-daylit’ area. Within the daylit area indoor illuminance levels due to natural light should be adequate, useful and balanced for most of the year. In this exercise you are asked to follow your own intuition and divide [name of study space] into a daylit and a non daylit area. Please visit the [name of study space or spaces on date and time range] and individually conduct your assessment without consulting with the other students.”

Fig 5.10 Carpenter Center, Cambridge, Massachusetts, by Le Corbusier, 1962

Photos courtesy of Dan Weissman. Used with permission.
Carpenter Center Study

Tasks:
1. Draw line of daylit areas. Note: tables may be present. Estimate around them.
2. Measure illuminance at each X @ 30° (table height)
Carpenter Center Study

PARTITION WALL

64.3FT [19.6M]

76.5FT [23.3M]

Tasks:
1. Draw line of daylit area. Note: tables may be present. Estimate around them.
2. Measure illuminance at each X @ 30" (table height)
**Partially Daylit Area**

Instead of a hard line between daylit and non-daylit we are looking for a transition, partially daylit area.

<table>
<thead>
<tr>
<th>Partially Daylit Area</th>
<th>Fully Daylit Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between 25% and 75% of students voted that the area is ‘daylit’.</td>
<td>Over 75% of students voted that the area is ‘daylit’.</td>
</tr>
<tr>
<td>Spatial Daylight Autonomy $DA_{150\text{lux}} &gt;50%$</td>
<td>Spatial Daylight Autonomy $DA_{300\text{lux}} &gt;50%$</td>
</tr>
</tbody>
</table>

*How well does this work?*
What is the Daylit Area?

- Daylit area
- Partially-daylit area
- Non-daylit area
- Glazing
Carpenter Center Study

Student assessments

sDA 300 lux simulations
Lorax Project
Daylight Area Study II

- Supported by MIT HASS
- Collaboration with Tarek Rakha and Dan Weissman
Lorax Project Participants

- University of Idaho
- USC
- Miami University
- Iowa State
- MIT
- Harvard
- Parsons
- Concordia University
- Ain Shams University
- Federal University of Paraiba
- Santa Catarina

Base layer of map © Google. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/.
MIT - I

- Christoph Reinhart, Spring 2012
- 18 Participants – Clear
Note that student responses correlated with architectural features such as walls and corners.
18 Participants – Clear
Simulation

Student Responses

DA_150 lux

DA_300 lux
Miami University
Miami University

- Mary Ben Bonham, Spring 2012
- 35 Participants – Overcast
Miami University

Simulation

Student Responses

DA_300 lux

DA_150 lux

Only toplit space.

https://dspace.mit.edu/handle/1721.1/106323.
Study Conclusions

- Encouragingly good agreement with new IESNA Spatial Daylight Autonomy predictions.

- Support the use of Spatial Daylight Autonomy as proposed by LEEDv3.

- Surprising since people cannot see illuminances and it is unlikely that they can predict how a space will look during different times of the year.
Rules of Thumb
Mantra in sustainable design
Sole quantitative justification for room proportions/façade design
An empirical rule
## Parameter Study

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>Range</th>
<th>Range</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>climates centers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daytona Beach, FL</td>
<td>L.A., CA</td>
<td>New York, NY</td>
<td>Vancouver, BC</td>
<td>Winnipeg, MB</td>
</tr>
<tr>
<td>facade orientation</td>
<td>North</td>
<td>South</td>
<td>West</td>
<td>East</td>
</tr>
<tr>
<td>window [%]</td>
<td>35</td>
<td></td>
<td></td>
<td>75</td>
</tr>
<tr>
<td>balustrade</td>
<td>yes</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>sill</td>
<td>yes</td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>occupancy</td>
<td>office</td>
<td></td>
<td></td>
<td>classroom</td>
</tr>
<tr>
<td>min ill. [lux]</td>
<td>300</td>
<td></td>
<td></td>
<td>500</td>
</tr>
</tbody>
</table>

Window head height identical in all 640 cases
Window-Head-Height Rule of Thumb

Frequency distribution of daylight penetration depths.
Window-Head-Height Rule of Thumb


**Diagram:**

In a sidelit space with a standard window and venetian blinds, the depth of the daylit area usually lies between 1.5 and 2 times the window-head-height.

If a space does not require the use of a shading device the ratio range can increase up to 2.5.
Daylit Area (for Massing Studies)

Daylit Area (2 times the window head height)
Non-Daylit Area
Case Study: Daylight Availability Study
Puerto Rico

SAN JUAN, PUERTO RICO  SCHEMATIC DESIGN: SECTION

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Neighboring Obstructions
Parametric Study

- Parametric study to evaluate the effect of neighboring building on interior daylit availability. A total of 2304 spaces.

External Obstruction

The effect of neighboring building on a sidelit space in a one- or two-story building is low (and can even be positive for north facing facades) for obstruction angles smaller than $30^\circ$. 

$\alpha = \text{obstruction angle}$

$q = \text{sky angle}$
Daylight Feasibility Test

The minimum sky angle, $\theta$, (in degrees) for an a standard sidelit space with a window to wall ratio, WWR, (in percent) is:

$$\theta > \frac{2000}{WWR}$$
Design Sequence for Diffuse Daylighting

(1) Urban Project
(2) Come up with an initial Design Variant
(3) Divide Building into Zones
Definition of Sky Angle

The reference point on the façade is the **glazing center**.

\[ \theta = 60^\circ \]

\[ \theta = 25^\circ \]
Daylight Feasibility Test

Carry out a daylight feasibility test for each zone. Cutoff level for the WWR is about 80% (fully glazed façade). Continue analysis for zones that pass the daylight feasibility test and revise your design/expectations accordingly.

Note: At this point you should start to adapt your design.
Atrium Rule of Thumb

In order to daylight all spaces bordering an interior atrium with diffuse daylight, the maximum atrium height is about 2.5 times its width.
Daylight and Building Massing: Rules of Thumb

Window-Head-Height Rule: In a standard, office-type sidelit space equipped with venetian blinds, the depth of the daylit area usually lies between 1 and 2 times of the window head height. For spaces that are not equipped with a dynamic shading system, the ratio range increases to 2.5.

Daylight Feasibility Test: The product of the sky angle $\theta$ (in degrees) and the window to wall ratio, WWR, (in percent) of a standard sidelit space should be larger than 2000.

Atrium Rule of Thumb: The maximum height for an atrium bordered by daylit spaces is 2.5 times its width.
Massing Study

Potential Daylit Area: 76%

Potential Daylit Area: 71%

Potential Daylit Area: 68%

Potential Daylit Area: 100%

Potential Daylit Area: 100%

Potential Daylit Area: 100%

Potential Daylit Area: 100%

Potential Daylit Area: 100%
Considering Urban Context

Placed in Center

Offset From Street

Raised Overhang

- WWR > 40%
- WWR > 90% (Cannot Be Daylit)
Is it really that easy?

- Rules of thumb indicate the **daylight potential** of a massing. Things can still go wrong, but if the rules suggest limited potential, the likelihood is high that any daylighting strategies applied later in the design process will have limited effect.

- Rules of thumb can be used as formgivers. Then simulations can be used to refine design concepts. Rules may also be used for quality control.
Rules of Thumb as Formgivers

Image courtesy of Jeff Niemasz. Used by permission.
Paper: T Dogan and C F Reinhart, “Urban daylight simulation: Calculating the daylit area of urban designs,” Proceedings of SimBuild 2012, Madison, Wisconsin, USA
New York Zoning Revisited

This image is from M Saratsis, T Dogan and C F Reinhart, “Simulation-based daylighting analysis procedure for the development of urban zoning rules,” *Building Research and Information*, 45:5, pp. 478-491, 2017. This journal is available online at https://www.tandfonline.com/doi/full/10.1080/09613218.2016.1159850
LM83/LEED vs zoning regulations

Conclusions

- We discussed three complementary approaches to predict the daylight availability in buildings:
  1. Daylight Autonomy Simulation-Based
  2. Based on Occupant Assessments
  3. Based on Rules of Thumb

- Occupant assessments largely support simulation results.

- Derived rules of thumb set can be used for massing studies.
Design Guidelines
Architectural Considerations

- Introduce setbacks on higher floors to increase the sky access for lower levels.
- If possible, reduce floor plan depth to less than 5-7 times the floor to ceiling height to maximize the daylit area.
- Open up the building through atria, windows, skylights, and clerestories.
- Place window as high as possible near the ceiling.
- Create a view to/from the outside.
- Use the daily and seasonal variations of daylight to enhance visual interest.
- High surface reflectances make rooms appear larger; a vertical/horizontal window near a bright wall/ceiling makes a room appear wider/higher.
Occupant Comfort and Well-Being

- Use daylight for full spectrum color rendering.
- Balance a view to the outside with occupants’ privacy (perforated shades).
- Avoid low solar angles onto facades.
- Maintain daylighting levels within acceptable limits.
- Develop a suitable shading device strategy (shading from neighboring buildings, venetian blinds, light shelves).
- Avoid work places too close to exterior glazings.
Questions?