Glance at the Dance of Photons

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The Physics of Light for Vision and Photometry

THOMY NILSSON

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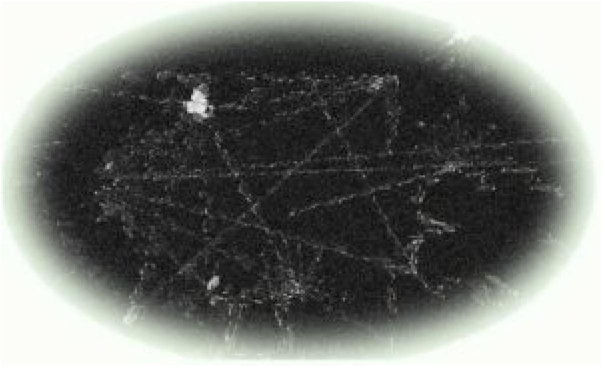
A GLANCE AT THE DANCE OF PHOTONS: THE PHYSICS OF LIGHT FOR VISION AND PHOTOMETRY



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This graphic essay began as a draft for part of a course being developed by the Canadian National Committee of the International Commission on Illumination. The course's objective is to promote the study of illumination engineering (There's a shortage – see end note 6.) and to increase general understanding of light and lighting. Having taught perception courses since graduate days, I had 50 years of notes about vision. Recruited from physics into psychology by Gillray Kandel at Rensselaer, those notes included more than the minimal basics about how light makes vision possible. So I offered to draft something about how the physics of light relates to vision.

A subtitle, "A Glance at the Dance of Photons" came while awakening one morning. Then I realized how well it captures the theme: that photons vibrate, that they scatter and "bounce" all over place, that their "dancing" causes them to swerve when passing from one media to another – swerving that enables focusing them into images; and that their waving transfers their energy initiating a cascade of molecular changes which convey the information in an image to the brain. As the title, its poetry may capture more attention.

1.

INTRODUCTION p. 1

Let's start with light, since every body ”knows” what light is. After all, we can see it – or think we can. Actually, we don't see light. We only see the surfaces that reflect or emit light. Whatever, ***light*** is a stream of ***photons***, yet only those within a narrow part of a near infinite range of electromagnetic radiation. Physicists count them and measure their energy, without ever knowing exactly where the photons are and can't even agree on what they are!

Some introduction, eh? Don't let that discourage you. Here is how I'll deal with photons as they relate to vision.

As many readers already know, photons have a dual personality – or maybe it's just the physicists. On one hand, photons are massless ***particles*** that speed along in straight lines called ***rays***. From this perspective, basic geometry is enough to see how rays can form images. On the other, photons are ***waves*** of energy describable by Maxwell's equations using calculus. Don't worry, the calculus quickly gets beyond the abilities or interests of general readers. Still their waviness can't be ignored. The wave perspective is necessary to grasp how light interacts with matter – interactions that make images possible and that enable those images to be sensed.

This "glance" compromises between the particle and wave perspectives. Photons are treated as quantal packets of energy that vibrate transversely to their direction of travel. Taking the average of their vibrations as location enables treating them as rays, while their vibration alters the probability of where they go when interacting with matter.

Avoiding calculus and using the *outdated (?)* Rutherford-Bohr model of the atom may cause apoplexy amongst some physicists. Yet as Paul Dirac pointed out "All the same the mathematics is only a tool and one should learn to hold physical ideas in ones mind without reference to the mathematical form." [1]

Until someone comes up with a better pictorial analogy, photons as vibrating packets of radiating energy will have to do.

2.

2. WHAT PHOTONS ARE p.2

simple answer: ***traveling packets of vibrating energy***

Electromagnetic radiation is emitted by all matter above absolute zero (0o Kelvin or -273o Celsius).

It is streams of energy bundles – ***photons***.

A photon’s energy depends on its frequency of vibration:

Energy = frequency x Planck’s constant

Planck’s constant is 6.625 x 10-34 joule-second). It is the smallest amount of power possible.

Therefore photons only come in discrete (***quantal***) steps.

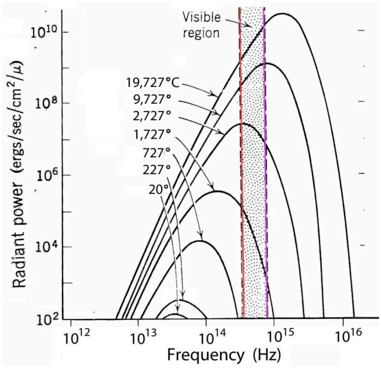
Multiplying their **frequency** in *vibrations per second* by **Planck’s** *joule-seconds*, cancels the

seconds, leaving ***Energy*** as *joules* – the unit of measurement for pure energy.

p. 3

It takes more energy for matter to release higher frequency photons. Therefore, as temperature increases, more high frequency photons are emitted:

To picture the relationship between energy, frequency and wavelength, consider this: It takes more effort to shake a rope, carpet runner or bed sheet faster thereby increasing how many waves occur.



For ideal matter, the relation between temperature and energy of the emitted photons is called the ***Black Body Radiation Law***:

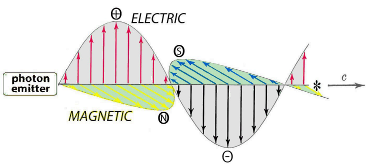
It's only an average. Real matter deviates from this ideal, but it's a good place to start.

At room temperature, a square meter of ordinary stuff (stairs, spoons, etc.) emits one photon in about every 42 seconds – virtually none of them visible.[2] That's why we need lamps – even if we turn up the thermostat.

Photons vibrate transversely to their direction of travel. This results in sinusoidal-like envelops of energy around each photon's path:

p. 4

Their vibration expresses two kinds of energy: electric and magnetic



energy: ***electric*** and ***magnetic***

It is a stable mutually reinforcing association:

> The varying electric field induces a corresponding varying magnetic field at a right angle to itself, The varying magnetic field similarly induces a varying electric field at a right angle to itself.

Having no mass and vibrating so fast is why photons for many purposes can be successfully treated as traveling along the average location of their combined electric and magnetic fields.

For most lighting, chemistry, and vision work, attending to the electric wave is sufficient. So to simplify this glance, the magnetic component will not be discussed further.

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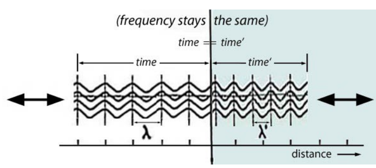
The speed of a photon depends on the medium through which it travels.

(*Shortly, we shall learn why this is very fortunate.*)

Photons travel 300,000,000 meters per second in vacuum and nearly as fast in air. This speed is generally called "***c***".

They slow substantially in media such as glass and water. How much they slow is specified by a medium's ***refractive index (n):***



n = **c** / speed in medium

For example:Photons entering glass (***n*** = 1.5) slow down to:

$\text{speed}_{\text{glass}} = 3 \times 10^8$ m/s/ 1.5 = 2×10^8 m/s.

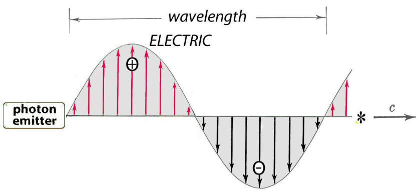
Why? Their vibrating electric field is hindered by fields of the electrons in the medium – an effect I'll call "***drag***". Denser media, tend to have stronger fields, larger refractive indices and exert more *drag*.

Traveling in the opposite direction from right to left above, the photons are released from the *drag* and resume their speed and wavelength.

p. 6

The distance a photon has traveled during one complete cycle of vibration is called its "***wavelength***". A photon's wavelength therefore depends on its velocity:

$$\text{wavelength} = \text{speed} / \text{frequency}$$



When photons go slower in a medium denser than air, their frequency stays the same.

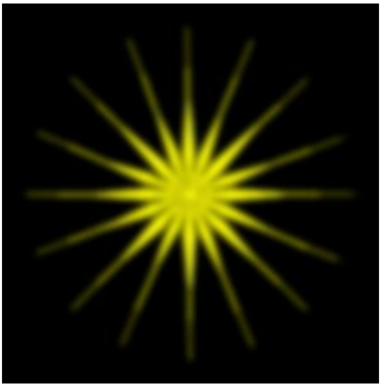
Their wavelength shortens because they travel a shorter distance during one cycle of vibration. They do not loss energy when slowed, because that is determined by frequency (page 2).

Nor do they gain energy when they speed up on leaving a denser medium.

3. 3. PHOTONS ARE POLARIZED

3. PHOTONS ARE POLARIZED
p. 7

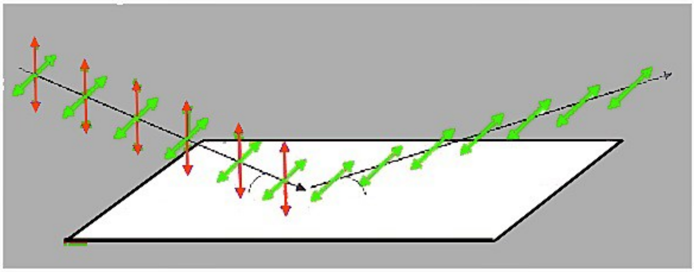
In a ray of photons emitted by most sources such as the sun or the heated wire in a light bulb, any particular photon's electric vibration is randomly oriented transversely to its direction of travel. A head-on view of a ray of many such photons' vibrations would look like this – with others vibrating at in-between orientations:



Ideally their *vibrations* extend indefinitely, but become vanishingly weak beyond a few microns.

p. 8

When a ray of photons hits a horizontal surface, the horizontally vibrating photons tend to be reflected while the vertically vibrating photons tend to get "*dragged in*" and be absorbed. Depending on how mirror-like the surface is, other photons get reflected or absorbed according to how close their vibrations are to horizontal or vertical. A ray of photons that vibrate mostly in a particular orientation is said to be ***polarized***.



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Some materials have molecular arrangements that selectively transmit photons vibrating at a certain orientation. Placed before an ordinary light these *polarized filters* can also provide a source of polarized light.

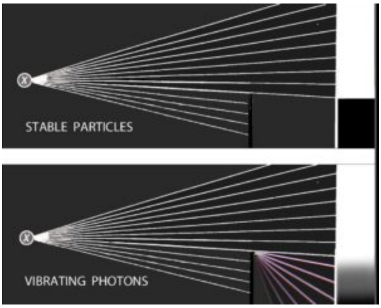
Wearing vertically polarized filters can reduce the glare from horizontally polarized photons reflected from surfaces such as roads and water.

Another way to reduce reflective glare is to polarize the light source or coating the reflecting surface with a polarizing material.

4. 4. PHOTONS DIFFRACT

4. PHOTONS DIFFRAC T p. 10

Streams of particles don't swerve when they meet a barrier – they either pass or not:



Because photons vibrate, those passing too close to an edge encounter a slight electron field *drag* on their edge side causing them to swerve behind it. [3]

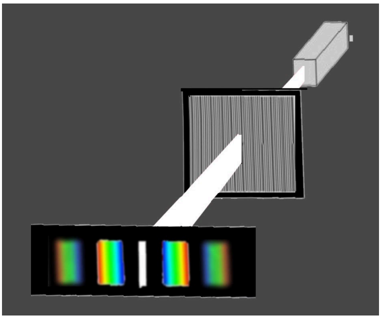
How much they swerve depends on their wavelength and phase as they encounter the edge. Look closely. Notice the slight color fringe in the bent rays. Like the last rays from a sun below the horizon, long wavelengths are bent more than short ones due to longer proximity to the edge:[4]

Such "bending" around an edge is characteristic of waves in general. e.g. Long wavelength (low frequency) sound waves bend around walls and rocks. However, sound waves bend as a result of spreading air or water pressure behind an edge. Photon diffraction does not depend on the medium it travels through.

Altough it occurs for a different reason than the bending of sound waves, this similar bending of light around an edge was an early clue to its wave-like nature.

p. 11

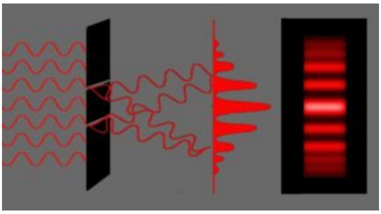
While these fringes are scarcely noticeable with a single edge, this effect from hundreds of edges close together (a *diffraction grating*) adds up producing vivid spectra:



Similar spectral effects also appear in reflections from the fine grooves on compact audio disks.

p. 12

More compelling evidence of the wave properties of photons appears when photons of a single wavelength are directed at two adjacent slits:



With two edges, each slit diffracts photons in both directions. At various locations photons diffracted in the same direction from each slit cross paths. When these photons are in the opposite phase of vibration, their energies cancel producing darkness at that location. At another location photons from each slit will arrive in phase, and their energies sum resulting in brightness.

Treating streams of photons like linear rays is great for visualizing how images are formed and lighting application. **Yet it is their vibration that determines what they do and how to control them.**

5. 5. PHOTONS RADIATE

5. PHOTONS RADIATE

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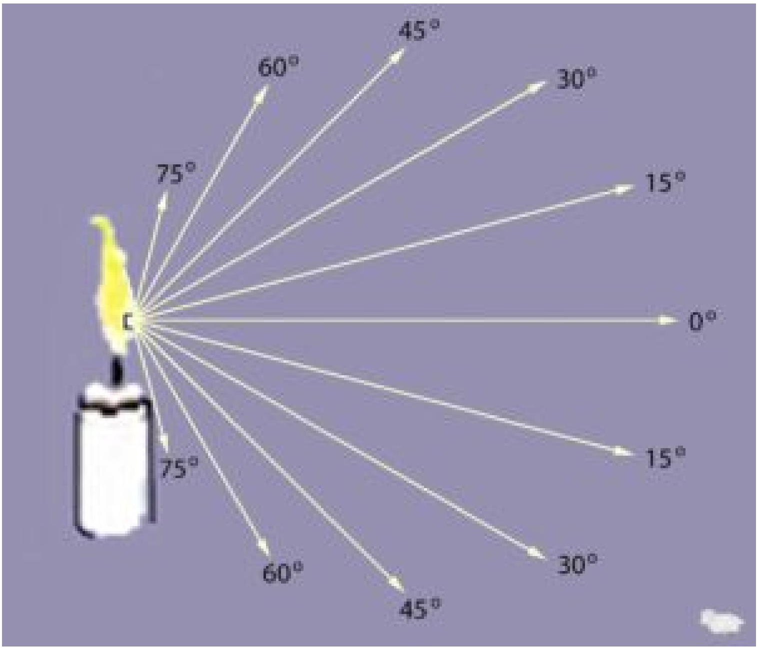
Most light sources (other than lasers) emit photons in all directions – namely they ***radiate***. They tend to radiate more directly out from their surface and less to any side



This is true for any point in a candle flame, on a glowing wire in a light bulb, and in a light emitting diode.

The number of photons emitted in various directions from any point on an ***ideal*** source looks like this:

The line lengths are proportional to the number of photons in the ray (***its intensity***) in that direction.

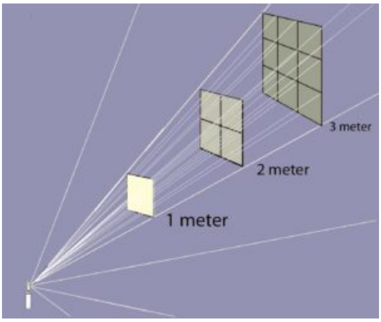
e.g. The 60 degree ray has half the intensity of the direct ray.

In 1760 Lambert found the decrease in photons at any angle could be estimated by multiplying the intensity of the direct ray by the angle's cosine.

Surfaces the emit light in this manner are therefore called "Lambertian".

p. 14

This radiation of photons from a source has serious consequences for lighting: The further the source, the weaker the radiation's *strength per unit area* (or ***illuminance***, but that comes later, page 80):



The same number of photons reaching a square at 1 meter, spreads out over 4 squares

at 2 meters, spreads over 9 squares at 3 meters, and so forth.

By simple geometry the number of photons per unit area decreases with distance squared.

At 3 times the distance, a light meter finds the illumination to be 1/9 th of what it measured at 1 meter from a source.

Thus we have the **Inverse Square Law** describing the effectiveness of radiation at a distance.

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Then why doesn't a candle look dimmer as you walk away?

This question actually applies not only to candles or light bulbs, but also to everything we see.

The explanation (page 36) comes from physics not perception.

However, that requires understanding some optics.

First, let's consider why it applies to (almost) everything we see:

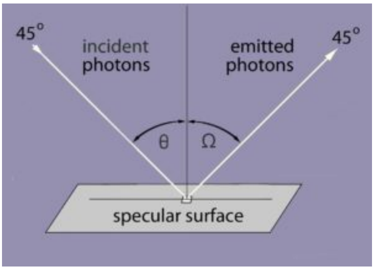
6. 6. PHOTONS ARE REFLECTED

6. PHOTONS ARE REFLECTED p. 16

There are relatively few natural sources of visible light in our world: sun, moon, stars, wild fires, volcanoes. We would live in darkness if most of the surfaces around us did not reflect photons from those sources.

Reflection can be characterized by how photons leave again after encountering either of two ideal surfaces:

SPECULAR REFLECTION



Some surfaces are mirror-like and perfectly smooth. How photons "bounce"***** off them is entirely predicable. The angle at which they leave equals the reverse of the angle at which they hit – ***Snell's Law***.

ANGLE OF INCIDENCE θ

=

Ω ANGLE OF EMISSION

*****NB – A reflected photon does not "bounce" off a surface. If it is not absorbed (page 42), its field is repelled by the fields of the electrons in that surface.

p. 17

LAMBERTIAN REFLECTION

These surfaces appear uniformly *dull*. At the microscopic level, they can be likened to being very bumpy. Therefore photons "bounce" off them in various directions even while each obeys Snell's Law.

ANGLE OF INCIDENCE θ

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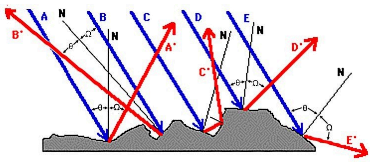
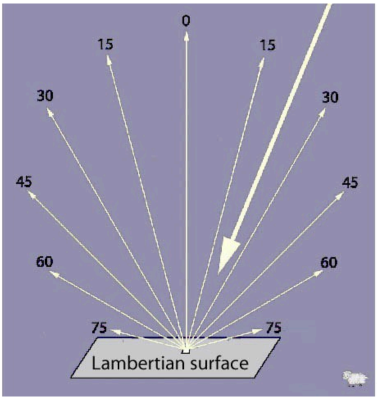
Ω ANGLE OF EMISSION



p. 18

An ideal such surface reflects photons similarly to how blackbodies radiate them – obeying Lambert's Law.

The length of these reflected rays at various angles illustrates their intensity:

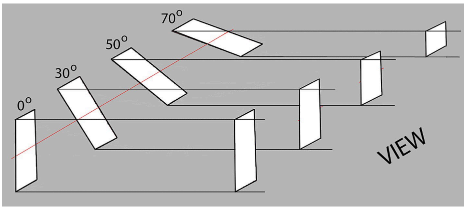


Whether emitting or reflecting light, such ideal surfaces are said to be *Lambertian*.

p. 19

Despite the reduction in amount of light reflected at various angles, you may have noticed that *dull* surfaces still tend to appear equally bright regardless of the viewing angle!

At first counterintuitive, it is logical when one considers the size of the "per unit area" doing te reflection. Viewed head-on (at 0o) that unit area appears largest. It decreases at larger angles to the same extent as the amount reflected decreases. Thereby the amount of light received per apparent unit area stays the same.



Few actual surfaces come close to either ideal. Most are blend of specular and Lambertian properties. However, this analytic approach helps approximating actual situations. This can be useful in for designing lighting environments.

7. 7. PHOTONS MAY BE SCATTERED

7. PHOTONS MAY GET SCATTERED

p. 20

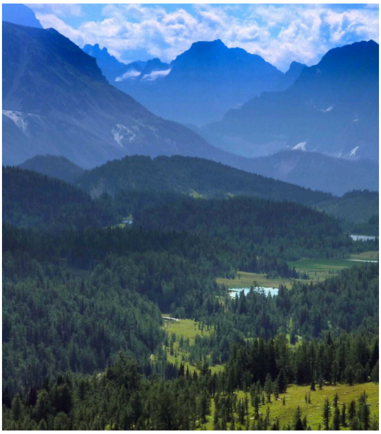
If photons encounter particles whose size is similar or smaller than their wavelengths, they can get reflected off to either side depending on phase of their vibration at the encounter. If the particles are less than <10 nanometers, their scattered direction becomes random *(Rayleigh scattering)* – some photons may even barrel on through. The chance of such encounters increases with photon vibration frequency. Higher frequency vibrations are more likely to sweep them into such particles, while lower frequencies are more likely to let them slip past. Put another way, more short wavelength photons are scattered than longer ones.

Were it not for this scatter, on a clear day the sky would look black every where except when you looked directly at the sun. (DON'T EVER.) However, clusters of water molecules from 0.3 to 100 nm suspended in the atmosphere are the right size to scatter photons. Therefore rays of sunlight original headed elsewhere will have some of their photons scattered in your direction. Since more short wavelength photons are scattered, they predominate. Their blue sensory effect is attributed to the sky in the direction from which they arrived.

The water droplets that make up clouds are several orders of magnitude larger. Therefore clouds are *Lambertian*, reflect all wavelengths equally, and appear white. A continuous range of particle sizes from single atoms of water to rain drops provide a range of effects depending on conditions.

8. 8. PHOTONS ARE DISOBEDIENT

Unlike good little electrons, proton and neutrons, photons do not obey the *Pauli Exclusion Principle*. Any number of photos can pile up on top of each other while traveling in the same direction at the same time. This is fortunate. Since one photon would probably always be coming from every direction, everything would look dim grey. Differences in brightness depend on photons being able to bunch together.



Their disobedience can result in a bit of collateral color distortion which gives them away. For example, take those distant mountains' purple majesty. Despite appearances, up close they do not appear purple at all. What happens is this:

While traveling from afar, those mountain photons get joined by other photons from the sun that have been scattered by water molecules in the air along the way. Because more short wavelengths get scattered, more short wavelength photons than long ones join those coming from the mountain. Given enough distance these hitch hikers predominate.

9. 9. THE TROUBLE WITH PHOTONS

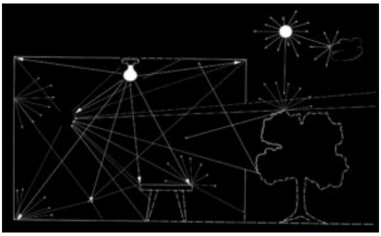
They are all over the place!

Radiated, diffracted, reflected and scattered ***photons*** come and go in all directions every where around us. And we can't even see them. We only see the surfaces from whence they came.

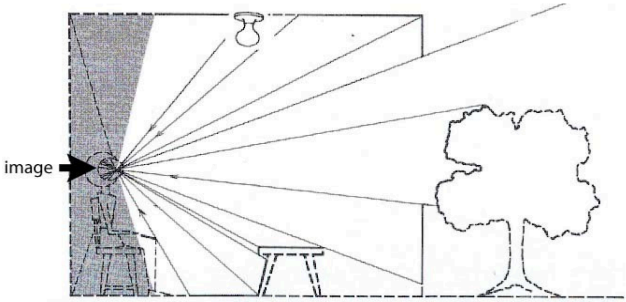
At any location in a room or elsewhere, their rays are all mixed together:

There are no images in the natural world.

This enlightened statement is not philosophy, it's physics.



To know their source, those rays would have to be sorted with respect to the direction from which they came. Doing that for all of them at once creates an ***image*** of the world around us.



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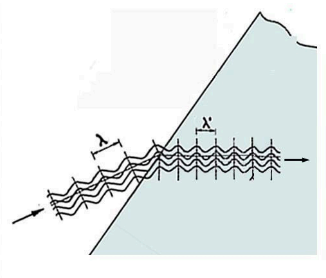
10. 10. PHOTONS GET REFRACTED

Of particular value is what happens when photons enter a denser transparent medium at an angle. For the briefest of moments, “drag” slows down the first portion of the wave while the remainder continues normally. This changes the photons’ direction of travel inside the new medium.

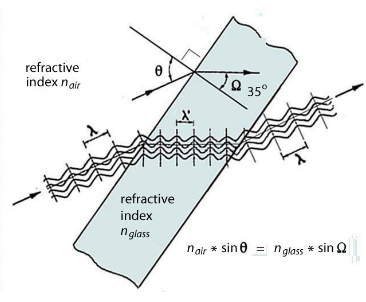


How much their direction is changed depends on the ratio of their speeds in the two media.

To determine the bending, it is not necessary to calculate those speeds The ratio of their ***refractive indexes*** (see page 5) will do. The refractive index for various materials is listed in tables available from many sources:

The following math illustrates that these matters are simple trigonometry:

e.g. For air ***n*** = 1; for water ***n*** = 1.33; for crown glass ***n*** = 1.52.In this example, if the medium on the left is air, the denser medium is crown



glass, and the angle of incidence on the glass, θ, equals 60 degrees:

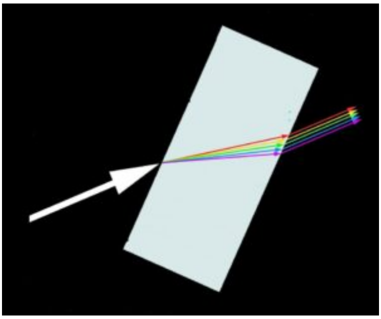
sin of the refracted angle Ω =
(n_{air} / n_{glass}) x sin incident angle θ
sin Ω = $(1/1.52)$ x sin 60^{o}
= 0.66 x 0.87= 0.57 So the refracted angle Ω = 35^{o}

These calculations are the same when photons leave a denser material.

In the above example, the glass surfaces are parallel. Therefore the incident and exit angles are reversed, and the photons leave in the same direction at which they entered – albeit laterally displaced.

Higher frequency photons slow more in denser media than low frequency photons. (The refractive index, ***n*** of most substances increases with frequency.)

Consequently, on entering a higher refractive index medium, "violet" photons change direction more than lower frequency "red" photons.



(**N.B**. This is opposite to what happens when photons are diffracted – page 10.)

Refraction sorts photons into slightly different directions depending on their frequency. This is why *white* light gets spread into a rainbow by prisms and water droplets.

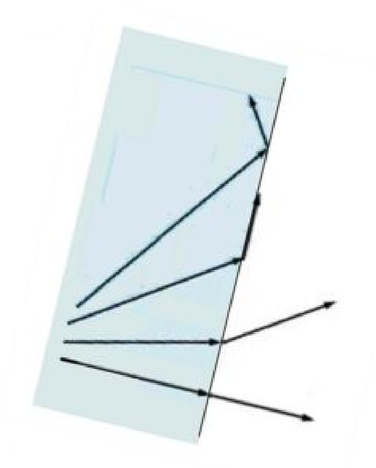
As the photons leave, note how the internal angular differences restore the original direction of each wavelength, though they are now laterally displaced according to wavelength as well as laterally displaced from their original path.

Colors from diffraction can be used to produce some novel lighting effects. Yet the effect can also result in nuisance colors fringes (***chromatic aberration***) in some lighting applications.

The above example used a prism with parallel entrance and exit surfaces. If the exit surface had a slightly steeper angle, the various frequency photons could arrive at the same point after traveling a certain distance. This enables correcting chromatic aberration to a limited extent.

(**N.B.** In contrast, the angle at which a surface ***reflects*** photons is the same for all wavelengths and does not depend on its refractive index. That is why mirror telescopes are preferred over lens telescopes.)

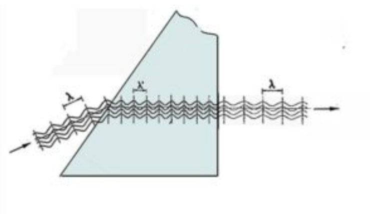
If the denser medium has a sufficiently high refractive index compared to the less dense medium, photons arriving at sufficiently shallow angles of incidence get trapped.Instead of exiting the photons get diffracted so much they stay inside:



Internal Refraction is the basis of fiber optics. The ability to transmit light by flexible fibers makes medical and industrial endoscopes possible. Single fibers can be chronically implanted in neural tissue for optogenetic stimulation and recording. They can also be used as light pipes for daylight illumination of interior spaces.

Thanks to their disobeying the *Pauli Exclusion Principle*, photons of many different wavelengths can be travel through a single optic fiber simultaneously. This wavelength multiplexing combined with a lack of field interference when many fibers are packed together, enable optical fibers to carry more information than electrical wires.

The above illustrations of refraction had the photons entering and leaving parallel surfaces. Consequently they continued in the same direction afterwards. However, if the two surfaces are not parallel, the photons will exit in a different direction. Here is an example:

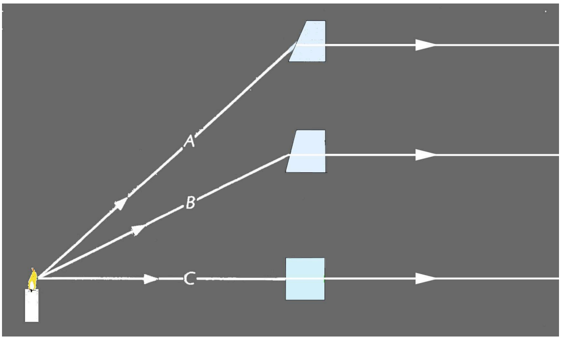


When these photons exit a medium across a perpendicular surface, their diffracted direction is not changed. (All parts of the wave *escape* at the same time.)

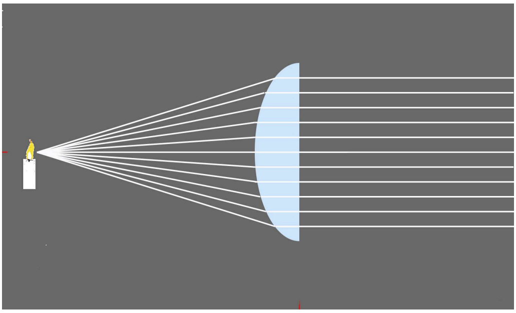
Non-parallel media surfaces are the basis for changing the direction of light.

11. 11. WHERE PHOTONS CAME FROM

A stack of appropriately shaped prisms can stop rays of photons from continuing to radiate:



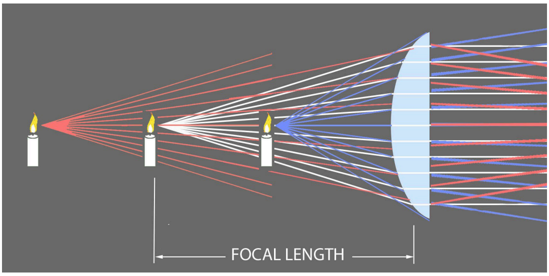
One could add more prisms with “in-between” front angles to catch more rays radiating from the candle. However, there is a simpler solution. It turns out that a continuous curved surface can do the same thing.



Lenses like this enable projecting rays of photons radiating from a source to a distant location without the loss of intensity with distance squared. The process of producing parallel rays of photons so they form a *beam* is called *collimation*.

Any given lens curvature only bends the rays a certain amount depending on its refractive index. The above lens only collimated the rays from a candle at a certain distance.

Rays from a closer candle enter the lens at angles too steep be bent parallel. They still spread out, though less. Those rays from a further candle that reach the lens, diverge less. Being diffracted the same amount as rays from the other candles, they get bent too much and converge:

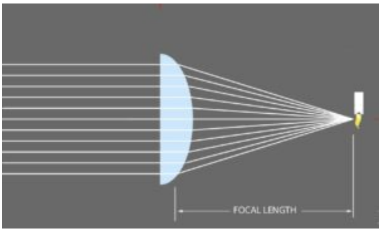


The source distance at which a lens produces collimated rays is the lens' ***focal length***.

Now consider the reverse of the above figure. (Physicists are fond of proclaiming that their laws are the same regardless of the direction of time.) But rather than think backwards, let's reverse the above figures. Now rays from a candle far out of sight to the left are collimated when they arrive.

A distance over 3 meters is *far* enough for most optical applications.

Therefore the rays from that candle will converge to a point a ***focal length*** behind the lens. At that distance there is an ***image*** of that candle:

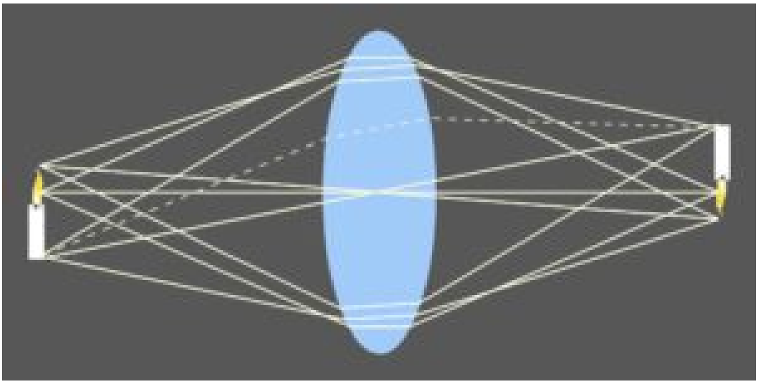


But the image is upside down ?

Though off page, the real candle **is** right side up.

To see why the image is inverted, follow the rays on the next page:

By bending the rays even more, it is possible to bring them all back together for an image of a source that is closer than *infinity.* This could be done with steeper rounding of the front surface of the above lens. However, recall that light also gets bent when it speeds up as it leaves a denser medium. Also recall that Lambert's Law operates in reverse too – rays striking a surface at a steeper angle enter less effectively. Therefore a more elegant solution is to curve both sides of the above lens:



Simple geometry determines that ***lenses*** invert (and also reverse) the resulting ***image***

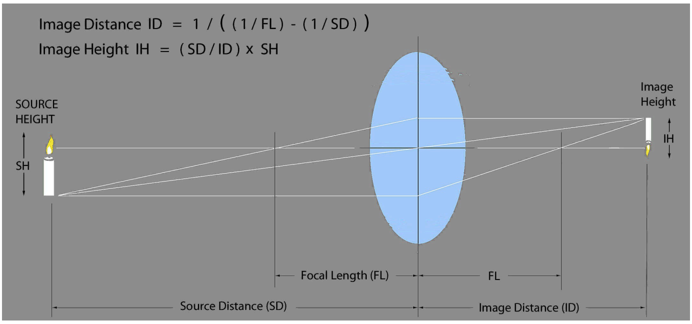
Two geometric principles govern how simple lenses transmit rays:

1. Rays passing through the lens' center continue in the same direction.

2a. Rays passing through the lens' focal point emerge perpendicular to the lens.

or – since rays work the same in reverse

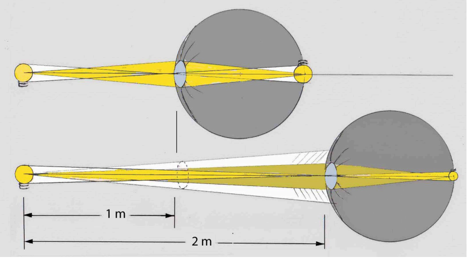
2b. Rays perpendicular the lens pass through its focal point after emerging.



Distance and size of an image depend only on source distance and the lens' focal length – ideally.

Now For That Page 15 Question About Brightness And Distance:

Since light intensity decreases with the square of distance from a source, why don't lamps get dimmer as you back away from them?

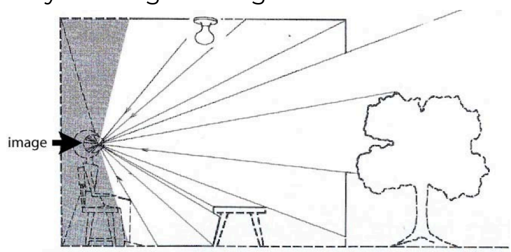


Only 1/4 as many photons reach the eye at 2 meters. However, the image extends over only 1/4 as much area. Therefore the image is just as bright.

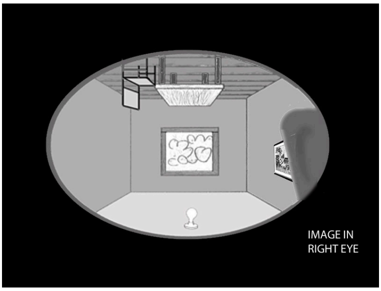
The same occurs at any distance for any thing that emits or reflects photons.

12. 12. PHOTONS AS RETINAL IMAGES

Lenses are how our eyes sort the confusion of rays to produce an ***image*** that contains the information about where the rays came from. They do this by forming an image –



– an IMAGE like this on the ***retina*** at the back of the eye:



When inversion and reversal of the image in our eye was discovered in the Middle Ages, it mystified philosophers.[5]

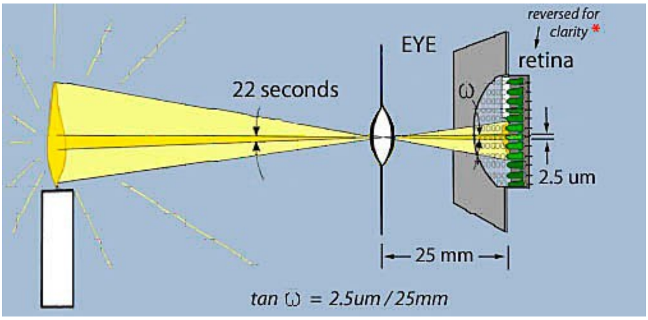
The answer to that "little" inconsistency between optics and perception turns out to be more profound than any mystery in physics.

It is not explainable by some possible 1800 twist of neural connections from the *retina*. Here's why: After a few days' confusion, persons wearing "glasses" that turn the image right side up find the world appearing normal.

Evidently the ***visual*** image is not constrained by neuroanatomy.

Consider the retinal image. Though it appears to be continuous, that image is sensed by individual receptor cells in the *retina*.

The ability to sense the direction from which photons have arrived depends on the size of the retinal receptors and focal length of the eye. A typical photoreceptor has a diameter of 2.5 micrometers and is located at the focal point of the eye, some 25 millimeters behind the lens. By trigonometry the receptor subtends a 22 second angle with respect to the lens' center. Because congruent angles are equal, that is the receptor's ***field of view*** – how much of the world it responds to.



*****NB In vertebrate eyes the light sensitive end of the photoreceptors not only faces away from the lens, it is also covered by the rest of its cell body and by several types of nerve cells and nerve fibers that, fortunately, are nearly transparent. (Why this backwards design, and only in vertebrates? That's another story.)[6]

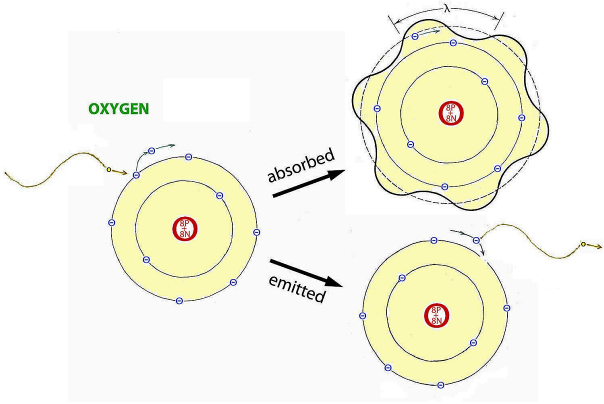
However, the photoreceptors would not respond to the photons in the image were it not for another property of photons:

13. 13. PHOTONS CATALYZE

More important than enabling the formation of images, is the ability of photons to initiate chemical reactions. Indeed, without this ability, their would be no visual response to images in our eyes.The frequency of electromagnetic radiation is constant whether in space, air, or water. Therefore electromagnetic radiation is defined in terms of frequency. However, in everyday use, we generally refer to its wavelength because:

*It is easier to visual length than frequency.
*Wavelength determines how photons interact with matter.
(Though this is based on the Bohr atomic model, frequency resonance works too.)

Whether a photon will be absorbed by an atom or rejected depends on whether its wavelength will *fit* (resonate) the orbit of an outer electron.



Atomic absorption of photons has a variety of consequences that range from slightly heating the substance to catalyzing changes in molecular structure. Depending on wavelength and substance such changes include:

*photosynthesis – photons trigger this chain reaction which oxygenates the earth's atmosphere while simultaneously producing the ultimate energy source for most life.

*odorant release

*germicidal sterilization – including potential for non-medical containment of airborne viruses.7

*chromosome mutation

*photoisomerization – You are currently experiencing consequences of this effect:

Photons within a narrow range of the electromagnetic spectrum can be absorbed by specific molecules in the ***receptor*** cells of the retina.

This triggers a chain reaction that disrupts neurotransmitter release by these cells.

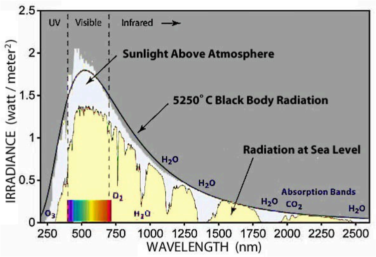
That in turn results in a series of

nerve impulses which convey the effect of the image at that location.

Because such photons are our primary source of information about the world, they are accorded a special name:

14. 14. LIGHT

Most of the electromagnetic radiation available on earth comes from the sun:

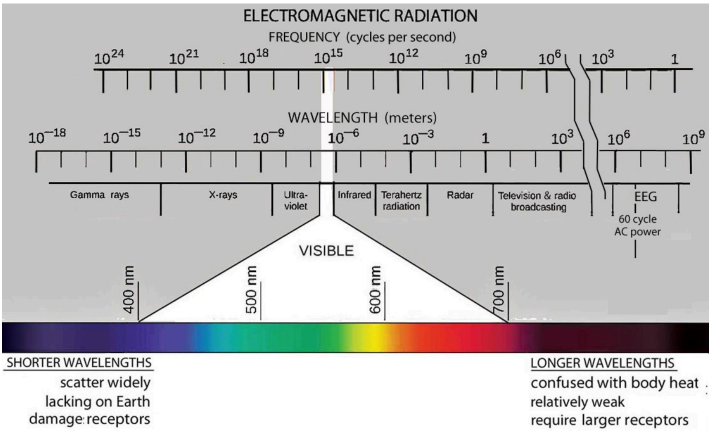


At sea level, radiation below 400 nm (***ultraviole****t*) and above 750 nm (***infrared***) is reduced due to absorption by water molecules in the atmosphere.

The sun's stark white appearance through a light overcast sky reveals its true color above the atmosphere.

The clouds reflect all wavelengths uniformly. This overrides the scattering of the short wavelength photons amongst the light that gets directly through the cloud cover.

Given the abundance of radiation in the 400 to 700 nm range, it follows that receptors evolved specifically to detect radiation in this range. Several other factors listed below contribute to making this a "Goldilocks" range for vision – the radiation we call ***light***.



A Little History

From agriculture to manufacturing, from work to recreation most of life's activities depend on light. Yet not till the 19th century did realization arise about the advantages to be gained from measuring light. It began with profiteering from government allowances for the lighting of Bavarian work houses by a former Loyalist spy in the American Revolution, Benjamin Thompson. Inventing a photometer in 1793, enabled him to develop more efficient lamps and pocket the savings on lamp oil.[9]

(Nonetheless, his research on heat as energy and led to co-founding the Royal Institute in London. There an assistant named Michael Faraday discovered the interaction of electricity and magnetism. Faraday's student, James Clerk Maxwell then developed wave equations that unified light, electricity and magnetism in 1865. These equations describe the basis of the technology that has revolutionized our lives and understanding of the universe. On the other hand, Thompson's insight into measuring brightness led the way into an even greater mystery: His measurement of brightness was one of the earliest quantitative steps to studying consciousness.)

That the effectiveness of light depends on its *brightness* is intuitively obvious. Everyone knows we see better with more light in dim conditions. Yet Thompson recognized that brightness was a subjective phenomenon. It changed depending on both the observer and the conditions of observation. How can something like that be reliably measured? By matched the brightness of two sources, Thompson's photometer canceled the subjective aspects. Changing the distance of one source precisely varied its brightness according to the ***inverse square law*** (p.15). The distances at which they matched then provided a quantitative measurement of their relative brightness.

Today we have easier ways to vary the energy emitted by lamps, but Thompson's matching method is still the basis of how brightness is defined. He recognized that matches depended on both the observer's sensitivity and variations in the candles and lamps. These problems could be solved by always comparing various lamps with the same light source – a ***standard source***. That would provide an absolute scale of measurement.

Thompson tired various types of candles and lamp fuels as standards; even gave the moon a shot.Since then flames from several types of candles, lamps, and later electric incandescent bulbs were used. In 1948 an electric incandescent source was widely adopted: the intensity (technical definition comes later, page 75) of light from a tiny window to thorium dioxide glowing at 2042^{O}K. While closely matching a former candle, it was named the ***candela*** to avoid confusion.More recently this has been replaced by a ***standard detector*** for light.

One might think that a standard detector enables measuring brightness without having to compare the brightness of an unknown light to a standard. This can work, but first another problem with photons must be solved:

15. 15. PHOTONS VARY IN VISUAL EFFECTIVENESS (But It’s Not Their Fault)

Subjective ***brightness*** depends on the number of photons forming an image. That number can now be measured directly in terms of energy. Yet we’ve also seen that whether a photon is absorbed to catalyze a reaction depends its wavelength and the substance’s atomic structure – including receptor molecules in the eye. Therefore the visual effectiveness of a bunch of photons in an image will vary depending on their wavelength as well as their number.

The response of visual receptors to various wavelengths can now be directly measured using micro-electrodes. Yet receptor response is only a first step. Brightness results from complex neural processing that culminates as a conscious experience. This experience can not be measured directly. Therefore we must still rely on brightness matching to find the relative visual effectiveness of different wavelengths.

This relative effectiveness function enables weighting a detector’s energy reading at various wavelengths to obtain a number that approximates brightness. The required brightness matching method is essentially the same as what Thompson used – only repeated at many wavelengths.

However, doing so is more complicated than you might think. **Physics is simple compared to vision:**

1. The visual effectiveness of photons differs substantially for two types of receptors:

photopic receptors operate in daylight conditions.

scotopic receptors operate at night and are 100 X as sensitive.

2. The sensitivity of both types increases or decreases over time to compensate for (adapt to) decreases and increases in the overall level of light.

During ***dark adaptation***, photopic receptors reach maximum sensitivity after about 10 minutes; the scotopic receptors after about 30 minutes.

By comparison ***light adaptation*** (going from darkness to a bright region) is remarkably fast – most of it occurring within a few seconds for both types.

(Briefly turn on a lamp to record a measurement, and you must dark adapt all over again.)

3. The number of each type of receptor varies greatly with location on the *retina*.

Therefore the results differ depending on where the observer looks to make the matches.

4. The two types differ in sensitivity to wavelength.

5. Different wavelengths acting on the photopic receptors result in different colors as well differences in brightness.

6. Even when the matches are made by observers who by other tests have normal color vision, individual differences can be substantial – plus or minus 10 % or more even after substantial practice.

These visual factors have been controlled by making the brightness matches when the eyes have been fully dark adapted, presenting the image at the same place on the retina, using the same size image for all wavelengths, averaging the results for ten or more experienced observers, and averaging the results from several laboratories. Different matching methods were used to minimize the effects of color differences on brightness judgement – particularly for the daylight conditions that involve photopic receptors.

Based on many such measurements, the International Commission on Illumination (**CIE** – *Commission Internationale de l'Eclairage*) created two standards: ***photopic*** for daylight conditions and ***scotopic*** for night time conditions to describe visual sensitivity as a function of wavelength.

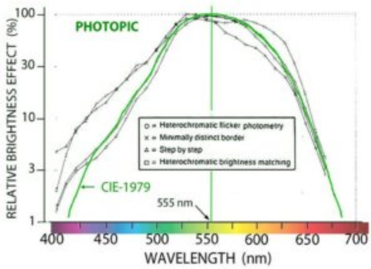
Avoiding the pros and cons of the different "matching" methods, the general procedure goes as follows:

Photopic matching is done by adjusting the amount of energy at each wavelength to equal the brightness of constant "white" (e.g. 3,000o K *Black* Body – page 3) spot of light set to a moderately bright daylight condition such as 100 candelas/ meter2 (brightness of white paper in a classroom – page 86). The relative values of those energy matches can then be used to correct energy measurements to numbers that represent apparent brightness – approximately.

These factors can be used by analyzing any light into its constituent wavelengths, applying the factor to each wavelength's energy measurement, and the total summed. However, a more convenient way is usually satisfactory. By adding to the energy sensor a *filter* whose wavelength transmission matches these relative values, a single energy measurement is corrected for all wavelengths present.

These relative values are sufficiently consistent, so that various wavelengths still look equally bright enough for most purposes across a wide range of light energy levels. **In practice a single set of corrections has proven more useful than attempts to apply various corrections depending on the amount of light, size and direction of the area being measured, etc.** Such conditions are then described separately.

555 nanometer photons produce the brightest response in the ***photopic*** system.



Light at this wavelength had to be reduced by a factor of 100 to match the brightness resulting from 400 and 700 nm photons.

In other words, for the same energy reading, 400 and 700 nm photons produce only 1 percent as much brightness as 555nm photons.

Matching to the other wave- lengths provided a scale of the visual system's relative brightness response:[10]

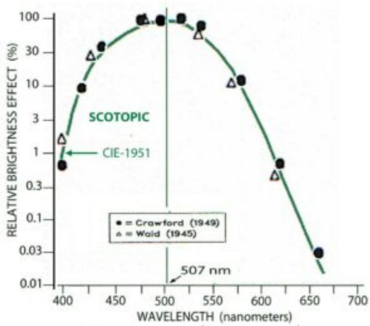
Accordingly, energy readings at any wavelength can be converted to reflect relative brightness by multiply the

reading by that wavelength's percent relative brightness effect.

The CIE publishes these correction factors for energy measurements as a function of wavelength.[11] In practice, photopic light meters are made with sensors whose sensitivity is filtered to match this photopic brightness function.

Sensitivity of the ***scotopic system*** to various wavelengths was measured in terms of the minimal amount of light needed to detect some brightness – the system's *threshold*.(It is tacitly assumed that at threshold the wavelengths are matched as equally "dim".)

Photons at 507 nm required the least light, so their relative effectiveness was set to 100%.



Photons of other wavelengths required more light to be seen. For example, 400 nm photons required over 100 times more light – thus being less than 1% as effective:[12]

A light meter with a detector whose sensitivity matches this brightness function will provide readings of dim lights that are comparable to their brightness. Nonetheless, scotopic measurements are often used simply to determine whether dim lights can or can not be seen.

You might also wonder how light is measured in twilight conditions that fall between the photopic and scotopic. (Then again, you might not).

However, think about it. These may be the very conditions in which being able to provide adequate light becomes really important.) For various levels of dimness, a series of relative brightness functions have been measured by the matching method. These are proposed as ***mesopic*** standards.[13]

16. 16. DISTINGUISHING PHOTON WAVELENGTH

(The “Glance” Gets Complicated)

Images are not just about distinguishing the shape of things out there in terms of the direction from which photons arrived. Being able to also distinguish their wavelength can provides lots of ”added value”. Again we take up the refrain: Which wavelengths get absorbed or emitted by a substance depends on its atoms.

What makes substances different is their atomic structure. Therefore different substances can be identified by which wavelengths they absorb or kick back out. Measuring those wavelengths enables determining the composition of that substance be it in a test tube, fruit hanging from the next tree, or a distant star – ***spectroscopy***.

For this reason even primitive visual systems evolved means of distinguishing which wavelengths are reflected by a substance to sense its composition – initially to identify food. As more directional sensitivity evolved, distinguishing different substances also helped to sense the shape of things. (You may jump ahead for a peek at page 63, but come back.)

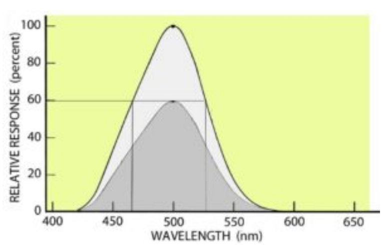
Photons of different wavelengths could be distinguished by receptors containing molecules that absorb only one wavelength. Once selected by survival, response to that particular wavelength would require minimal information processing. However, adapting to other light conditions or different substances would require new genetic codes for other molecules to absorb new wavelengths – a slow process.

Having many different wavelength receptors would enable more adaptive responding to different substances in different lighting conditions. However, that creates a different problem. Being able to sense any of those photon wavelengths from each direction would involve clusters of receptors which together would have a much larger *field of view* (p. 39). The result would be a loss of directional acuity in proportional to the increase in spectral acuity.

An alternative approach has evolved that is based on photon receptors that respond to a wide range of wavelengths. These are then backed up by information processing to distinguish wavelength.

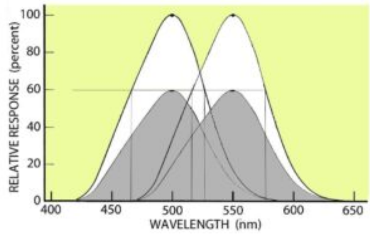
Receptors with a molecule that reacts to a wide range of wavelengths can take advantage of more of the available light at any point in an image. Reacting optimally to a certain wavelength and less to others provides a limited ability to distinguish wavelengths. But not much. Here's why:

In lots of light this receptor's response is strongest to its optimal 500 nm wavelength and less to longer and shorter wavelengths (e.g., a 60% response to 465 and 535 nm). Though 465 and 535 nm would be indistinguishable.



Furthermore, the response to these wavelengths would be the same as the response to 60% less light at 500 nm.

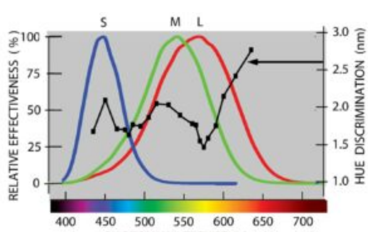
However, adding a second wide range receptor maximally sensitive to a different wavelength, does make it possible to distinguish the wavelengths to which they both respond:



The ratio of the their responses indicates wavelength regardless of the amount of light. The more precise those calculations the finer the distinction – and the more brain needed.For even better wavelength discrimination over a wider range most vertebrates (from fish to birds) have three or more types of such receptors.

However, most mammals have only two for daytimeconditions. (Why is also another story.[14]) For example, dogs have one receptor whose spectral sensitivity is veryclose to the one on the right in the above theoretical example – the other peaks at about 430 nm.

Primates and squirrels are unique amongst mammals in having three types of broad spectrum daylight receptors. (Living in trees increased the survival value of better wavelength discrimination to recognize food in distant trees. Thereby they avoid descending to the ground, where they are vulnerable, and then having to climb again.)



Based on their spectral sensitivity range, these receptors are called **S**HORT, **M**IDDLE, and **L**ONG wave-length ***cones*** – the latter from their shape:[15]

(Erudite readers never say *blue, green***,** and *red* ***cones*** lest others think that they think the cones are colored by colored photons.)

The black function shows our ability to discriminate photons by wavelength based on ***hue***.[16]

Note how the best discrimination occurs at wavelengths (480 & 575 nm) where the overlapping cone functions change most rapidly. (In these regions, small differences in wavelength result in large differences in the cone response ratios.) The average ability to discriminate differences of about 2 nanometers is consistent with our ability to distinguish over 100 different *hues*.

17. 17. ANOTHER PROBLEM WITH PHOTONS:

THEY'RE NOT COLORED!

Perhaps the most convincing evidence is the changes in hue produced by pulsing single wavelengths of light.[17] This indicates that hue perception involves a temporal code which was altered by flashing, as well as by the cone neural pathways.

Let's consider, "How could the wavelength information available from photons be made evident in a conscious representation?" That picture in our head is filled to the finest possible directional detail available in the retinal image from point to point variation in the number of photons. Adding some kind of symbol to also indicate the wavelength point by point would obscure the directional detail. Alternatively copying the auditory system, by adding some effect like"twinkling" would take time to play out, thereby reducing the speed of perception and ability to notice change.

Somehow evolution hit upon the same kind of solution physicists use when they can't explain an idea – invent a new "dimension" like *strings*. Color is an additional dimension in consciousness added to the directional detail of the internal image to represent photon wavelength point by point.

Because photons are not colored, our brain has to do it.

The wavelength information gathered by three types of cones is sent to the brain as impulses along six types of neural pathways:

RED EXCITATORY - *GREEN INHIBITORY*
GREEN EXCITATORY - *RED INHIBITORY*
YELLOW EXCITATORY - *BLUE INHIBITORY*
BLUE EXCITATORY - *YELLOW INHIBITORY*
WHITE EXCITATORY - *BLACK INHIBITORY*
BLACK EXCITATORY - *WHITE INHIBITORY*

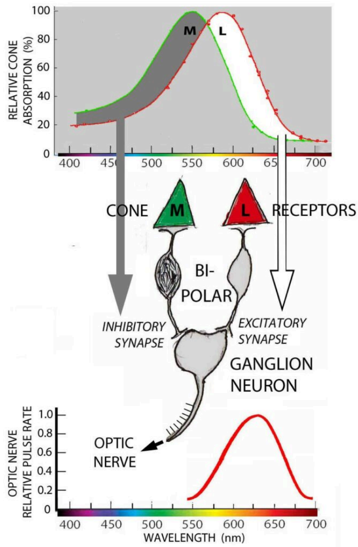
N.B. We are now referring to *pathways* in the brain where the sensations arise, and not to specific things that might be mistaken as being colored. Therefore, it is OK to use color names. (Sure beats writing "long wavelength pathways" every time – shortening to "long pathways", etc. doesn't work :)

These relatively *simple* neural computations in the retina are the first in series of steps analyzing the relative responses of the three cone receptors.

The next two figures show the basics of how these computations are done.

The ***red excitatory – green inhibitory*** calculation:

Note that the LONG wavelength cone absorbs the most photons at 590 nm which looks yellow orange. Pitting the MIDDLE wavelength response against the LONG wavelength response, results in a neural response that peaks at 625, which looks red.



Various non-mammalian animals have three or more types of receptors whose wavelength absorption curves are spread out more evenly. Therefore their systems need less processing to achieve good wavelength discrimination. As primates, we use our brain to make up for poor genetics.

Perhaps that's how we got started down that road!

Switch the excitatory and inhibitory synaptic connections around, and you get a ***green excitatory – red inhibitory*** pathway.

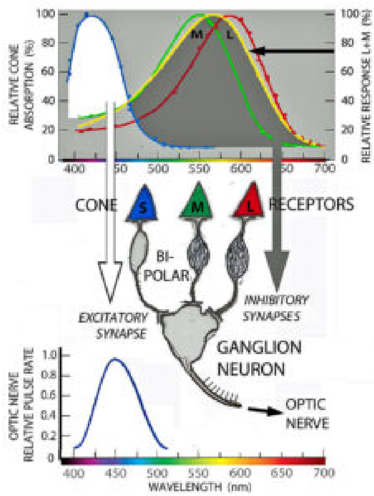
Four to go:

Here is a ***blue excitatory – yellow inhibitory*** calculation:

It explains how "yellow" comes into the picture. Both the LONG and MIDDLE wavelength cones inhibit the ganglion cell for this pathway. Note that their combined effect is strongest at the mid point between them, 575 nm, which looks yellow to us.

An excitatory synapse from the SHORT wavelength cone completes the calculation.

To get a ***yellow excitatory*** – ***blue inhibitory*** – – – . Well, you can probably guess.



Make all the synapses excitatory and you have pathway that responds to any wavelength. Even better if all the wavelengths, white light, are present at once. Thereby one gets a ***white*** pathway.

Finally, make all the synapses inhibitory and nothing happens. What good is that? Next page:

Nerves are not inactive when not stimulated. Their sensitivity makes them a bit unstable. Left alone, they irregularly release a nerve impulse, perhaps 1 or 2 every second or so on average. Yet that is also information.

The nervous system is often referred to as being "binary" – like current digital computers. But that ain't so. It is actually a trinary system:

Table 1. Neurons as trinary signal processors.

impulses per second	neuron's state	numerical equivalent
0	inhibited	-1
1 or 2 random	resting	0
> 2	active	+1

It can be just as important to know that there is no light coming from a particular direction "out there" as spotting something bright in darkness. Your reading these black letters proves that point.

However, there is more to getting a ***black pathway***.

Some neurons are so "unstable" they fire continuously unless inhibited. Cone activated inhibitory synapses on these result in a true ***black pathway*** that actively signals darkness.

Yet there is more. These *black* and *white* pathways join onto two other types of ganglion neurons with alternating excitatory and inhibitory synapses to create **white excitatory – black inhibitory** and ***black excitatory- white inhibitory pathways***. Between them the subtlest differences in shades of gray (i.e. the number of photons) become noticeable.

These two pictures illustrate how much information is added by superimposing the information available from photon wavelengths onto the directional detail in a retinal image:[18]

Note how easy it is to see the apples as well as to tell whether they are good to eat.

There is a lot more about color than its hues, but those are other stories.[19, 20]

18. 18. PHOTONS CAN FOOL YOU

As the sun sets, many of its horizontal traveling photons get scattered by water molecules in the air. Because shorter wavelengths are more scattered (page 20), an excess of the longer wavelength photos creates an image with a reddish sky. This excess of longer wavelengths also changes the light reflected by surfaces near you.

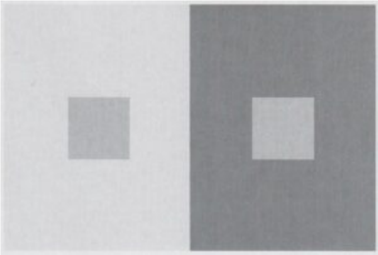
For example, consider the above apple tree earlier in the year when the apples were still green and bitter:

Believing each receptor's response to the photons' wavelength information at sunset, a simple creature might think the apples had suddenly ripened:

But we are not fooled. Processing the entire spectral scene holistically, our brain estimates the prevailing level and spectral distribution of the lighting conditions. Then automatically corrects the color balance – ***color constancy*processing**.

Lest we think too highly of ourselves, goldfish do this too.[21]

Photons can also fool you when they are measured.



A photometer will tell you that the two squares in the center are equally bright (as measured in terms of *luminance* – see page 81). How have the photons managed to fool the photometer?

Just like photons' varying effectiveness when it comes to wavelength, again the "fault is in our stars". It seems that by using holistic processing our own visual system deceived us. How come this flaw was not "weeded out" by evolution?

Actually it is not a "flaw". It reveals that our visual system has a higher priority than informing us accurately about what is "out there."

That higher priority is making us more aware of what is going on even if it means using deception to enhance details that otherwise we might not notice. (After all, we are continually fooled by all the colors we see.)In this case the visual system has exaggerated the differences in brightness to make the small squares easier to see in an otherwise dull scene – ***brightness contrast processing***.

19. 19. BEYOND PHOTONS, THE VISUAL IMAGE

Though critical, optically sorting the rays in terms of their direction of origin and catalytically sorting photons in terms of wavelength is only the firststage in seeing the world.

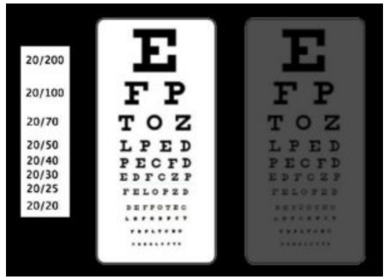
We use the greatest computer on earth to process the photoreceptor impulses evoked by photons to obtain a right side up ***visual*** image consistent with our body and other information about the world.

Once we get beyond the direction and wavelength of photons, the reach to explain the picture in our head soon extends beyond our present grasp.

Here is one example:

The effectiveness of an image (or an eye at focusing the image) can be measured in terms of how many receptors are required for its recognition.[22]

These 20/40 letters are twice as high and wide as those at 20/20:

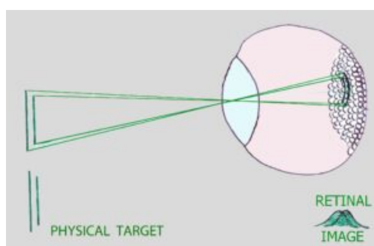


Therefore they cover 4 X as many receptors.

Decreasing the number of photons and decreasing the ratio of photons between the letters and background (***contrast***) increases the number of receptors needed for recognition.

However, there is more to acuity than the number of receptors and photons.

Receptor size would seem to determine the smallest distance between two lines that keeps them distinct. Yet matters are not that simple: Eye lenses are not perfectly clear, and the rays must pass through other cells in the retina before reaching the receptors.6 This scatters the photons so their images overlap.



Nevertheless visual testing reveals that two lines can be distinguished even though their images are closer than the width of a receptor cell.

Clues that there is more involved than the photons' effect on each receptor arises from what other photons do nearby.

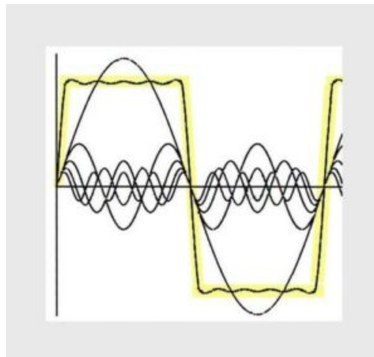
Lengthening the lines, changing their orientation, and adding more lines all help overcome the blurring of the retinal image.

There is an alternative to grabbing images point by point:

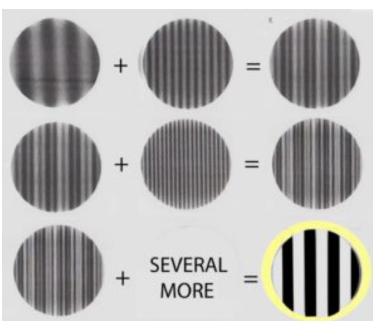
Images can also be described holistically in terms of multiple waves spread across the entire image (***Fourier analysis***).

Any pattern, no matter how complex, can be described in terms of a combination of sinusoidal waves varying in frequency, amplitude, and relative phase.

Here is how a rectangular wave can be *analyzed* into many sine waves:



Reversing this principle,a spatial rectangularpattern can be ***Fourier synthesized*** from several ***spatial waves*** of various frequencies:



It would take hundreds of "neurons" each representing a single point to encode the information in this pattern of bars. A dozen or so "neurons" each representing a certain spatial frequency do that too.

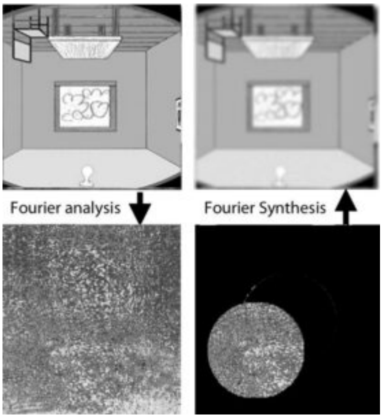
Any two-dimensional image (also 3-d images) can be Fourier analyzed into spatial frequency waves at various orientations. Here is the image of that room analyzed into its spatial frequency components in two dimensions:[23]

An image stored in this manner is called a ***hologram***.Proof that the apparent randomness (it's anything but) contains the entire image becomes evident when just a portion of the hologram is re-synthesized as shown on the right. Note that the entire image is still there – though less sharp.

Fourier analysis and resynthesis is the most efficient means of transmitting, storing, and retrieving information yet discovered.

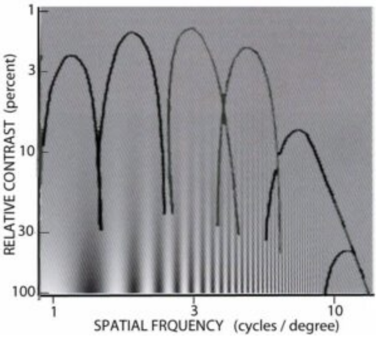
Are you asking yourself, “What do these computer algorithms have to do with biological vision?”

This efficiency led visual systems to gradually evolve neural networks that transform images into response pathways equivalent to spatial frequencies.



To start, the structure of our eyes makes them more sensitive to spatial frequencies around 3 cycles per degree than higher and lower ones. See for yourself:

This figure cascades a range of spatial frequencies horizontally and continuously decreases the contrast vertically.



Seeing the modulations higher up indicates greater sensitivity to that spatial frequency.

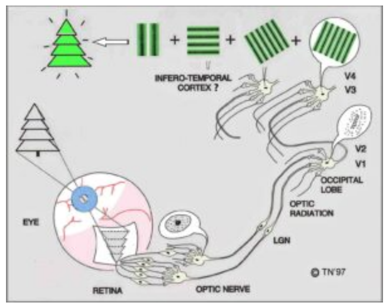
Note the decrease in contrast sensitivity at the lowest frequencies. Larger features in an image are not always more visible!

In 1969 Blakemore & Campbell published evidence of neural networks selectively tuned to various spatial frequencies in human vision.[24]

Here a representation of their spatial frequency tuning curves is laid over the spatial frequency sensitivity demonstration:

Pribram (1990) further developed the theory that our image of the world is obtained by re-synthesizing the information conveyed by such spatial frequency processing.[25]

Here is a representation from my lectures:



LGN is the *lateral geniculate nucleus*, whichrelays impulses from the optic nerve to the visual cortex.

Areas V1 & V2 and V3 & V4 are the primary and secondary areas in the *occipital lobe* that receive and initially process the information in those impulses.

The balloons depict what that neuron responds to best.

(The APPENDIX has a schematic brain diagram.)

Technology enables looking both deeper and wider at the what happens in the brain as we see the image on our retina. Yet neither the ionic impulses surging through neural networks, nor the chemical soup of released neurotransmitters, nor the myriad of protein modifications within neurons would seem to be the “picture in our head”.[26] While it must be the result of neurophysiology, the picture itself is not physical.Might it reside in the “dance” of 1 to 400 Hz electromagnetic radiation photons emitted by the brain? A simple version seems ruled out by Lashley’s (1951) experiments:

Grounding out such fields in rat and monkey brains had little effect on their behavior.[27]

Nevertheless, it seems the picture must be something like a field – one yet to recognized. To speculate on where to seek further, consider how electricity was discovered. Using the technology available in the 1700's, Galvani discovered it by studying something that was more complex than any human technology at the time – a frog. What is the 21st Century analog of a frog?

Sensory awareness is the aspect of consciousness most amenable to experimental research. While physiological probes can reveal correlations between neural activity and sensations, psychophysical methods can reveal how that activity is experienced.[16 & 28] Thus seeking how activity in our brain results in a non-physiological picture may extend the Standard Model.

So much for speculation. There remains another concern about photons of more immediate usefulness:

20. 20. MEASURING PHOTONS

The rest of this story is about ***photometry***. To do more than glance at photons, knowing a bit about measuring light can help using it more effectively and pleasantly. As Benjamin Thompson found, such knowledge can lead to a financially rewarding and fulfilling career in illumination engineering. (That's my plug for the proposed CIE course that inspired this Glance.) Otherwise, skip ahead to the **Epilogue**, and thanks for reading this far.

There are two main types of electromagnetic measurements:

RADIOMETRIC – concern physical energy

PHOTOMETRIC- translate that energy in terms of its wavelengths' effectiveness for vision based on the above CIE relative sensitivity standards (pages 51 & 52)

The measurement principles are the same for both types of measurement. Each has its own terms for the same method of measurement.

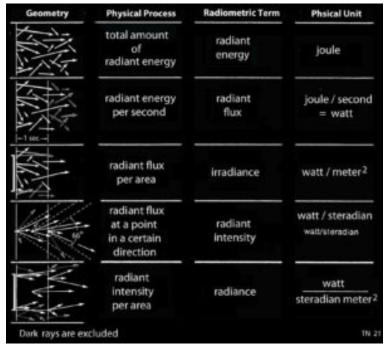
Radiometric units are based on the ***joule*** – the standard unit for defining **energy**.

Illumination engineers, architects, and vision researchers are unlikely to use these measurements – unless working on applications such as green houses, certain manufacturing processes, and certain medical aspects of radiation. Even so, they are worth a look, because they represent the physical basis of the photometric measurements..

Radiometric Units

These diagrams portray photons in various ways that they can be captured for measurement.[29]

While shown being emitted from a source on the left, these concepts and terms apply equally to radiation being received at a surface – just reverse the direction of the arrows.



Total radiant energy can be a critical factor for certain chemical reactions.

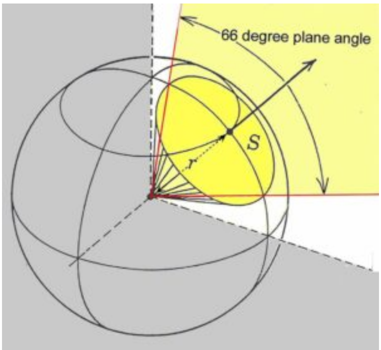
Flux describes the rate at which the radiant energy is emitted or received. The effectiveness of various radiation sources is characterized by how much flux they emit. Ongoing processes such as photo-electric reactions depend on the rate at which radiation is received.

Irradiance Whether that radiation is spread over a broad area or concentrated is likely to matter more than the total rate for processes occurring within a certain area. It tends to be used more with respect to being received than emitted.

Radiant Intensity takes into account the directionality of the radiant flux. This is necessary when the radiation is focused to efficiently apply it to a particular location. The ***steradian*** is the unit for measuring the three- dimensional specificity of direction – further explained below.

Radiance is the amount of radiant intensity emitted per unit area of a source, or received per unit area. Most sources of radiation are not point sources, therefore their effectiveness is better described by how much directional flux they emit per unit area. This applies equally to the effectiveness of radiation received per unit area of a sensor.

We tend to think of direction as linear, but being infinitely thin, pure direction lacks enough reality to actually contain any energy. A ***steradian*** is the physical measurement of direction – a 3-dimensional solid angle.



The solid angle in *steradians* of a cone-like space with an open surface area, **S**, at any distance, **r**, from the origin is the ratio of that area divided by the surface's distance:

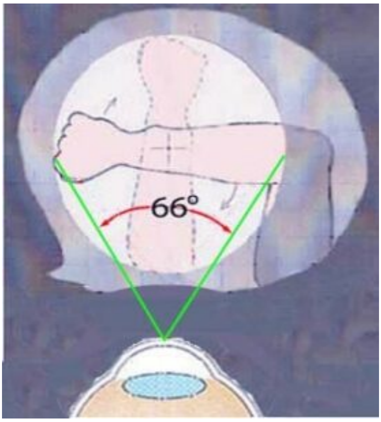
steradian = S / r^2

For a circular cone, 1 steradian always subtends a plane angle of 66 degrees.

(Steradians can have any shape as long as they comply with the above formula.)

Compared to the unit for measuring plane angles, the *degree*, the *steradian* is quite large and difficult to visualize.

This may help:

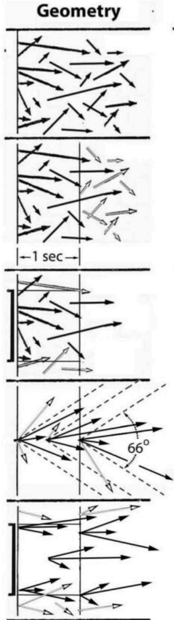


- Extend your arm straight out from one eye and close the other eye.
- Bend the forearm 90 degrees.
- Make a fist.
- Focus on the forearm’s mid-point.
- Swing the forearm in a circle around that mid-point as much as possible perpendicular to your line of sight.

The circle described by your knuckle and inside of the elbow is about the size of a steradian.

21. 21. MEASURING LIGHT 29

Luminous energy means electromagnetic radiation whose energy per wave-length has been weighted to reflect its visual effectiveness as defined by the CIE 1978 visual sensitivity function (page 51).



Geometry	Physical Process	Photometric Term	Photometric Unit
	total amount of luminous energy	luminous energy	lumen-second
	luminous energy per second	luminous flux	lumen
	luminous flux per area	illuminance	lumen / meter^2 = lux
	luminous flux at a point in a certain direction	luminous intensity	lumen / steradian = candela
	luminous intensity per area	luminance	candela / meter^2 = lux / steradian

White rays are excluded

TN 21

The ***lumen*** replaces the radiometric *watt* in these units to indicate the rate at which ***light*** is emitted or received.As explained below, the basic unit of photometric measurement is actually the ***candela***.

(On that basis the *lumen* would be replaced with *candela-*

steradian. That's not done to simplify matters and maintain similarity with the radiometric units.)

While the *watt* is defined in terms of physical energy, doing so for its photometric equivalent, the ***lumen***, is more complicated. Photometric measurements are based on a totally subjective effect – brightness. (Check back to Section 15 – Photons Vary in *Visual* Effectiveness, page 48.) Apart from correcting for visual sensitivity to various wavelengths, the experience of *brightness* involves a focused image in the eye of a beholder. That means a need to take into account that the energy is received from a certain direction.

The oldest system of measurement still in use is totally subjective: the *stellar magnitude* scale created by Hipparchus in 127 BC to describe the brightness of stars. It is still accurate because its standards, the brightness of certain stars, has not changed over thousands of years. Thus a star could be the standard for ***luminous intensity***. (While calibrations would be restricted by weather, its universal availability compares favorably to the cost and exclusiveness of the present standard.)

In the 1700's candles were used as brightness standards to enable measuring light by comparison. When candles were replaced by electric arc point sources emitting a similar number of watts/steradian at 555 nm, this quantity was named ***candela*** to reflect its history.

In 1979, the point source was replaced by a standard radiometer measurement of this amount of *radiant intensity*. In use it is aimed at a point source of light that is filtered across wavelength to match the CIE 1979 visual sensitivity function. When the radiometer reads 1.5*10-3 electromagnetic watts, the light from that source is1 candela of *luminous intensity*.

Only two of the photometric measurements are widely used:

Illuminance measured in ***lux*** (*lumen/meter* ^{2}*)*) is the amount of luminous flux arriving (or leaving) per unit area of a surface. This flux density determines the possible brightness of materials at that location depending also on their reflective characteristics. It is typically used to describe lighting conditions. However, it can also describe the effectiveness of light sources and reflecting surfaces in terms of how much light they emit per unit area.

Luminance measured in ***candela / square meter*** is the directional density of light emitted per unit area of a light emitting surface. Because it describes how light can be focused into an image, it is the measurement closest to physically describing brightness of light sources or reflecting surfaces. That's because the same photometric measurement is equivalent to describing the directional density of light received per unit area of a light receiving surface.

When light is focused as an image sensed by discrete receptors, it may be useful to describe how much luminous flux is received per receptor. Whether a biological or technological, photo-receptors tend to respond at a rate proportional to the rate at which they receive light. This would seem closest to the basis of a "brightness" signal. That rate can be measured by multiplying the luminance measurement by the pupil area of the eye (its *entrance pupil*) and the visual field of a representative receptor.[30]

Yet there is still more to brightness than how many photons meet the eye and holistic processing. The observer's state of light-dark adaptation, level of attention, and expectancy all influence the brightness experience.

22. 22. LIGHT METERS

Some instruments do both radiometric and photometric measurements. This presentation concerns the ***photometric*** instruments, which relate to human performance. Illumination engineers and most everyday applications will mostly involve instruments that measure either ***illuminance*** or ***luminance***.

Some photometric instruments can also measure scotopic illuminance and luminance using the CIE scotopic sensitivity function (page 52). Other can measure color – *colorimeters*. (There are various types, but that is also another story.[18])

ILLUMINOMETERS

These are the instruments for measuring ***illuminance*** (rate and density of light received at some location) in terms of ***lux***.

Often called "light meters", they are simple to use and relatively inexpensive. Photographic light meters are generally of this type, and it is possible to convert their exposure readings to ***lux***.[31] Illumination meters range in price from under $100 to several hundred dollars. Their cost relates to their

1. sensitivity – for use in dim lighting,

2. accuracy,
3. long term stability.

This one cost under $100 and uses two AA batteries:

Having the white sensor separate makes it easier to read without blocking the light.

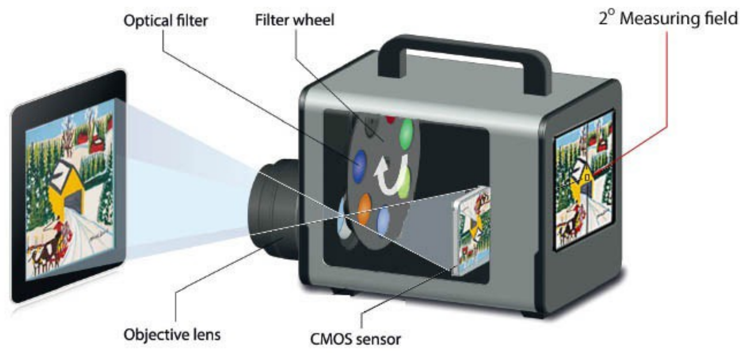
The 200 lux scale would be useful for living rooms and hallways; the 2000 scale for work areas such as offices and classrooms.

Here are some examples of various measured levels of natural illumination in ***lux***

CONDITION	ILLUMINANCE
direct sunlight	110,000
daylight	11,000
overcast day	1,100
drafting & assembly rooms	1,000
recommended classroom	300
dark day	108
typical living room	50
early twilight	10.8
late twilight	1.0
full moon	0
quarter moon	0
starlight	0
overcast night	0

PHOTOMETERS

These instruments measure ***luminance*** (the rate and density of light emitted or received from some direction) in terms of ***candela-per-meter***^{2}).



A lens focuses a light source, a display, or a surface that reflects light onto a photosensor.[32]

Instruments for general applications provide a display of the overall field of view together with an indicator for the specific area being measured.

The added complexity raises their cost to over 10 times that of illuminometers. Still more expensive models have the equivalent of a filter wheel that enables making radiometric and colormetric measurements. Costs also increase with increasing accuracy, duration of accuracy, provision for internal calibration, selectable measuring field size, and how small an area can be measured.

However, with proper arrangement of the measuring situation and a bit of math, it is possible to measure luminance with a simple illuminometer. 30

Here are the luminance values of everyday sources of brightness.

LIGHT SOURCE	LUMINANCE (*cd/ m 2*)
the sun (Do not look at it!)	10,000,000
maximum eye tolerance	6,000
60 watt incandescent light bulb	2,700
full moon	2,500
white paper in full sun	2,500
white paper under cloudy sky	1,000
white paper in drafting & assembly lighting	250
white paper in classroom lighting	75
white paper 1 meter from 60 watt bulb	18
white paper in living room lighting	12
white paper in minimal light for color	1
white paper in full moon light	0.06
dimmest visible light	0.003

EPILOGUE

How the physics of light produces images for vision is relatively simple compared to grasping what happens next. There is more to the visual image than determining where the photons came from. It is also important to know what they came from.

Part of that "what" is the shape of their source. To overcome the immediate limitations of a blurred retinal image and individual receptors, the visual system has "discovered" the physical principles of spatial holistic processing and incorporated them into its neural processing. This results in a *visual* image with acuity that surpasses these limitations by taking into account information available from all the photons in an image.

The other Part is what their source is made of. This involves distinguishing the various wavelengths of those photons. Primates have used information processing to overcome wavelength limitations of their photon receptors. Holistic processing is used to take into account the spectral information of the entire image to evaluate the response of individual receptors.

This Glance has gone from the physics of how photons dance to the periphery of the neural responses they initiate leading to vision. A bit of photometry was added to help apply some this information to practical matters of using light to improve our lives and just maybe to explore further.

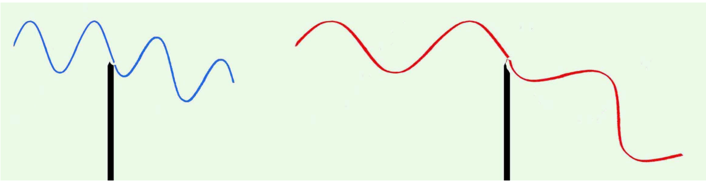
To follow this Glance further into vision, you could begin with some basics such as my "An Introduction to Neurophysiology", *International Encyclopedia of Ergonomics-2nd Ed.*, W. Karwowski – editor, CRC Press, 2006, p 412-424, or an updated preprint available on Research Gate. Before too long however, the complexity of the information processing becomes describable only in terms of operating principles discovered through years of perception experiments. Introductory university textbooks on perception can provide comprehensive coverage. (I used several editions of J.M. Wolfe, et al's *Sensation & Perception*, Sunderland, Mass.: Sinauer Associates until retiring.) There are glimmers of how some of these principles are achieved neuro- physiologically. Therein lies a real challenge. Finally, we lack even a glimpse of how all that produces the picture in your head, its colors and shapes representing things outside your body – the greatest mystery of all.

Thank you for reading,
Thomy Nilsson, Professor Emeritus,
University of Prince Edward Island

References & Notes

The figures presented here were cobbled together and modified over the years, first as overhead transparencies then as computer images. Early influences were: D. Halliday & R. Resnik (1960) *Physics: For Students of Science and Engineering*, New York: John Wiley & Sons; R.S. Longhurst (1957) *Geometrical and Physical Optics*, London: Longmans; R.H. Woodworth & H. Schlosberg (1954) *Experimental Psychology*, New York: Holt, Rinehart & Winston; C.H. Graham (Ed.) *(1965)Vision and Visual Perception*, New York: John Wiley & Sons; and T.N. Cornsweet (1970) *Visual Perception*, New York: Academic Press. More specifically to this essay are the following references along with notes:

1. p. 1 Dirac, P. (1930) *The Principles of Quantum Mechanics*, Oxford, UK: Clarendon Press, Preface.
2. p. 3 Black-body Radiation, Wikipedia, https://en.wikipedia.org/wiki/Black-body_radiation
3. p. 10 This drag is analogous to what happens as waves approach a shore. When the depth decreases to half their wavelength, the bottom of the wave slows while the top keeps going. Thereupon the top tips over.
4. p. 10 As illustrated by this figure, the longer wavelength is near the edge for a longer time. Subject to more *drag*, it bends more:



5. p. 38 A.C. Crombie (1964) Early concepts of the senses and the mind. *Scienctific American*, May, reprint 184.

6. p. 39 & 68 See Polyak, S. (1957) The Vertebrate Visual System. Chicago: University of Chicago Press.
7. p. 41 Buonanno, M.; Welch, D.; Shuryak, I. & Brenner, D.J. (2020) Far-UVC light (222 nm) efficiently and safely inactivates airborne human corona viruses. *Nature*, 10:10285 https://doi.org/10.1038/d41598-020- 67211-2 . See also David Brenner's TED Talk: 11 August 2020, Can light stop the coronavirus?
8. p. 42 Figure modified from Van Roozendael M (2016) Remote sensing of atmospheric composition. *European Space Agency*, https://earth.esa.int/documents/973910/2642313/MR1.pdf
9. p. 44 Brown, SC (1979) *Benjamin Thompson, Count Rumford*. Cambridge: MIT Press. Thompson B (1794) An account of a method of measuring the comparative intensities of the light emitted by luminous bodies. *Proceedings of the Royal Society*, IX, 67-106. Thompson did not invent this method of measuring light. Though not cited, he surely knew about the method from Pierre Bouguer's 1729 treatise on its use to measure the decrease in light by transmission through air. Middleton W.E.K. (1971) The beginnings of photometry. *Applied Optics, 12*, 2592-2594.
10. p. 51 Figure modified from: Wagner, G. & Boynton, R.M. (1972) Comparison of four methods of heterochromatic matching. *Journal of the Optical Society of America*, 62, 1508-1515, Figure 9.
11. p. 51 & 52 CIE (2004) *Photometry – The CIE System of Physical Photometry*, CIE S 010/E:2004, Vienna: Central Bureau of the International Commission on Illumination., US$70 (PDF download available). Lists of the correction factors by wavelength are available in various sources, e.g. Wyszecki, G. & Stiles, W.S. (1982) *Color Science – 2nd Ed.*, New York: Wiley.
12. p. 52 Figure modified from: Hood, D.C. & Finkelstein, M.A.

(1986) Chapter 5, Sensitivity to light. In *Handbook of Perception and Human Performance; Volume I, Sensory Processes and Perception*, K.R. Boff, L. Kaufman & J.P. Thomas (Eds.), Toronto: John Wiley & Sons, -p. 5-1 to 5-6, Figure 5.9, p. 5-10.

13. p. 52 CIE (2016) The Use of Terms and Units in Photometry: Implementation of the CIE System for Mesopic Photometry. CIE TN 004:2016, Vienna: Central Bureau of the International Commission on Illumination.
14. p. 56 It is an amazing story. First read: Jerison H.J. (1991) *Brain Size and the Evolution of Mind*. American Museum of Natural History, New York; then: Bowmaker, J.K. (1998) Evolution of colour vision in vertebrates. *Eye*, *12*, 541-547.
15. p. 57 Figure modified from Wald G (1964) The receptors of human color vision. *Science, 145,* 1007-1017.
16. p. 57 & 73 The wavelength discrimination function is from Nilsson T.H. (2020) What came out of visual memory: Inferences from decay of difference-thresholds. *Attention, Perception & Psychophysics*, *82*, 2963- 2984.
17. p. 58 Nilsson, T.H. (1972) Effects of pulse rate and pulse duration on hue of monochromatic stimuli. *Vision Research, 12*, 697-712.
18. p. 63 Apple tree picture is from a Home Depot web page: https://www.homedepot.com/c/ah/how-to-grow-apples/9ba683603be9fa5395fab901f33a6977
19. p. 63 & 82 An introductory university text on perception (see the Epilogue) is a good start. Kaiser, P.K. & Boynton's, R.M. (1996) *Human Color Vision. 2nd Ed.*, Washington, D.C.: Optical Society of America, has been the authoritative technical source.
20. p. 63 For a look at artistic possibilities of just hue, see Quiller, S. (1989) *Color Choices*, New York: Watson-Guptill.
21. p. 64 Ingle, D.J. (1985) The goldfish as a retinex animal. *Science, 227*, 8 Feb., 651-654.. Fish also don't want to misjudge the presence of predators and food as light

changes with time of day or the weather.
22. p. 67 Nilsson, T.H. (2001) Evaluation of target acquisition difficulty using distance to measure required retinal area. *Optical Engineering*, 40, 1827-1834.
23. p. 70 The hologram in the figure is not of the pictured retinal image. It just illustrates the principle.
24. p. 71 Blakemore, C. & Campbell, F.W. (1969) On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *Journal of Physiology*, *203*, 237-260.
25. p. 72 Pribram, K.H. (1990) *Brain and Perception*. Hillsdale, N.J.: Lawrence Erlbaum Associates.
26. p. 73 For example: Jibu, M.; Pribram, K.H. & Yasue, K. (1996) From conscious experience to memory: Storage and return of quantum brain dynamics and boson condensation. *International Journal of Modern Physics – B, 10*, 1735-1754.
27. p. 73 Lashley K.S.; Chow, K.L. & Semmes, J. (1951) An examination of the electrical field theory of cerebral integration. *Psychological Review*, *58*, (2) 123-136.
28. p. 73 Graham, N. V.S. (1989 Neurophysiology and psychophysics. In *Visual Pattern Analyzers* , Oxford: Oxford University Press, p.3-34.
29. p. 75 & 79 Figures modified from: Nilsson, TH (1983) Incident photometry: specifying stimuli for vision and light detectors. *Applied Optics*, 22, 3457-3464,Table 1, p. 3460.
30. p. 81 & 85 Nilsson, T.H. (2009) Photometric specification of images. *Journal of Modern Optics, 56*, 1523- 1535.
31. p. 83 Long, W.F. & Woo, G.C.S. (1980) Measuring light levels with photographic meters. *American Journal of Optometry and Physiological Optics, 57*, 51-55.
32. p. 85 Figure modified from: Instruments Systems, LumiCam 2400B brochure – https://www.instrumentsystems.com/en/products/imaging-colorimeters-ir-testing-cameras

APPENDIX

A Schematic Diagram of the Human Brain

(*Not recommended as a guide to brain surgery.*)

Our central nervus system evolved from successive additions of more neural tissue at the front end of a spinal cord to improve motor control and to increase the processing of sensory inputs.