ATLA®

ALL THINGS LIGHTING® ASSOCIATION

Lighting and Acoustics Know Your Tools

Ian Ashdown, P. Eng. (Ret.), FIES Senior Scientist
SunTracker Technologies Ltd.

Concordia University
April 2022

Image by GarryKillian on Freepik

Lighting and Acoustics
Know Your Tools

Ian Ashdown, P. Eng. (Ret.), FIES
Senior Scientist
SunTracker Technologies Ltd.

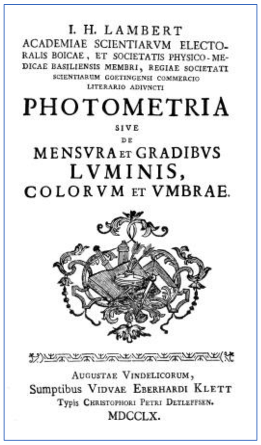
Whether it is in lighting or acoustics, engineering design and analysis invariably involves commercial software design tools. It can be challenging to master the intricacies of these programs, particularly when they offer idiosyncratic user interfaces … but it can be done.

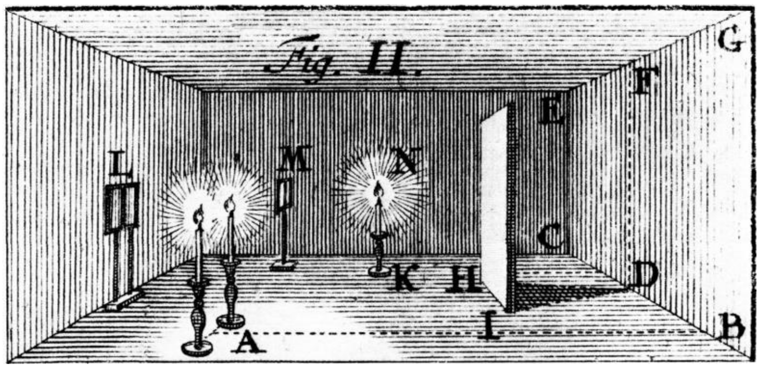
The far greater challenge, however, is to understand these tools. What calculations are they performing, and worse, what assumptions are they making? Worst of all, what are their limitations?

These are not questions that are easily answered by reading the software manuals. However, if you understand the basic engineering principles of a problem, you can often reason what the programs are doing on your behalf.

Lighting History

- Johann Heinrich Lambert (1728 – 1777)



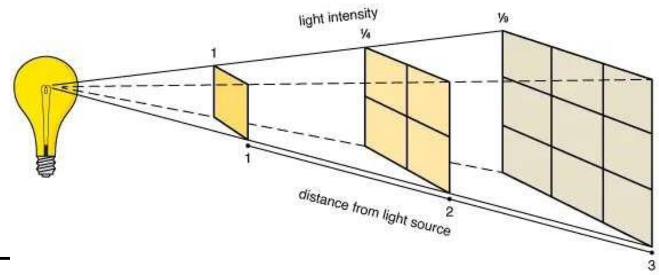


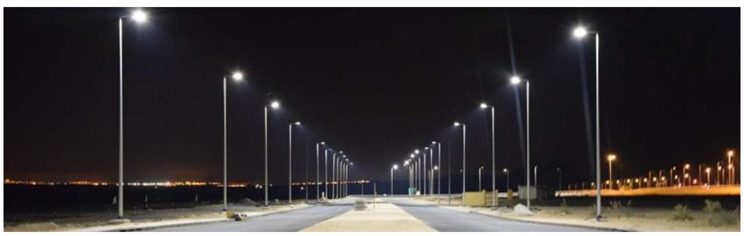
To understand the engineering calculations, it helps to have some knowledge of their history. In the case of lighting, it began with Johann Lambert, a Swiss-French polymath who single-handedly created the science of radiometry and photometry. It would be nearly 250 years before his masterpiece *Photometria* was translated from Latin into English, but one thing was clear: all of the engineering principles I will be discussing in this presentation began with his research.

Tools - Inverse Square Law

$E = I/d^2$

E – illuminance (lux)
I – intensity (candela)
d – distance (meters)



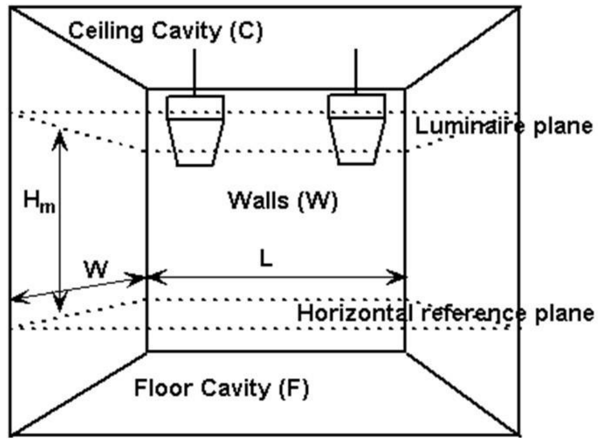


First, the rather mundane *inverse square law* of lighting. This law was actually discovered and experimentally demonstrated by a Chinese philosopher some three thousand years ago, but it was Lambert who formalized the equation in his book. Even today, it is basically all you need for roadway and outdoor lighting design.

Tools - Lumen Method

$$N = \frac{E \times A}{\emptyset \times CU \times MF}$$

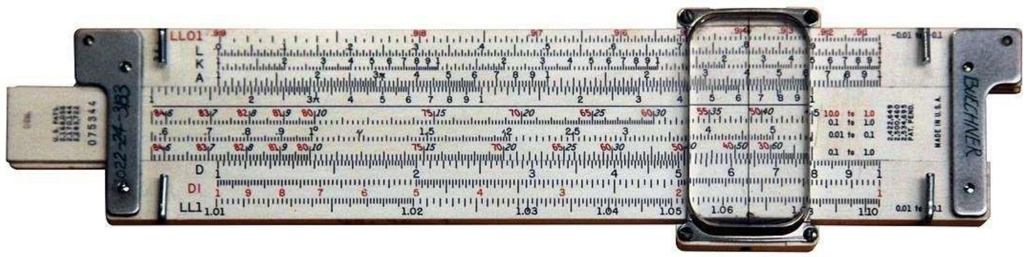
N – number of luminaires
E – maintained illuminance (lux)
A – area (square meters)
⍰–luminaire flux (lumens) CU
– coefficient of utilization
MF – maintenance factor



Architectural lighting in enclosed spaces is more challenging because you have to consider not only direct illumination from the luminaires, but also indirect illumination due to interreflections from the room surfaces. In a typical empty rectangular room like this, for example, the illumination of a workplane (such as a desktop) is roughly twice as much as the direct illumination received from the luminaires.

The *lumen method* was used from the 1960s onwards after luminaire manufacturers published Coefficient of Utilization (CU) tables for their products. These tables were produced from luminous intensity distribution measurements ("photometric data") of their luminaires, leaving lighting designers with an equation that could be solved with pencil and paper …

Lighting Calculations (1970s)*



*Batteries sold separately

… or a slide rule, the go-to calculation tool of almost every lighting designer engineer prior to the introduction of the personal computer in the 1980s.

Architects …

- “Forget the numbers! What will my design look like?”
- Charcoal sketches …

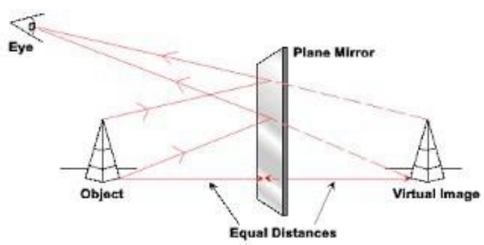
Most architectural lighting designers and electrical engineers, however, worked as consultants for architectural firms. Then as today, architects had little to no interest in lighting design calculations – they were only numbers. What they wanted to know was, what would the completed lighting design look like?

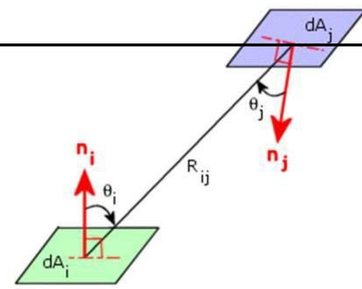
Unfortunately the only answers for thirty-odd years was either, “Trust me, it’ll look wonderful” … or charcoal sketches. What the lighting designers could never admit was that apart from empty rectangular rooms without windows, lighting design was equal parts artistry and hard-won experience.

This situation changed slowly but dramatically with the introduction of personal computer with full-color displays and increasingly sophisticated lighting design programs over the 1990s. In addition to programs like Lighting Analysts’ *AGi32*, Lighting Technologies’ now-defunct *Lumen Micro*, and the short-lived *Lightscape*, there were over 200 lighting design programs available from over 50 manufacturers in 1995. (Today, there are eight software manufacturers worldwide.)

Understanding Light

- Understanding light is key to understanding lighting design programs
- Two conceptual models
  - Geometric light rays that travel in straight lines (ray tracing)
  - Flow of light between surfaces (radiosity)



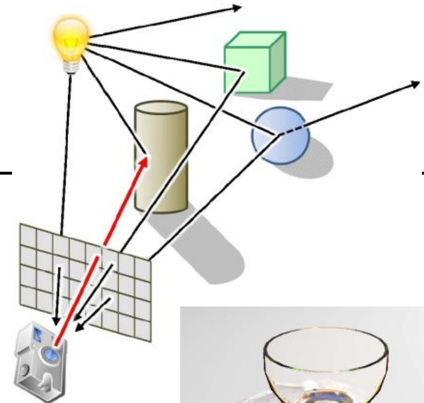


How lighting design programs work depends on how they model light. There are a number of textbooks and innumerable academic papers on the specific algorithms they may use, but it really comes down to two conceptual models; 1) ray tracing, which models geometric light rays; and 2) radiosity (better known as “radiative transfer” to thermal engineers), which models the flow of light between finite-area surfaces.

Somewhat surprisingly, both methods were introduced and discussed in depth by Johann Lambert in his 1760 book, *Photometria*.

Tools - Ray Tracing

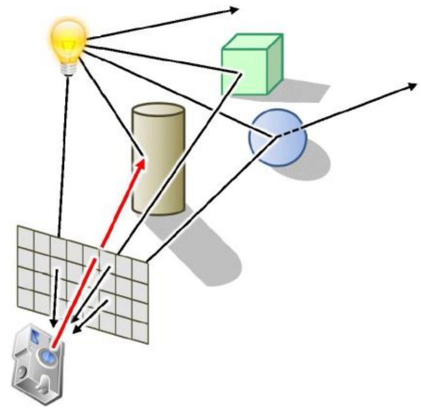
- Trace individual rays through scene
  - Photon mapping / backward ray tracing
  - Models all possible optical effects
  - View-dependent



Most lighting design programs today model light using various ray tracing methods, with photon mapping and backward ray tracing being the most popular. I will not go into the details – that is left as an exercise for the student – but a key advantage of ray tracing methods is that they are capable of modeling all possible optical effects, including diffuse, specular and glossy reflections, transmission, refraction, caustics, and even diffraction.

One particular disadvantage of ray tracing however is that it is view-dependent. In order to generate an rendering, you first have to specify a camera position and orientation.

Tools - Ray Tracing



• Beautiful images, but …

Regardless, ray tracing is a wonderful tool for architectural visualization. If you use measured photometric data from the luminaire manufacturer, specify appropriate properties for the surface materials, and choose realistic texture maps for things like paintings and wood floors, you can answer the architect's question, "What will the lighting look like?" with photorealistic renderings.

There is a danger here, however. It is possible to create beautiful images that still fail to capture what the design will look like in real life …

Tools - Ray Tracing

- … this is what you are really looking at.

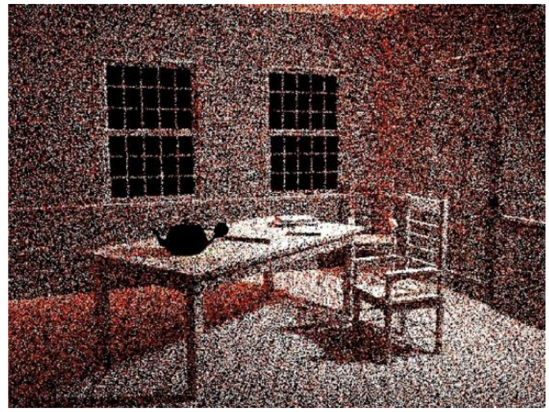
The image on the right shows the end result of the photon mapping method. Geometric rays are sent from the luminaires (or in this case probably diffuse daylight from a window) in random directions into the environment, where they will intersect visible surfaces. Each ray is then reflected from the surface to intersect another surface – this is the “first bounce” of light.

The photometric accuracy of the rendering – which is what is most important from an engineering perspective – depends on the number of rays that are traced and how many times they are bounced from surface to surface.

Looking at this particular image, you can see the reddish shadow underneath the table, which is due to direct light being reflected from the wall. However, the shadows in the corner near the ceiling are too bright, indicating that only one or possibly two bounces were specified. The image looks great, but the illuminance distribution on the floor may not be accurate.

Tools - Ray Tracing

- Hundreds of millions of rays still result in inherently noisy images
- Interpolated colors between points on each surface
- Billions of rays required for photometric calculations
- Architectural visualizations are less demanding

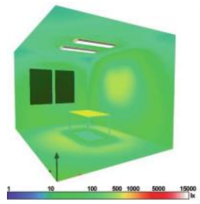


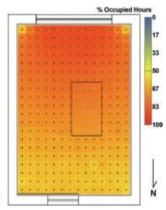
Ray tracing typically requires hundreds of millions of rays , which still result in inherently noisy images. The strength of the photon mapping method is that it interpolates the distribution of illuminance between the ray-surface intersection to produce beautiful images. It is all too easy, however, to choose program settings that result in pleasing images that may not be photometrically accurate.

Know your tools and their limitations!

Lighting Design Programs – Ray Tracing

- Relux
- DIALux
- Litestar 4D
- LightStanza
- LBNL Radiance

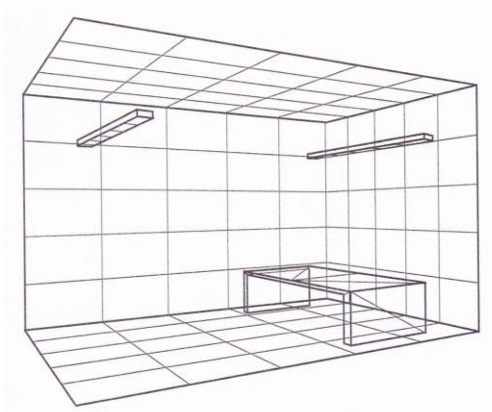


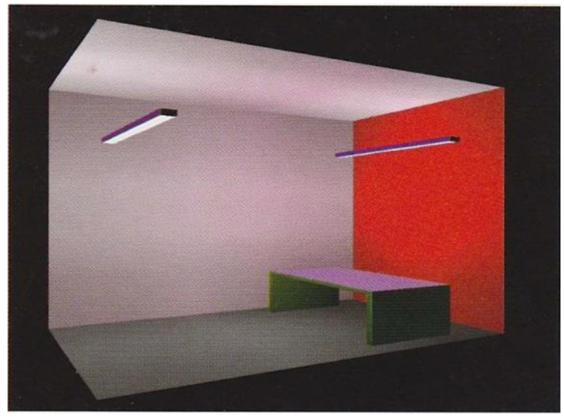


There are a reasonable number of commercial lighting design programs to choose from, each with the strengths and weaknesses for particular applications, and with different costs. *Relux* and *DIALux*, for example, are supported financially by mostly European lighting manufacturers, and are freely available for anyone to use. *LightStanza* is a suite of cloud-based Software-as-a-Service (SaaS) products, while Lawrence Berkeley National Laboratories' *Radiance* is open-source Linux software for those comfortable with stringing together some of more than one hundred Unix utility programs with perhaps one thousand options on the command line to generate an image.

Tools - Radiosity

- Follow the bouncing … light

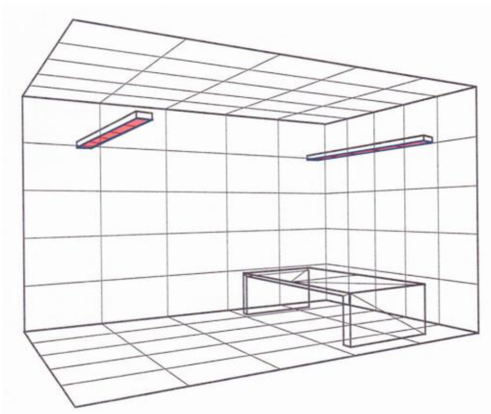


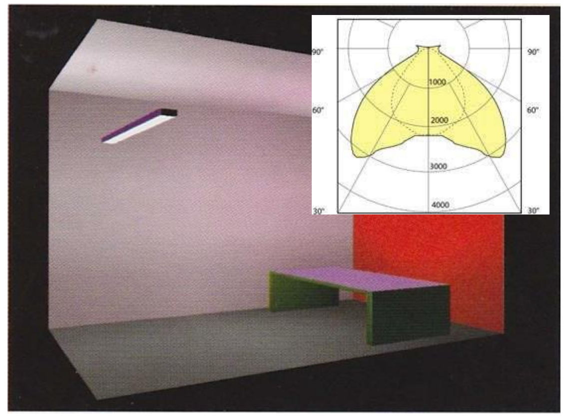


The alternative to ray tracing is the radiosity method. It begins by discretizing surfaces into arrays of patches. Commercial lighting design programs perform this meshing automatically for complex environments, but this simple model demonstrates the underlying principles.

Tools - Radiosity

- Determine luminous intensity distribution

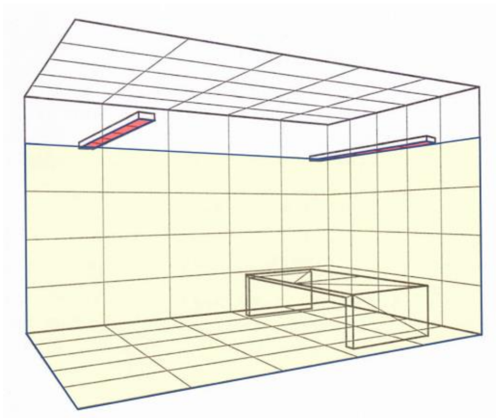


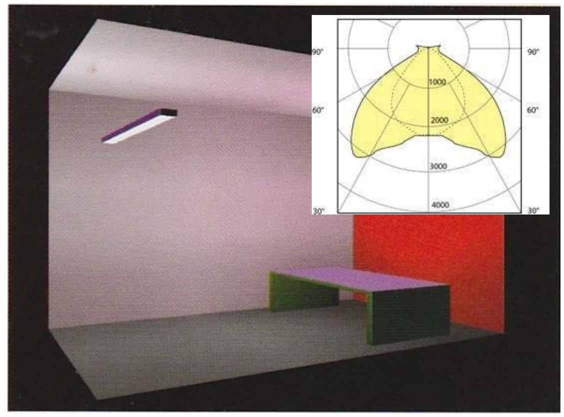


We begin with the luminaires, for which we have the manufacturer's luminous intensity distribution, often referred to simply as "photometric data." This data is the measured luminous intensity of the luminaire expressed in polar coordinates.

Tools - Radiosity

- Step 1 – directly illuminated patches

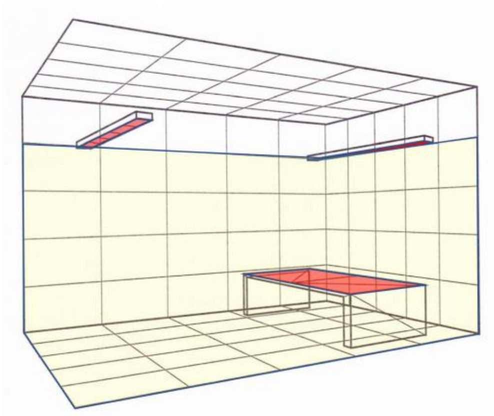


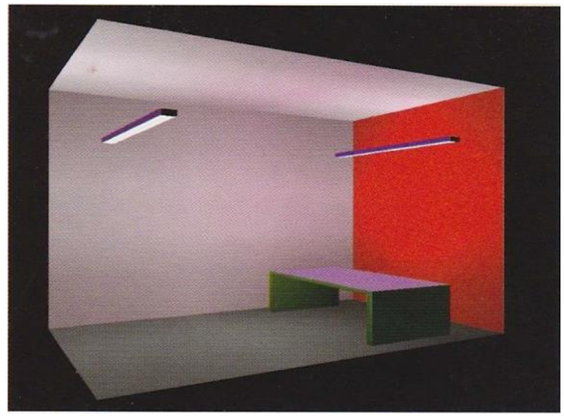


The first step is to calculate the direct illumination of patches due to light emitted by the luminaires. Note that the ceiling and upper wall patches receive no light.

Tools - Radiosity

- Indirect illumination

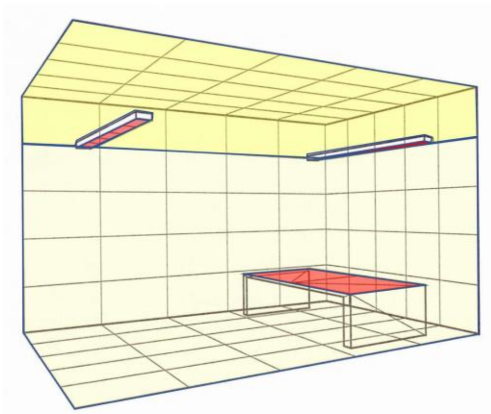


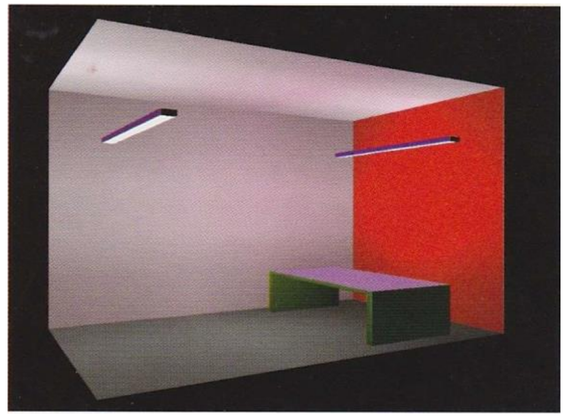


We now determine which patch has the most amount of light to reflect back into the environment …

Tools - Radiosity

- Indirect illumination





… and calculate the indirect illumination of patches due to light diffusely light reflected from the selected patch.

This process is iterated until most of the light has been absorbed by the environment patches typically 95 to 99 percent …

Tools - Radiosity

- Step 10,000 … convergence

… and after perhaps ten thousand such steps, we have a photometrically accurate rendering that can be used for photometric analysis.

Radiosity Equation

- Beguilingly simple problem:

$$\begin{bmatrix} M_{o1} \\ \vdots \\ M_{on} \end{bmatrix} = \begin{bmatrix} 1 - \rho_1 F_{11} & \cdots & -\rho_1 F_{1n} \\ \vdots & \ddots & \vdots \\ -\rho_n F_{n1} & \cdots & 1 - \rho_n F_{nn} \end{bmatrix} \begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix} \quad \text{or } \mathbf{M}_o = (\mathbf{I} - \mathbf{RF})\mathbf{M}$$

- Fredholm integral of second kind requires iterative solution:

$$\mathbf{M} = \mathbf{M}_o + \mathbf{RFM}_o + (\mathbf{RF})^2\mathbf{M}_o + (\mathbf{RF})^3\mathbf{M}_o + (\mathbf{RF})^4\mathbf{M}_o + \cdots$$

- In physical terms, follow the bouncing light!

The mathematics behind radiosity theory is considerably more complicated than ray tracing, but it is physically more intuitive.

Radiosity Equation

- Beguilingly simple problem:

$$\begin{bmatrix} M_{o1} \\ \vdots \\ M_{on} \end{bmatrix} = \begin{bmatrix} 1 - \rho_1 F_{11} & \dots & -\rho_1 F_{1n} \\ \vdots & \ddots & \vdots \\ -\rho_n F_{n1} & \dots & 1 - \rho_n F_{nn} \end{bmatrix} \begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix} \quad \text{or } \mathbf{M}_o = (\mathbf{I} - \mathbf{RF})\mathbf{M}$$

- Fredholm integral of second kind requires iterative solution:

$$\mathbf{M} = \mathbf{M}_o + \mathbf{RFM}_o + (\mathbf{RF})^2\mathbf{M}_o + (\mathbf{RF})^3\mathbf{M}_o + (\mathbf{RF})^4\mathbf{M}_o + \cdots$$

- In physical terms, follow the bouncing light!

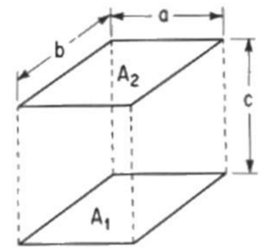
The vector **M** represents the amount of light diffusely reflected from each surface patch, whereas the M_0 represents the initial amount of direct illumination reflected form the patches. With each iteration, we add the amount of light received from the other patches. In other words, each subsequent term represents another bounce of light.

Such conceptualizations are important. If you do not understand the physical meaning of the equations your software is (presumably) solving, it is much more difficult to understand what the program is actually doing.

Tools - Radiosity

"Although this task appears very simple, its solution is considerably more knotted than one would expect … the highly laborious computation would fill even the most patient with disgust and drive them away."

Johanne Lambert, 1760

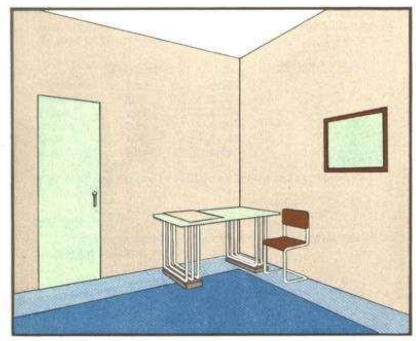


$$F_{1-2} = \frac{2}{\pi XY}\left\{ \ln\left[\frac{\left(1+X^2\right)\left(1+Y^2\right)}{1+X^2+Y^2}\right]^{1/2} + X\sqrt{1+Y^2}\tan^{-1}\frac{X}{\sqrt{1+Y^2}} + Y\sqrt{1+X^2}\tan^{-1}\frac{Y}{\sqrt{1+X^2}} - X\tan^{-1}X - Y\tan^{-1}Y \right\}$$

There is also a point however where physical interpretation and intuition fails, or at least stumbles. Saying "calculate the indirect illumination" of a patch does not of course say *how* this calculation is done. Johanne Lambert had this to say about calculating the amount of light reflected from one patch that is received by another parallel patch of the same size.

Radiosity History

- Illumination Engineering
  - Yamauti (1926)
  - Buckley (1927)
  - Higbie (1934)
- Thermal Engineering
  - Hottel(1954)
  - Eckbert & Drake (1959)
- Computer Graphics
  - Goral (1985)
  - Nishita & Nakamae (1985)



Moon & Spencer (1948) – First Radiosity Image

Lambert’s work was mostly forgotten, helped no doubt by *Photometria* being available only in Latin and written in a High German dialect. Today, there only about a dozen known copies of the original printing. However, the history of radiosity is once again … excuse the pun … illuminating.

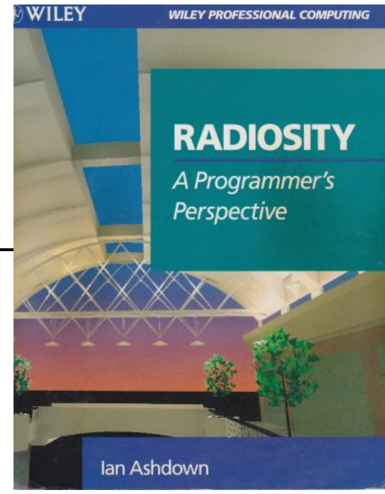
The radiosity method was rediscovered by illumination researchers in the 1920s and ‘30s, who were primarily interested in the theoretical aspects. It was used for a 1948 book on lighting design to create the world’s first radiosity image, calculated by a group of graduate students with hand-cranked calculators and produced with hand-cut card stock.

The radiosity method was rediscovered once again by thermal engineering researchers, who went onto develop large catalogs of equation for different patch-to-patch configurations, along with geometric form factor algebra. None of this, however, was useful as a practical method for complex architectural environments.

A practical method called “progressive radiosity” was finally developed by computer graphics researchers in the 1980s.

Radiosity: A Programmer's Perspective

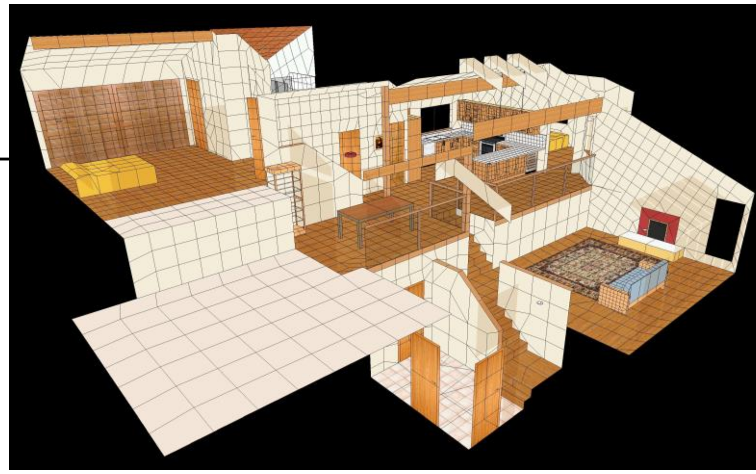
- Published October 1994
- 500 pages
- Complete introduction to computer graphics
- Includes full C++ source code for Windows
- Freely available on www.researchgate.net



There is no time to explain the details here, but it is fully documented in this book. Three decades later, the source code presented in the book still powers three commercial lighting design programs.

Tools - Radiosity

- CAD model import
- Automatic meshing
- Physical light sources



To briefly demonstrate the capabilities of the radiosity method, here is an example where a residence has been imported from a CAD program and then automatically meshed with physical light source data added …

Tools - Radiosity

- Physically-based lighting calculations
- Photorealistic images
- 25,000 polygons
- 10,000 bounces in 6 seconds
- Equivalent to 100 million rays / second
- Interactive 3D views

…and here it is six seconds later, ready for photometric analysis using virtual photometer and visual glare meters.

An advantage of the radiosity method – which may or may not be important, depending on the application – is that the rendering is view-independent. What this means is that the user can interactively tour the 3D environment in real time.

Tools - Radiosity

- Post-process ray tracing
  - Glossy surfaces
  - Specular reflections
- 40+ billion rays

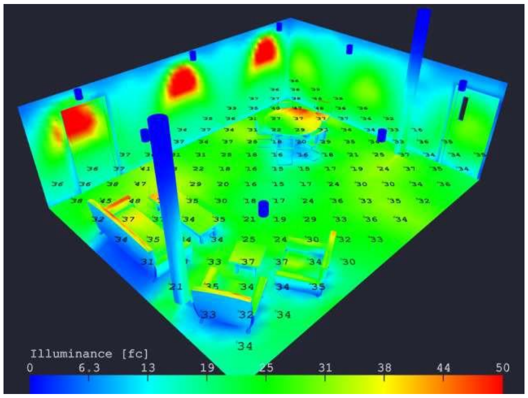
It is also possible to select a given view of the environment and apply post-process ray tracing for architectural visualization, but this is rarely needed for lighting design and analysis.

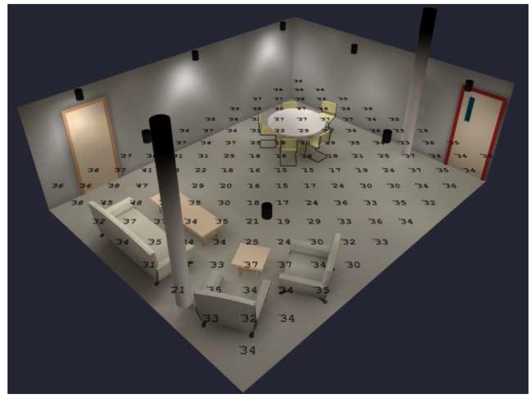
Lighting Design Programs - Radiosity

- AGi32
- Acuity Visual
- OptiWin 3D Pro
- ElumTools (Revit)

This is a listing of commercially-available lighting design programs that rely on the radiosity method. Again, however, choosing a particular program is entirely dependent on the needs of the application.

Lighting Design Programs - Applications

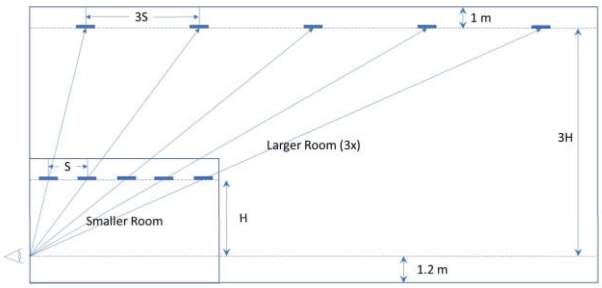


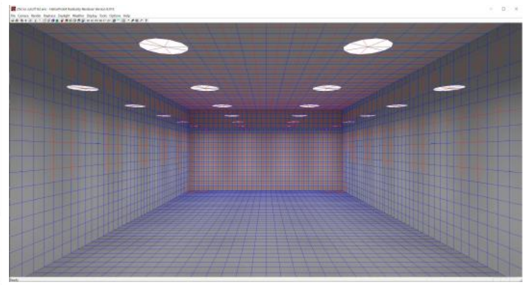


- Illuminance / luminance distribution

Speaking of applications, the most obvious is the calculation of the illuminance distribution on a workplane or the luminance distribution on a wall.

Lighting Design – Applications





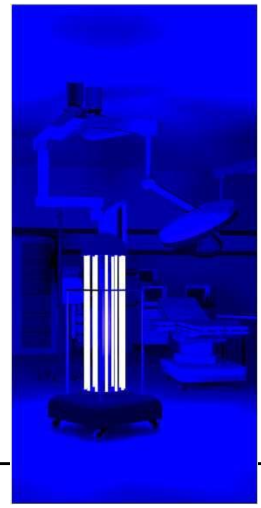
- Visual glare analysis
- NEMA LS 20001-2021, White Paper on Unified Glare Rating (UGR)

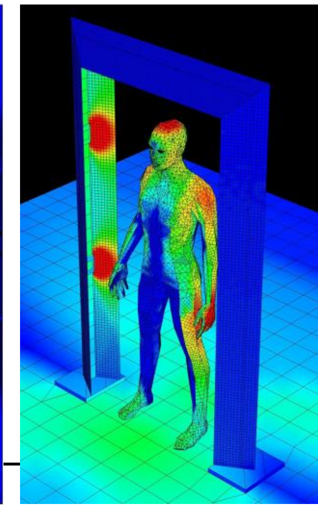
Another application that is becoming increasingly important is visual glare analysis.

From an engineering perspective, however, this topic has to be approached with considerable caution. A recently published whitepaper from the National Electrical Manufacturers Association (NEMA) provides a wealth of practical information for lighting designers.

Once again, know your tools!

Lighting Design – Applications

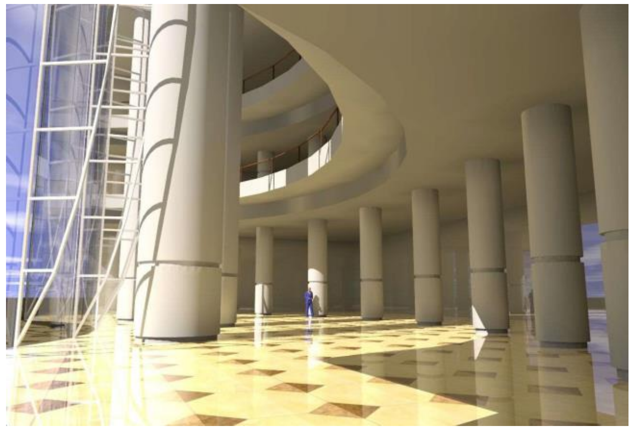




- Horticultural lighting
- Ultraviolet (germicidal) lighting
- Circadian lighting

Even more recent applications include horticultural lighting for greenhouses and vertical farms, ultraviolet lighting for germicidal disinfection, and circadian lighting that attempts to synchronize our internal biological clocks with our daily activities.

Lighting Design Programs - Applications

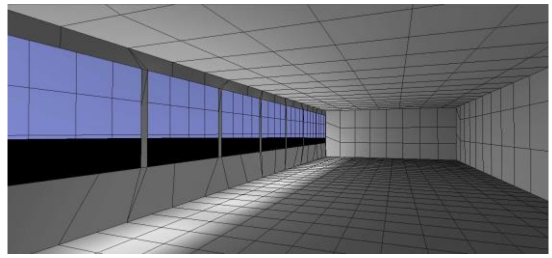


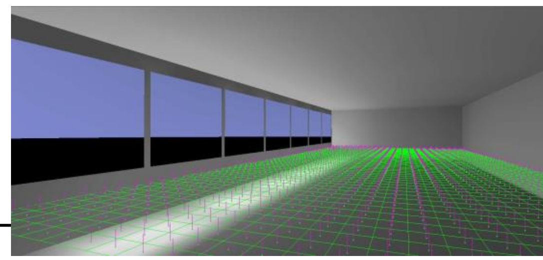
• Static daylight analysis

Daylighting design crosses the boundary between illumination engineering and architectural design. Building standards such as LEED and WELL include credits for architectural design that take daylighting metrics into account, but this requires lighting designers and electrical engineers to become more involved in the conceptual design of buildings.

Lighting Design Programs - Applications

- Climate-based annual daylight
  - IESVE
  - CoveTool
  - LightStanza
  - Solemma ClimateStudio
- Historical weather data
- Geographic location
- 4,380 hourly calculations
- Radiosity is 500 times faster than ray tracing …



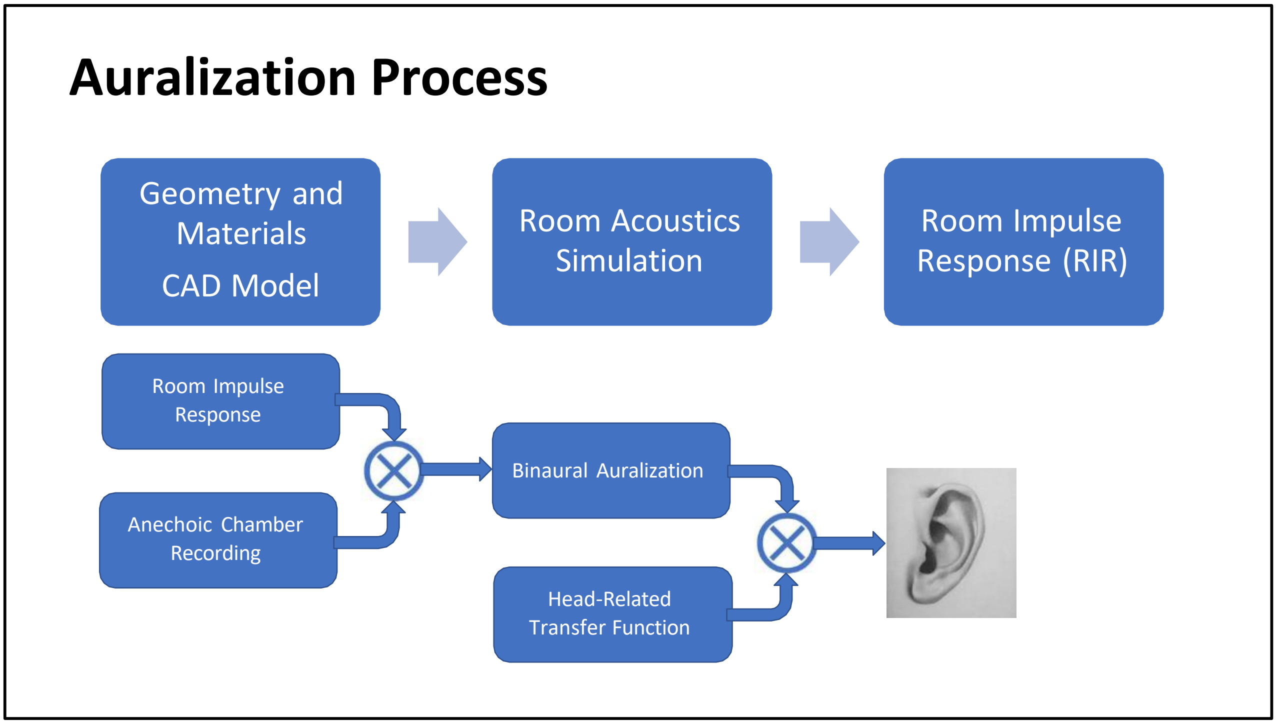


Some architectural design programs bridge this boundary by modeling daylight inside building on an hourly basis throughout the year using historical weather data. This is an evolving field for lighting design software, which currently relies on LBNL’s *Radiance* as the calculation engine. However, the radiosity method has been shown to be some 500 times faster than ray tracing, and it may be coming to market in the future.

Room Acoustics - History

- Allred, J, and A. Newhouse. 1958. “Application of the Monte Carlo Method to Architectural Acoustics,” JASA 30(1):1-3.
- Schroeder, M., et al. 1962. “Digital Computers in Room Acoustics,” Proc. 4th Int’l Congress on Acoustics.
- Krokstad, A., et al. 1967. “Calculating the Acoustical Room Response by the Use of a Ray Tracing Technique,” J. Sound and Vibration 8:118-125.
- Kuttruff, H. 1971. “Simulated Reverberation Curves in Rectangular Rooms with Diffuse Sound Fields,” Acta Acustica 25(6):333-342.

… and so on to the topic on modeling room acoustics, from small classrooms to concert halls. Unlike lighting, the history of acoustics design began with the availability of digital computers. The seminal papers were published between 1958 and 1971, and the field is still evolving.

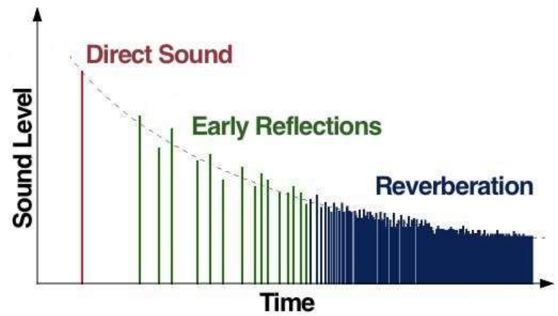


Conceptually, the problem is quite simple: begin with a simple CAD model, generate an impulse sound from one or more sources, and calculate the echoes within the room. This is the Room Impulse Response (RIR), which can be convolved with an anechoic chamber record to generate a binaural auralization, and again with a head-related transfer (HRTF) to generate a recording that simulates the sound using headphones.

There are a lot of details here, but let's look at the Room Impulse Response …

Tools – Room Acoustics Simulation

- Ray Tracing
- Image Source
- Radiosity
- Wave-based Modeling
  - Finite Difference / Finite Volume
  - Time-Domain Spectral
  - Finite Element
  - Boundary Element
- Diffusion Equation

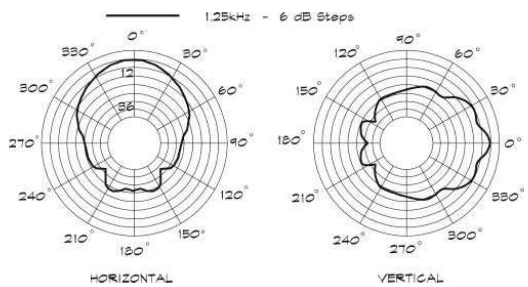


Room Impulse Response

… but only as an overview. There are numerous possible methods to calculate the Room Impulse Response, and commercial room acoustic programs may use multiple methods.

Tools – Room Acoustics Simulation

- Ray Tracing
  - Complex geometries
  - Non-isotropic sources
  - Frequency-dependent materials
  - Air attenuation

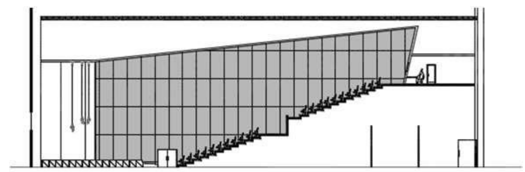


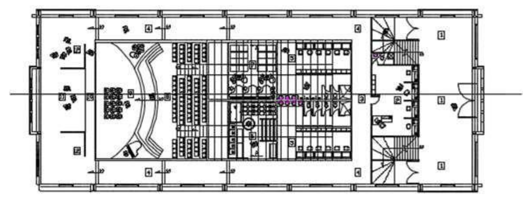
Rooms such as concert halls can be disconcertingly complex, but it is usually only necessary to model large surfaces. The hundreds of seats, for example, can be represented with greatly simplified geometry.

Other modeling issues include non-isotropic sources, frequency-dependent materials whose reflectance can vary from purely specular to diffuse depending on the wavelength band, and air attenuation of the sound through multiple reflections.

Room Acoustics Simulation Programs

- Odeon
- Ease
- CATT-Acoustic





ISO 3382-1:2009 Standard

Parameter	Perception
Reverberation Time (RT)	N/A
Early Decay Time (EDT)	Reverberance
Strength (G)	Loudness
Clarity (C_{80})	Clarity
Early Lateral Energy Fraction (J_{LF})	Apparent source width
Late Lateral Sound Level (L_1)	Listener Envelopment

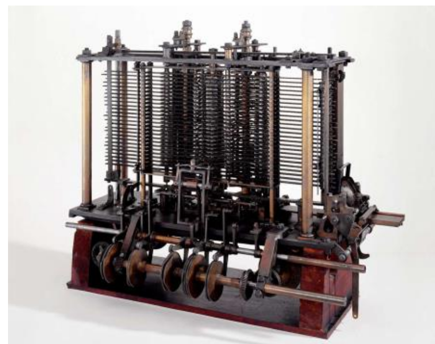
There are only a few commercial room acoustics modeling programs available, likely because it is a much smaller market compared to lighting design. On the other hand, there are significantly more design metrics compared to lighting design, and international standards that define them.

With this, I will echo (sorry) my call to “know your tools” with an explicit recommendation: read the Odeon User Manual. Its chapter describing the theory of the algorithms used, and also the very detailed discussion of their limitations and program usage recommendations, is simply unparalleled when compared to lighting design program manuals.

Know Your Tools

- "Pray, Mr. Babbage, if you put into the machine wrong figures, will the right answers come out?"

Charles Babbage, 1864. Passages from the Life of a Philosopher



Portion of Babbage's Analytical Engine

Once again and finally, know your tools! The 1960s' expression "garbage in, garbage out" actually originated a century before with Charles Babbage and the world's first programmable computer, his never-completed Analytical Engine. (Still under construction today, it will have 645 bytes of memory and a clock speed of seven Hertz.)

But this is only half of the equation – the other half is you.

Know Your Tools

- The trust you put into your engineering calculations … is directly proportional to your understanding of how your software tools work.

I have given at best an overview of the software tools available for lighting and room acoustics design. The usefulness of this presentation is (I hope) not in the information itself, but in the admonishment that in order to properly use your design tools, you need to know how they work.

In a sense, I had it good when I was a lighting designer and electrical engineer in the 1970s and ‘80s – a slide rule made it immediately obvious when my calculation were off by an order of magnitude. Today’s software programs offer no such protection – if you are going to use them, you can only trust their results to the extent that you know what the results should be.

… and as my friend says, thank you for your time.