Scientific Facts for You

All light sources make photons in specific ways. How each type of luminaire physically works determines how useful it is in any application. The physics controls the output. That spectral output in visible light impacts the presentation (what beauty is seen or hidden) and preservation (the damage rate).

Fast facts are brief articles designed to arm you with information.

Learning accurate data about LEDs is particularly difficult, yet very beneficial. The internet, sales literature, university lectures and lighting industry articles are packed full of quasi-science, misstated facts and frankly confusing descriptions of how these lamps actually work. Knowing the science based in marketing fails to provide the tools to sort LEDs. And sorting LEDs is critical. Products vary from good performance to outright garbage light sources. Reading this WHOLE article will let you sort LEDs for quality, durability and performance, teach you how to buy wisely and how to know when to use LEDs and when to definitely avoid using this semi-new technology.

LED = Blue Pump Phosphor Lamp

All **light emitting diode** lamps (LEDs) that produce white light instead of a single indicator color (but a white light that is not tristimulus RGB) are “blue pump phosphor” sources. **All of them.**

The lamp takes electricity, flows it through a diode, pairs electrons into photons which are blue wavelength photons…really, really it-hurts-your-eyes **blue** light…and then uses phosphors to convert that blue light into white light.

To say it again…a diode “pumps” blue light through phosphor. Even the best light-quality “white” LEDs are naturally cool white. A LED that is slightly blue instead of very blue is harder to make, more expensive and not as energy efficient. But it is still blue.

Electronic Basics about Diodes

Semiconductors are the foundation of modern electronics. A diode is a solid-state, semiconductor circuit that lets electricity pass as a free flow in one direction. That same diode will block the electricity from going the opposite direction. The electricity flows one way.

This means electrons move easily through the material of half or “semi” the circuit or “conductor”. Electrons are semi conducted. The diode works because the other half of the circuit will not let electrons flow, but will back them up.

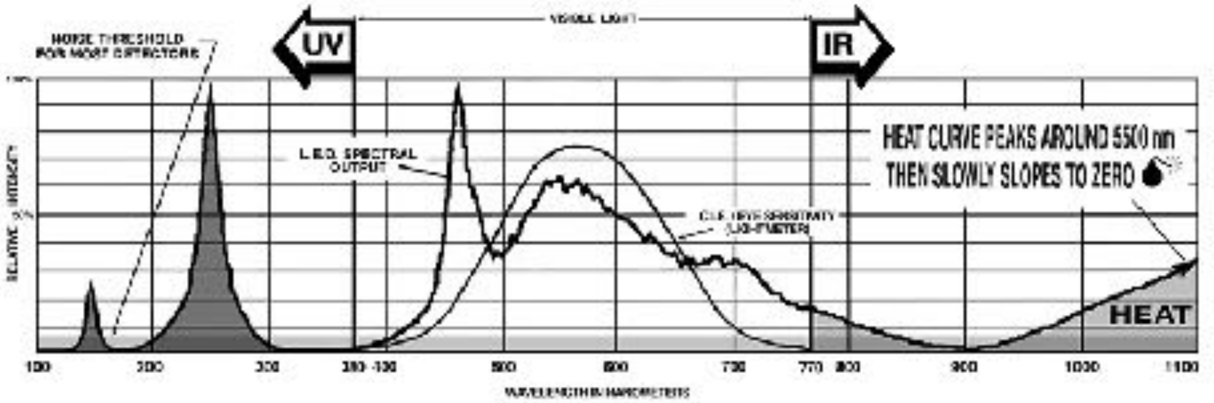
The circuit uses this flow and barrier combination to build a negative charge on one side and a positive charge on the other at an interface. Where the charges meet, thin layers of materials or even patterns of materials can be added to manipulate the electrical charges to do something.

Diodes are used in all sort of applications and are produced in mass. Many diodes cost pennies instead of dollars. LEDs are light emitting. But they are still diodes. Therefore, there is an effort to rename LEDs as light emitting DIODES and instead call them light emitting DEVICES. Devices are more complex. Devices can demand higher pricing.

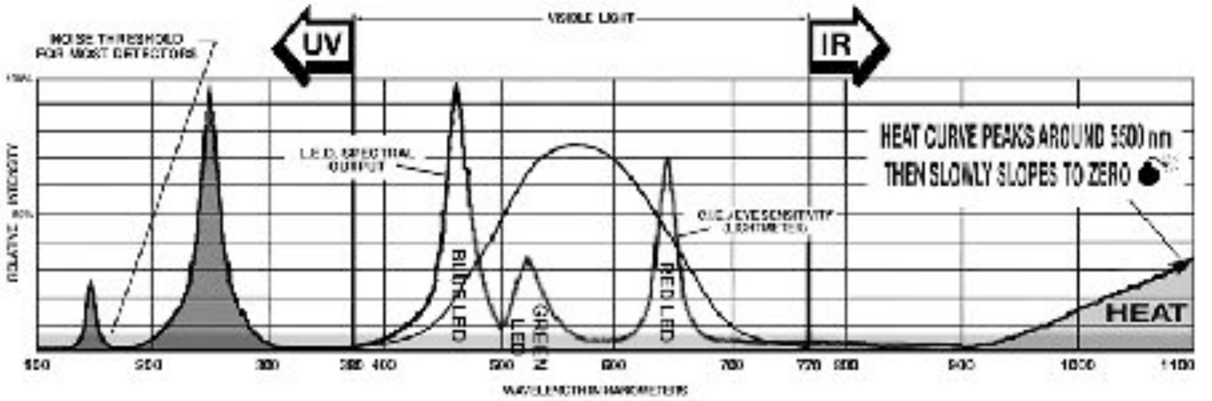
How a LED Lamp Works

A diode is made of two thin pieces of semiconductor material doped with a very thin layer or layers of chemicals in the middle. One half of the circuit easily conducts electricity. The other half or side resists. At the middle intersection of the sandwiched material, electrons from both sides of the material combine at the interface into photons (light).

Different semiconductor materials with different coatings (chemistry) and different layering techniques in the center make different wavelengths as a single probability curve of color. LEDs designed for white light produce blue light. Blue light does a better job of stimulating phosphors to create other colors. The industry describes blue as having a “greater emission power.” The output of a well-designed and well-manufactured LED using high-quality phosphors looks like this.



The photons exit through a mechanical slot cut at the gap or through into the gap. If the LED is for a mono-color application or the LED is actually three LEDs as RGB blended to make white light. Many of these LEDs have little or no phosphor. The output looks like this.



LEDs manufactured as a white light source to replace others choices in lighting all use a coating, layer or layers, or a specially spaced film that the photons encounter. This is an area of phosphor. It further spreads the light as it is blended into a white by mixing in other colors created by the phosphor.

The blending happens as a surface emitter. Therefore, the output of a LED is never tightly focused. LEDs are small.

But optically they tend to spray light in a general direction. Some LEDs emit light from all four edges of the circuit. But most LEDs have the output from the diode directed by the slot, and then the light is further spread by the phosphors in the coating. This means the optical control is poor compared to the tighter aim provided by filament sources.

Using LED terms, the two layers of material are described as a P-type (P for positive) semiconductor with ”positive” holes; and a N-type semiconductor (N for negative) with “negative” electrons. Since the diode only allows flow in one direction, the electrons with their negative charge are crowded towards the interface or doped center of the sandwich between the two layers. This interface is called a “gap”, an “empty space”. “a valence gap” (valence? like in how atoms combine or displace particles in chemical reactions), a “space absent of holes” or a “space to inject carrier holes.” Note the uncertainty in the science.

On the other side, in the second piece of the sandwich, are the holes. The LED description is that holes are the “absence of electrons” and are positive. In the P-type material, holes move the opposite direction of the diode’s electrical flow.

The holes randomly connect with the negative “free” electrons (electricity is the flow of free electrons) giving off energy as a color of light. As mentioned before, the mechanical slot or physically drilled, literal hole (as opposed to the positive electronic holes in the P-type material) lets the light escape from the middle of the two layers at the interface.

Different materials for the layers create different results. Different chemicals used between the layers further separate and determine performance. Tolerances are vital. The gap’s width also impacts the color and the efficiency of the light source. Then phosphors, what types, how the diode is doped, how well it matches the blue light, how thick, what pattern or how it is layered down, etc. control the output as well as the light quality. Encapsulate the diode with some sort of cover and this is the complete “light packet” as a LED.

Keep Reading! Arm Yourself with What Is Taught About LEDs

LED explanations talk about grouping holes and electrons in clusters, claiming the material traps or holds them until there is a build-up at the PN junction. The semiconductor material has “molecular spaces” that act as holding pens until enough holes and enough electrons are collected closely enough to each other to combine.

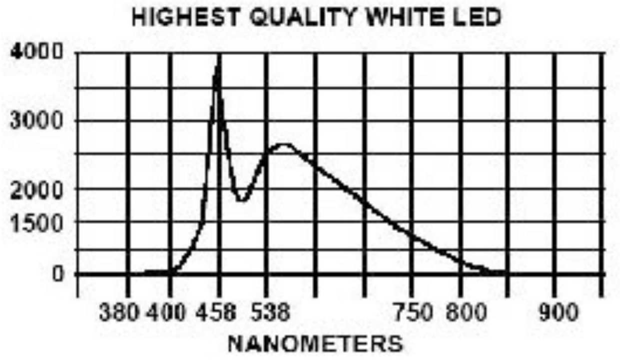
The hole has a “highly-excited energy level”, because of its neighboring holes. With nowhere to go, the hole finally gets crowded into the gap. It encounters a “carrier” electron that is free with no orbit around an atom.

The hole drops its excited level as energy in the form of light. No longer excited, the **hole** and electron REPEL (but isn’t one positive and the other negative?) with the hole balancing back to a “normal rest state” defined as “being absent of electrons.”

The blue light created has a much higher level of energy. (This is not true, but a common belief.) Blue light has “great efficiency.” (Again, not true, but often taught.) So the blue light is more ideal for pumping through phosphor and converting it to other wavelengths. (True, but not because of higher energy.)

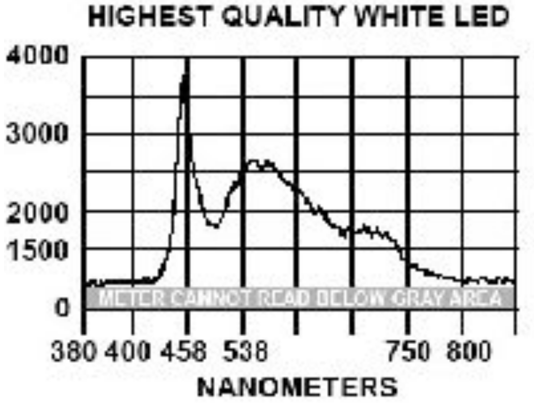
Creating blue from a diode was the great breakthrough in lighting. LED manufacturers claim that these new blue pump phosphor LEDs will have a big impact. (True.) But they also claim LEDs are ideal for every kind of application and superior for the environment as LEDs always save more in energy. (That is marketing puffery.)

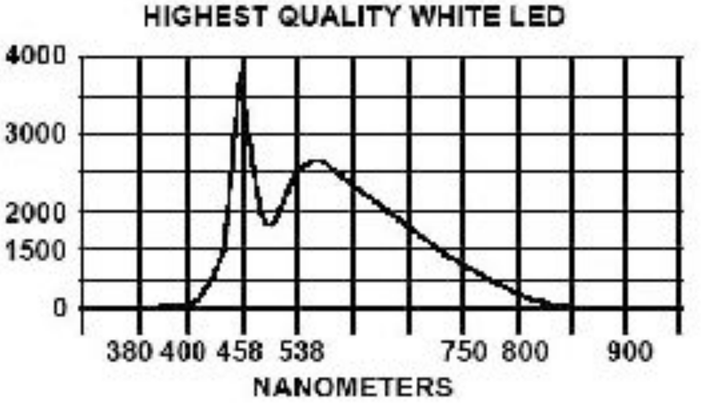
With the industry's intentional focus on the visible spectral output, the data published is for visible light only. You see only the spectral output. No, that needs to be rephrased. You see a simplified, "visual spectral" distribution for the lamp. The tall output spike of blue can move slightly left or right on the graph depending upon the LED's manufacturer. But the edited curve looks like this. And this curve is used everywhere.



To be fair, manufacturers state it is only visible light. Notice how the curve drops to zero at 380 nm where UV light starts. And it goes to zero at 800 nm or 850 nm. IR begins at 770 nm.

Some technology driven manufacturers of just the emitters or "LED light packets", opposed to the manufacturers of whole lamps or light fixtures, show a curve like the one on the left compared to the familiar curve on the right. The left curve is more accurate. The curve on the right is the popular one we talked about earlier.

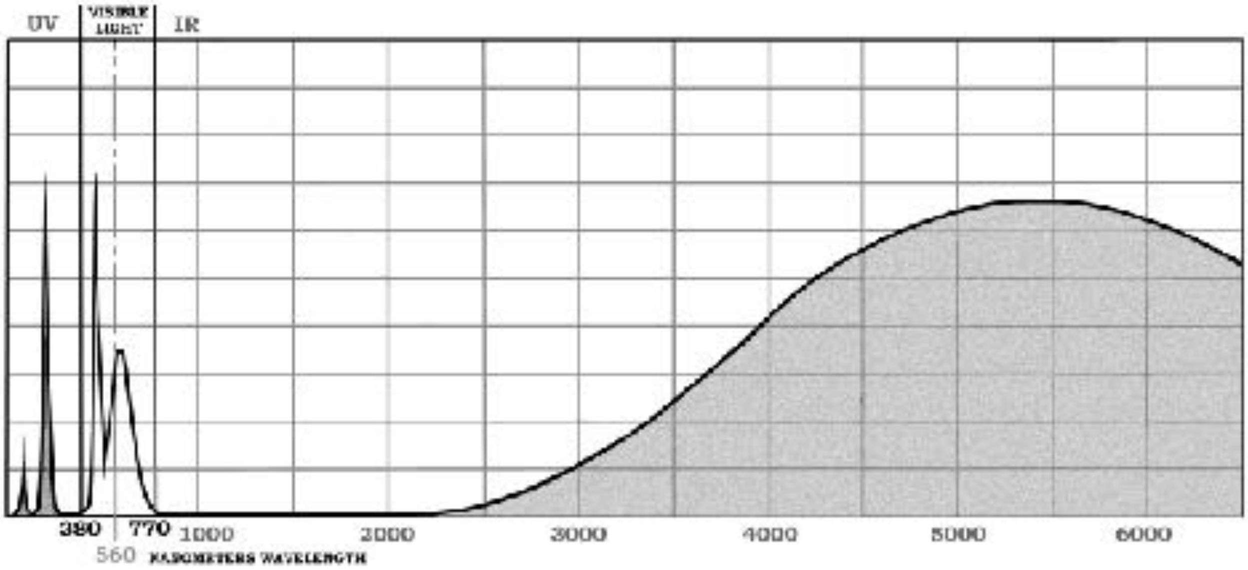




First, look how the more accurate curve does not go to absolute zero. There is a threshold. This is where the meters used to collect this type of data cannot read. Many light detector equipment and light meters have problems accurately reading or not reading very low light levels including UV and infrared meters. There is a threshold where data is nonsense. This has to do with how the meters work internally.

The popular curve assumes data that does not exist. It automatically drops data below the threshold to zero. This is intentional.

It looks like the LED has no output past the visual spectrum. Some of these curves will end in air where the output data just stops. But many published curves today complete the curve to zero. Marketing will tell you the reason is that a floating curve is disturbing or a threshold is to complicated to explain to customers. But the motive is to allow sales to claim that LEDs are without UV and without IR. The graph below shows in gray all the light or energy outside the visible spectrum. This curve shows the data missing in the popular curve. This curve is rarely seen.



Top-quality LEDs add an acrylic filter to the encapsulation above the phosphor to filter out the UV. Cheaply constructed LEDs don’t. Or they use an inferior filtering plastic like styrene. The UV content. If not filtered, this UV can be very harmful.

So some LEDs are without UV. Some. But all LED sources have heat.

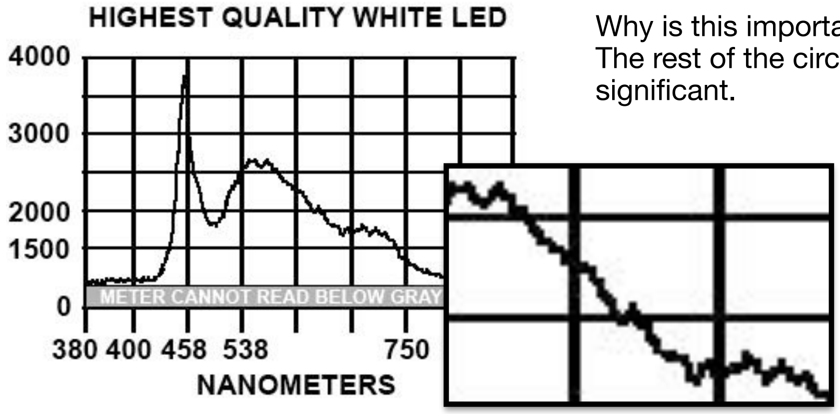
That heat effects the operation of the lamp. This missing IR in the explanation of how a LED works is an unaccounted critical part of LED design. The diode gets hot. It radiates infrared light. The PN junction makes more than blue light. It also makes UV and IR. The content is in the LEDs beam. And the PN junction expands the diode’s materials. The effects function.

So heat sinks, free air operation, micro-fans buried in a lamp’s housing and cycling the LED on and off to cool are key to making a LED work. The diode will burn out without heat control. The circuits that drive the LED fry. LEDs have claims of long life. But if driven hard to produce footcandles, the diodes have IR obstacles that greatly reduce lamp life in the field. The industry has had a chronic problem with premature lamp failures.

Therefore, heat sinks are part of the engineering that make a LED work. But heat sinks require mass. LED lights consume a great deal in materials and energy to manufacture.

An ordinary light bulb wastes energy as it operates. But it is thrifty in materials and energy to make, ship and dispose of. Therefore, there are a lot of questions about how green LEDs really are overall. Sometimes LEDs save a lot of energy. Sometimes LEDs requires so much energy to manufacture that they consume more energy than the save. Overall they are less energy efficient than other choices in lighting.

Now go back and look at the visual spectral output curve. Note that the accurate curve is not clean or smooth. The line is ragged. The circuitry that controls the flow of electricity into the diode fluctuates the light’s output.



Why is this important? *LEDs are input sensitive.* The rest of the circuit that drives the LED is significant.

If the input (the electrical flow into the diode) is not right, the output gets more and more sawtooth and varied. Load too many LEDs into one space and it can set up electrical feedback. Have the wrong lighting controls? The output can be erratic. Marry an old LED system into new software driving the input, and the light output can be too irregular. The lights can flicker. Most of the time LEDs work fine. But if input becomes poor, humans notice this lack of smooth output when it's aggressive. The light bothers people. It causes eye fatigue. It can even give us headaches.

Diode Lamp Life Verses Phosphor Lamp Life

How a LED works also changes over time. LEDs have the marketing luxury to claim predicted or calculated lamp life. Predictions are long. But, in less than twenty years, LED predicted lamp life has shrunk from 100,000 hours to 80,000 hours to 65.000…you get the idea.

Today the predicted lamp life is 35,000 hours to 24,000 hours depending upon the manufacturer. However, you will find LEDs in the field that have failed in just a few years and some with shorter lamp life than a typical halogen lamp life of 2,000 hours.

Blue light is directed by the slot and "pumped" through the phosphor. This slot erodes. It gets bigger. The blue light has less aim. The LED is less effective.

That inefficiency converts into infrared photons. The LEDs operating temperature climbs. The lamp gets hotter. The circuits controlling the semiconductor or the semiconductor itself fails.

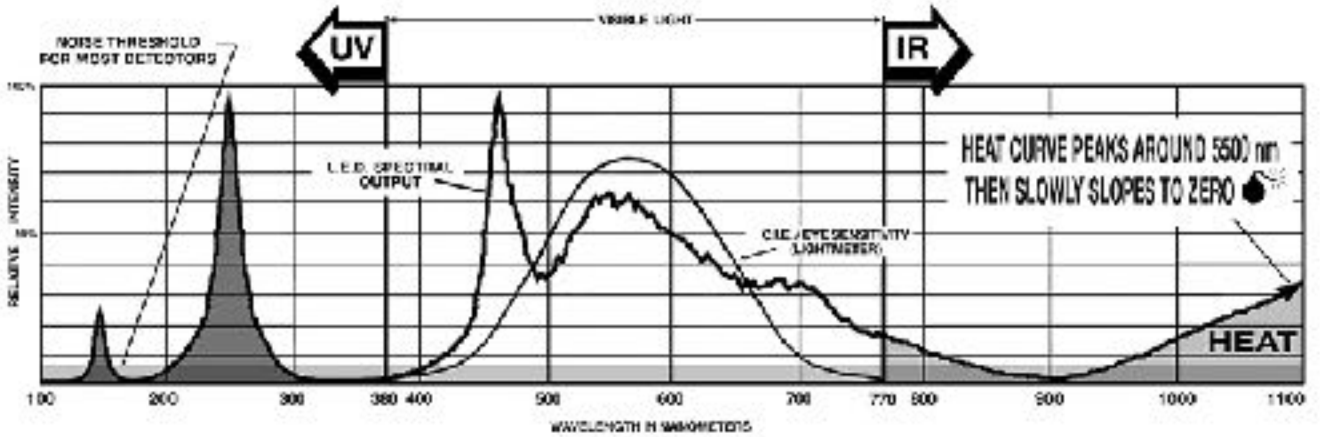
This is why LEDs use heat sinks, fans and can requirer free air operation. But it is also why manufacturers state the LED's lamp life is high. The LED never fails in a few thousand hours. The LED works. It is the circuitry that failed. And the circuit does not count in lamp life calculation even if the lamp emits no light.

The point is, over time, the phosphors always degrade. They literally get consumed by the photochemical processes. So LEDs grow dimmer. The circuitry grows hotter.

An older LED is half as bright. Good quality LEDs offer long lamp life. The diode survives. But the light output in footcandles can drop by 1/3 or 1/2 in less than two to three years. That is a 33% to 50% loss in light.

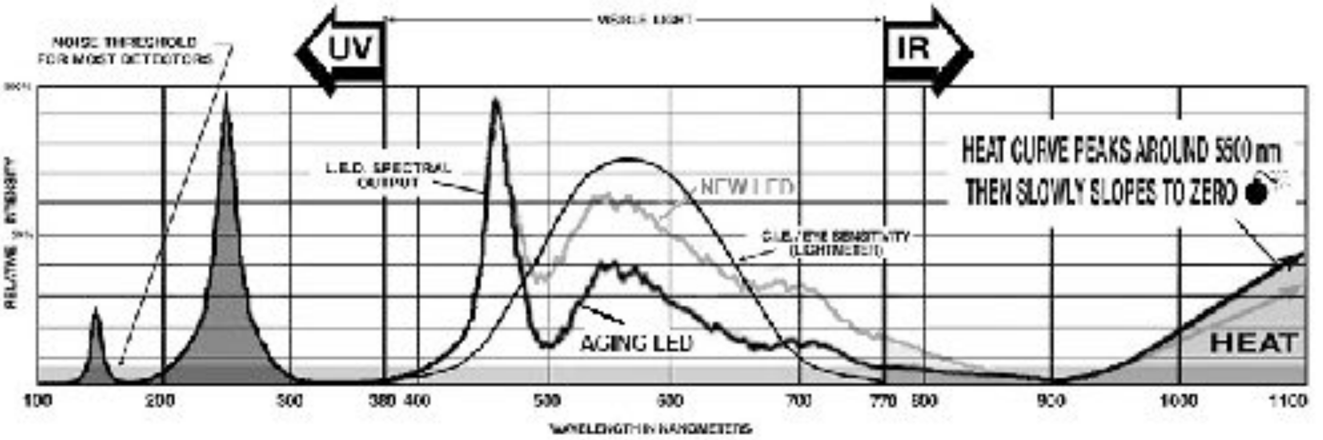
The slot growing in size as it wears away its sides helps as the blue light is spread over a wider area of phosphor. So the lamp tends to stabilize at the half footcandle level and then ever so slowly gets dimmer over the remaining operating life. That is, if the heat does not get too intense to destroy the LED's circuit.

A brand new, out-of-the-box, good-quality LED's output looks like this.



Pay attention to the stipulation. This is the performance of a very good-quality LED. There is a lot of marginal and poor product on the market. This is top performance.

A few years later that same good-quality LED's output changes to this.



Comparatively, the blue output hasn't changed much, because more of the LED's photons created at the PN junction make it through the phosphors without converting to other colors of light. The ultraviolet is not really effected. The best LEDs filter the UV. So the UV should be no concern. Of course, the infrared output rises and so does the lamp failure caused by internal heat.

If the lighting design takes this degradation into consideration, beginning installations are overly bright. They are full of glare. This is why dimming LEDs has become so important. But the design has a harder time passing the energy saving calculations for the building. More lights and controllers are used.

If the lighting design ignores the fact that LEDs loose footcandles in a short few years, the light levels may not be high enough over time. The degrading happens. It is inevitable. Once the phosphors are gone, it does not matter if the diode still works. The LED needs to be replaced. Technically the lamp has many more years of lamp life left. But practically, the lamp is just as worthless as if it produced no light at all. The installation is too dark.

How a LED Lamp Really Works

If you have not figured it out yet, “holes” in the P-type semi-conductor do not really exist. Holes are a term trying to explain the quantum physics (actually quantum electrodynamics or QED). LED scientists, many of them brilliant, define light as energy. It is a wave and a ray. Light is never presented as what it really is…particles.

If you would like more information on photons, go back to the home page of the web site and at the bottom of the page by the space shuttle image is the question: What is light? Click on the word, light, as it is a link. Read all three short papers on the science of light.

The holes are positrons. They are not an absence of electrons. They are electrons! They are just spinning backwards.

They are the anti-electron. And they make the world go around as part of the crown jewel of physics…that things like light are particles and that electricity as a flow of electrons can have electrons shifted into positrons to make photons. That same light changes the positrons back into electrons to create a flow of electricity. (How meters, solar panels, etc. work.)

It is the same physics. It is electrons (electricity) combining to become photons (light). It is photons (light) dropping their couplings to become electrons again (electricity again).

What is really happening? How does a LED ***really*** work? Let’s go back to the start.

Remember, a diode is made of two thin pieces of semiconductor material doped with a very thin layer or layers of chemicals in the middle. One half of the circuit easily conducts electricity. The other side resists electrons.

What is left out of the description is that semiconductors are made of atoms with an exacting, perfectly spaced structure. This atomic spacing becomes even more specialized as the atoms are stable, or at rest, with extra electrons or even missing electrons.

The atom does not care if its outer valence ring is missing (has a hole to fill) or if it is full and won’t accept more. Then to make the material even more specialized (which is why inventing “white light” blue LEDs has been so difficult), close to the atom’s nucleus are electron orbits that are not tightly bound. Excite this type of atom enough and an electron will escape out of the center rings as the outer valance ring is too agitated to respond.

Science on the Side

Light is made up of photons. Photons are two-particle systems. The electron links with a positron, a spinning backwards electron, with the distance between the particles, the diameter, establishing the wavelength in nanometers. This wavelength is also described as frequency.

As far back as the 1920’s, Paul Dirac discovered a key equation that started to unlock atomic theory. The math produced a negative AND a positive answer. So light was discovered to have two particles, a negative one and a positive one.

Physicist Nick Herbert summarized it this way. “A more recent example of the fertility of applied mathematics is the case of Dirac’s equation for the electron. When Paul Dirac solved this equation, he got not one solution, but two. Taking the extra solution seriously, he predicted the existence of a new particle - the anti-electron, or positron - with charge and spin values opposite the ordinary electron.”

The genius physicist, Richard Feynman, just a few decades later proved Dirac’s conclusion. There was asymmetry between positive and negative energy. Author James Gleick stated it this way in the book, Genius*, about Feynman. “The collision of an electron with its antimatter*

Different semiconductor materials have different atomic structures. But let's simplify to a single electron that likes to orbit its atom in the outer shell. The neighboring atoms are on all six sides as the atoms are a volume with XYZ axises. The neighboring atoms are the same. They are close enough to share the same electron.

The atom we are focused on will have this outer electron leave and circle its neighbor. Then, as all these atoms are in motion, the electron will come back to its original atom. All the atoms are content to share, loose an electron to a neighbor or pick up a spare electron from another neighbor. The structure is stable. There is no chemical change happening. But holes open and close depending upon if the shared electron is there or not.

Think of it another way.

Picture a big military unit doing jumping jacks on a field in perfect rows. Every soldier has enough room to be active without touching or impeding the soldiers around him or her. But there is just enough room, if the soldier wants, to toss a sweat towel to a neighbor, front, back or sideways. A fellow soldier is that close.

The electron is like the towel. Some solders have a towel. Some have two or more. Some have none…a hole for a towel.

No one cares. The soldiers are like the atoms sharing outer electrons. The tosses might be untidy, just like electron orbits are usually messy; but the formation holds.

However, start throwing towels into the formation and once all the soldiers have two towels, they've had enough. The over abundance of towels get tossed back to the thrower that is outside the unit. The structure is full. Towels end up flipped, kicked, abandoned on the ground…it is towel chaos.

The semiconductor works the same way. The N-type semiconductor (N for negative)

Science on the Side Continued

cousin released energy in the form of gamma ray(s)…nothing more than high-frequency particles of light."

Because Richard Feynman is being discussed, note this quote from the book, QED: The Strange Theory of Light and Matter, *written by Feynman. "The cycles of reflection repeat at different rates because the stopwatch hand (measuring spin velocity) turns around faster when it times a blue photon that it does a red photon. In fact that's the only difference between a red photon and a blue photon (or a photon of any other color, including radio waves, x-rays, and so on) - the speed of the stopwatch hand."*

The diameter distance between the two particles is the only difference between blue light and red light. As the particle system travels at light speed, the blue photon takes more revolutions. Its spin diameter is smaller. But it has the same mass, the same energy, the same forward speed and the same structure as red light.

Again, Richard Feynman writes in QED, "I want to emphasize that light comes in this form - particles. It is very important to know…every instrument that has been designed to be sensitive enough to detect weak light has always ended up discovering the same thing: light is made of particles."

The point is that there are no "holes" in applied quantum electrodynamic theory, the crown jewel of physics.

Holes are a lighting industry answer to "why" LEDs produce light. But it is a fabricated construct for simplification. It is not fact.

This convenient ignorance lets LEDs state marketing benefits that are not true without repercussions; because the science about photons is nebulous. LEDs claim the light is not damaging. False. LEDs state there is zero heat. LED IR content is 72% to 75% heat. LEDs claim deep blue light is always safe. Not true for artifacts and can even be untrue for humans. LEDs state the energy savings are automatic. Again, false.

Know the science. Keep reading about LEDs here. But for details and references about QED, see the pdf on this site, "Light and Matter: the Dangerous Romance."

fills up with electrons (towels). But it has a flow. So the extra electrons flow through from atom to atom, but stay free and unattached.

The soldiers work in sync. The spare towels are all tossed from soldier to soldier and out the other side of the formation, because there is a big receptacle at the other end that accepts towels. The laundry bin has a sign on it that states, “Spare Towels Here.” The formation is designed for towels to enter one end and exit the other end.

No one steps out of line. The electrons flow to the end gathering at the gap or PN junction. The circuit flows. The electrons shift fast enough through that there are alway atoms with unfilled electron rings or space to except more electrons from the direction the towels are coming in. There is flow. There are even holes or open spaces. Some soldiers get out of timing and are without a towel for a fraction of a second. This is why the design of a LED’s circuit is so important. The electricity has to be controlled within tight specifications.

For the P-type (P for positive) semiconductor with ”positive holes”…well, no holes and they are not positive. The P-type semiconductor has electrons. It has the same spaced atoms.

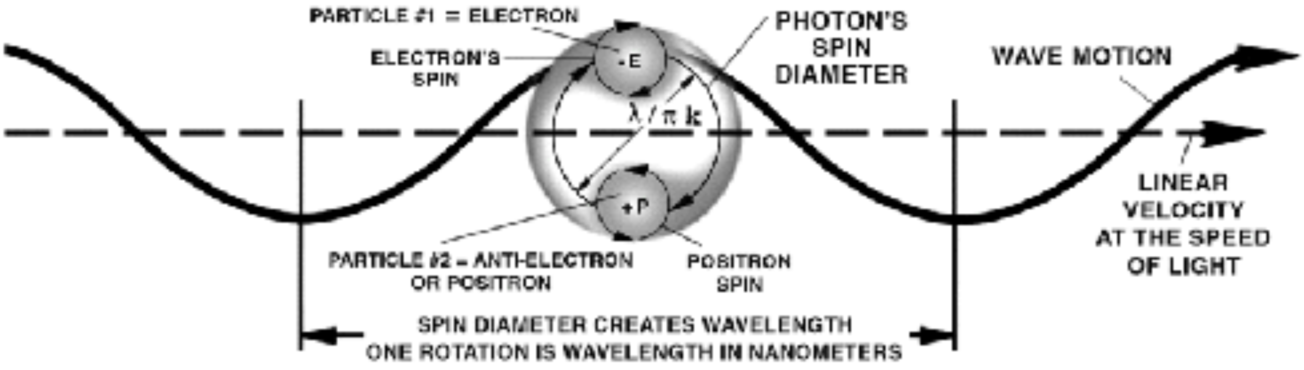
But these electrons gather at the entrance finding a dam. The soldiers form a barrier. Towels are not allowed in, because the soldiers are content with the number of towels they are sharing with each other and the first line of soldiers all have two towels which is more than any soldier should need or want.

Electrons from the flow of electricity try to find any place to fit. But as a whole, this side of the diode rejects the electrons. Towels get tossed in. But immediately kicked out or sideways in the formation or anywhere a towel might go. The migration of electrons is not allowed. The flow is blocked.

But more and more electrons are cramming in and piling up. The electrons are getting pressured from behind, even pushed into the structure. Electrons crowd from the back. So the lead electrons force past the atoms’ negative electrons in their orbit.

There is no room. The free electrons are so blocked that they skid around, bump, avoid other electrons and as they crowd into the gap at the interface, the electrons swap ends. Hitting the gap or interface was the last straw. The electrons start spinning backwards. They skid like a car swapping ends. They turn into positrons at the PN junction.

What happens? You get this. Light.



The worst of the crowding for both sides happens at the interface or the gap. So the odds favor positive charged positrons and negative charge electrons combining at the PN junction. As electrons and positrons are attracted to each other, they pair up. This bleeds off electrons that race to the gap as “holes” open up.

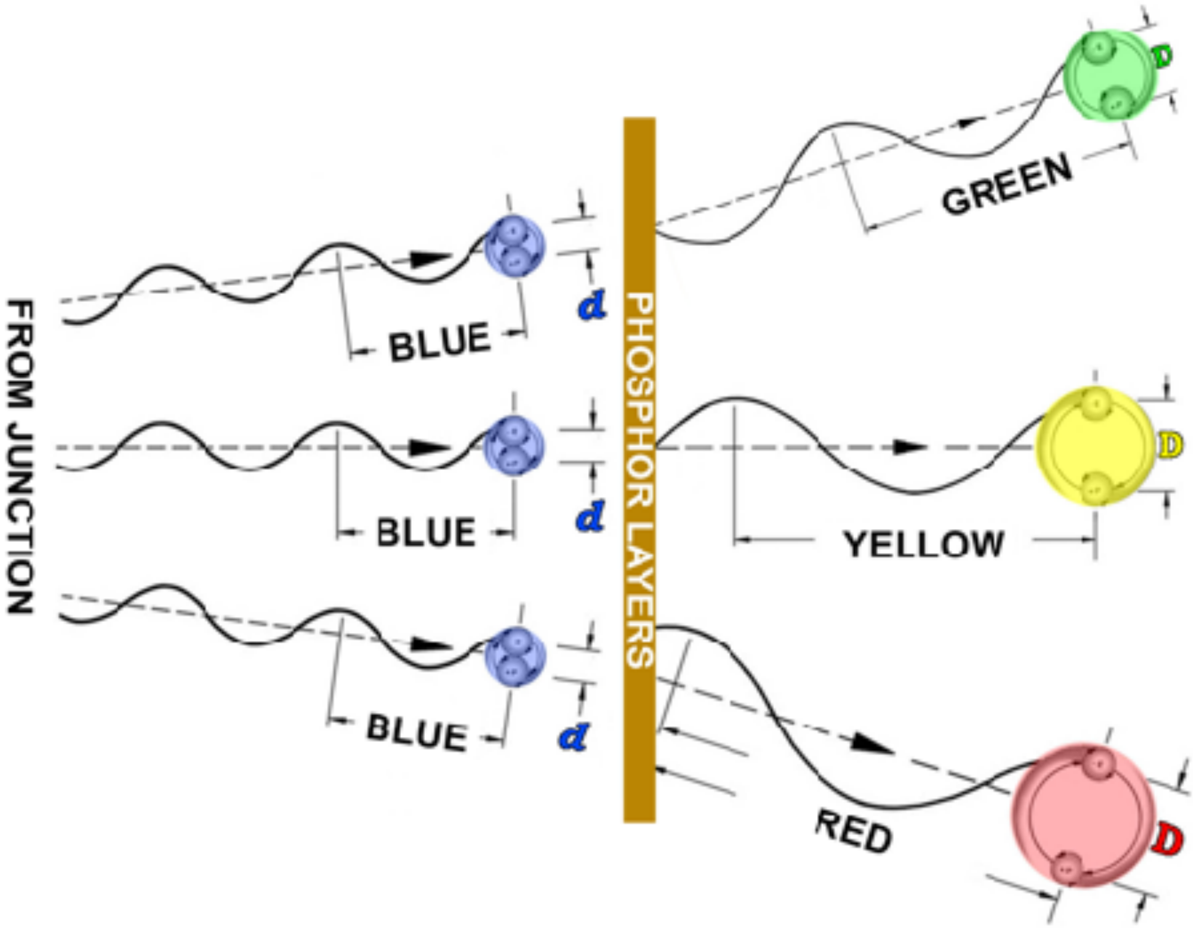
Remember those added chemicals as doping or patterned layers at the PN junction?

These atoms have specific orbits that favor linking the electron and positron at a certain distance. The wavelength, the color of light, is heavily influenced by the doping. The interface’s chemicals are designed to make blue light.

The electron swings in an orbit around the nucleus that attracts the positron into a mirror of the motion. Inside the doping, the pair is influenced by other orbiting electrons which push the pair into a certain distance. They combine. The distance between the particles are set by the chemistry of what was put between the semiconductor sandwich.

Light is two particles acting as one rotating around each other. The distance between the pairing is the spin frequency. In this case, it forms a tight wavelength. It is blue.

The photon (a two particle spinning system) races at light speed through the mechanical slot into the phosphor. Because the diameter is small, blue light stimulates the atoms of the phosphor. The blue light is absorbed by the phosphor and re-emitted. Phosphor is often described as a substance that gives off light when exposed to light. The blue photon crowds in, shuffles an orbiting electron in a ring that is further out. That electron is so buffeted, tossed and agitated, it spins backwards, becomes a positron and the positron grabs an electron from



a different orbit. The pair is the same structure. Note in the diagram the electron and positron are the same size. The only difference is “D” as the diameter.

Physicists debate over if the blue photon going in is the same photon re-arranged to another color. Or if the atom absorbed the one photon and spit out a new photon using two different electrons in another orbit. But the fact is that phosphors convert photons and are probability driven. Phosphors are blended to make white colors. These are specific materials known as rare earths.

What whiteness the LED light produces is determined by how much phosphor there is, how much blue gets through the phosphor without being converted, how much blue light is turned into a different color and how much is wasted as the system also produces heat. It has to do with how the electron rings move internally. The photon pairing is always over a probability curve. And as the phosphors are used up, the LED will change color and grow dimmer.

Knowing a LED aims blue light through a secondary process made of phosphor to make light unlocks not just how LEDs work, but when to apply the technology and what to expect as performance and lamp life in the field.

It can tell you when to use LEDs. How to sort LEDs for the best results for your application. And it can tell you when not to use LEDs.

Are you looking for energy savings where light quality is not important?

Pick LEDs with little phosphor. These lamps will have high Kelvin temperature from about 4200°K to above 5000°K. (Warning: Today some very energy efficient LEDs produce light at 8000°K. That is a horrid blue appropriate for a haunted house ride, maybe a warehouse, but not for space people are in for long periods of time as living under blue light is depressing.)

Many times the phosphor coating can be seen. If there is no color patch or very little color over the emitter, it will have the best lumens per watt. But remember, LEDs are a system with other components that can stifle the savings. Energy savings are not automatic.

Are you looking for lighting that is very green?

Find a LED with the most lumens possible per watt. But expect to pay with marginal CRI. Do not forget the hidden costs in the quality of life, how things look, less appealing merchandise, more eye fatigue and less productivity. People will comprehend and read slower as the light climbs in Kelvin temperature. Pay attention to the system’s actual useful life. Scrapping a LED system because it is no longer bright enough, it can’t be updated to interface with other lighting or the lamps cannot be replaced as the emitter is built-in is rarely green. It consumes energy to make products. You start installation with a net loss in planet resources.

Are you looking for long lamp life?

Be certain the LED operates as cool as possible. Usually the bigger and more massive the heat sinks, the better. Try to keep the LEDs in free air. Be careful about overdriven LEDs designed to get more watts per lumens. Often the cost is poor lamp life.

Again, check to see if the LED system has replaceable emitters (lamps). You want long fixture life, not just long lamp life. Buy from a well-known, reliable manufacturer that has proven it has the technology to hold the needed tolerances required of a well-made LED.

Are you looking for quality with fairly-good color?

Pick a LED with the most phosphors you can find. These lamps will have low color temperatures from 2000°K to 3500°K, maybe you can get away with 3800°K. LEDs below 2700°K will feel yellow, even though the LED contains a lot of blue light.

Many LEDs have a phosphor coating that can be seen. The thicker the coating, the more intense the coating's color looks to the naked eye. You prefer an almost neon yellow-green or yellow-orange.

Are you looking for excellent color rendition?

Pick another lighting source. No LED provides true beauty. From food to fine art, the lighting industry offers better choices.

But if you are using LEDs, get one with all the phosphor you can find and that matches the phosphor's color patch to a "Bastard Amber" color. This is a specific yellow-orange-brown. Search for a color temperature from 2800°K (remember the lamp has a lot of blue,) to 3400°K maximum. The best LEDs have a color temperature of 3200°K. But the color temperature will become higher and bluer as the lamp ages.

Are you looking for the best economic values in lighting?

LEDs save energy over time and use. They require less energy to produce footcandles. But they consume far more materials, energy and labor to manufacture, and even consume more for disposal.

Since the color can shift to being less and less acceptable as well as the light will get dimmer, the lamps can need to be replaced though the emitter still produces light. Predictable lamp life may be very different from actual in the field lamp life (meaning the light is useable). NoUVIR's testing has lamp life for good-quality LEDs to be about two years before unacceptable dimming. Overdriven or poorly made LEDs can fail in less than 2000 hours.

Lighting a closet? A garage that is used a few minutes a day? A storage unit? A rarely used basement or attic? An inspection space? A guest room used a few weeks out of the year? An ordinary light bulb takes a lot less energy to manufacturer. So it's a better choice. Over all, it's better for the environment.

Are you lighting a retail space? An office? An assembly area? For now fluorescent lamps still provide more footcandles over time using less watts per lumens over the life of the lamps and the life of the system.

Are you using effects? Changing colors? Lighting at low light levels that do not need decent CRI? Making something glow? Bouncing light off of a ceiling? Lighting architecture? Lighting a retail space, office or assembly area where you need some aim and control? LEDs can be a great choice. But the LEDs hav to be good quality.

Are you lighting collections? Collectables? Artwork? Historic artifacts? Valuable things in cases? Be very careful. LEDs color rendition towards blue, especially as LEDs age a few years, can make objects appear less valuable. It does not help to save energy if it means you sell less. It is not cost effective if it means museum visitors spend less time in your galleries.

Are you looking for LED performance?

Again, pay attention to the phosphors. Compare spectral curves. Pick companies that have been manufacturing LEDs for years and have good track records.

The manufacturing of LEDs is complex and full of trade secrets. Do not buy cheap lamps. You will regret it. LEDs are not really commodities in that there is a wide diversity in performance, quality and longevity. So do your research.

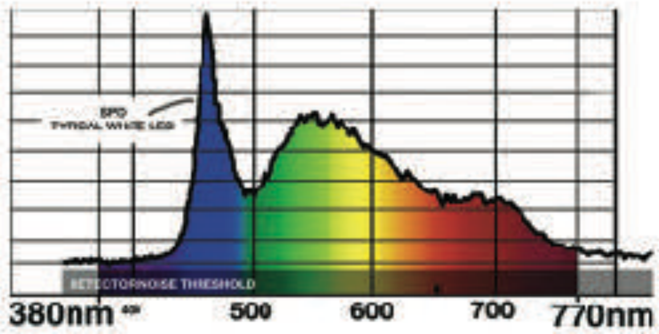
What You See! Is It Quality? Or Blue Light?

The phosphors create the other colors that fill in as white light. But blue light makes it through the phosphors without converting. Therefore, even very warm white LEDs have an underlying blue tone.

It should not be surprising that Blue Pump Phosphor Lamps are blue in color.

The color spectrum is fuller than a fluorescent. So the color rendition tends to shift blues to a more singular blue tone. The reason is the dominant blue spike of photons tend to overwhelm sky blues, aquas and blue greens.

The red is underrepresented for sunlight. But most of the oranges and reds are there. The deep reds tend to lessen, which can make complex blacks blue instead of warm.



The blue is dark enough that other colors will turn just a touch darker. The vividness drops and the contrast gets strong under the LED. This color shift is not very noticeable for colors that are monochromatic, for example, painted walls.

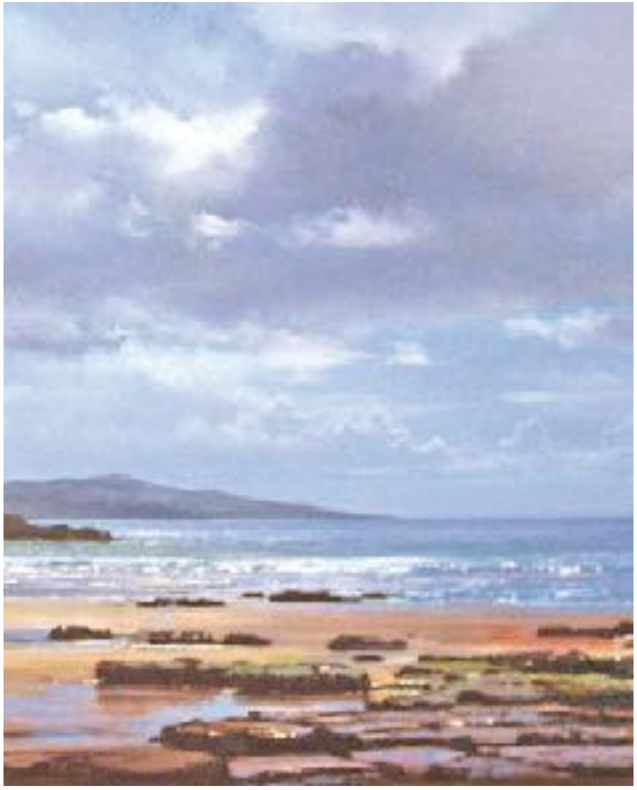
But it will appear in things that have complex colors (as opposed to printed objects). LEDs will rob beauty from objects like fine art, gemstones, minerals, tapestries, Native American artifacts, many Hollywood costumes, mounted birds, oil-painted carousel horses, fine decoys, flowers, red meats, chocolate, deli products, produce and other things that have complex coloring.

Below is a painting lit with indirect sunlight (as sunlight is the established standard) and a top quality LED lamp with the best CRI possible.

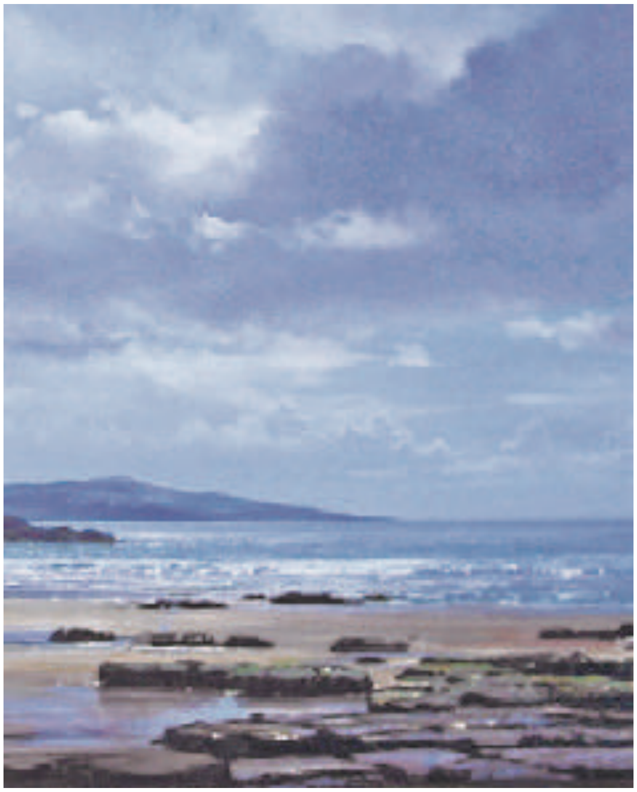
Notice the sky. It does not recede. It has lost some of its brightness as the more subtle blues shift to the blue output of the LED. The sky is actually bluer in the artwork. It is not gray or darker.

The spike of blue output in the LED have biased the whites. Not the white cloud to the left and compare the contrast to the cloud on the right. You would never notice unless you could see the images side-by-side. The sky blues towards the peak of the LED's blue tone. The wide variety of blues have been hidden by the light source.

Also look closely at the images' foregrounds. For this seascape the LED hasn't enough deep red to pick up a red layer of paint that is used as a foundation under the sand for the beach. Fine art builds layers of colors. The rocks die. The sheen of the wet sand is there, but it is different. The artwork has lost the brilliant manipulation of the artist's palette.



Indirect “Artist” Sunlight



Good Quality LED Light

Now this is really important.

The painting is still incredibly beautiful. This is fine art. But unless you had a comparison, you would not notice the difference. What is a spectacular seascape under ideal lighting becomes a very, very lovely seascape under LEDs. The LEDs have stolen some of the beauty. The colors are not all there.

This is not a problem in many applications. We need light to see to walk, work or read. But in places where we need to really see color, the energy savings are not worth the cost in quality of life. Or the costs in sales. If this were in a gallery, the painting on the right is harder to sell than the painting on the left. It is perceived as not as valuable. In this case, other choices in lighting such as halogen or fiber optic lighting is better.

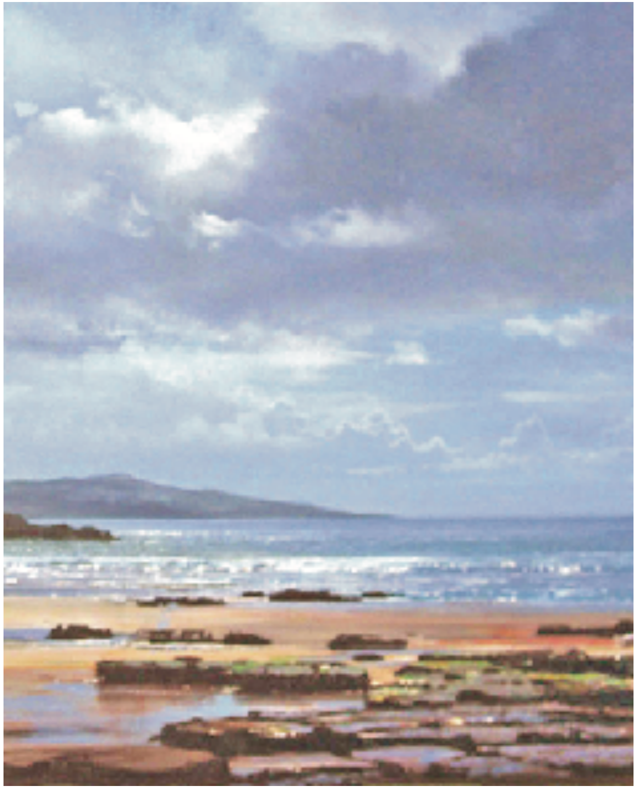
And what happens over time? LEDs loose their brightness in a few years as the phosphors are consumed. The light is dimmer.

The light gets bluer. More of the blue light weeps through the phosphor without being converted.

Compare below. This is still quality LED lighting. It is still a beautiful painting lit under LEDs that operated for three years. But the painting is twice as dark and is bluer. Half the footcandles are missing. This is the nature of how a LED work and age.

Because this is a sampling, the painting on the right looks really dark. But if you were to see it, your eyes would respond to the dimmer footcandles. The painting would not look nearly as dark. It would just be a little grayer. However, a camera is sensitive to the far lower light level. Remember, the painting on the right is lit at half the light level as the one on the right.

Indirect “Artist” Sunlight



Older Good Quality LED Light

Plan and design for this loss in footcandles and the installation costs go up, the lighting system may not meet the energy consumptions standards (may not pass inspection) and the system will be overly bright unless on a dimming system designed for the LEDs.

Don’t design for the loss and the end user is doing group relamping every two to three years. But that means the color rendition of the first set of images as the painting is still too blue with less variety in the blue and the light has deadened some of the reds.

If this painting were in a museum (and it is certainly worthy of one), the artwork at the opening of the exhibit would be limited to the Recommended Footcandle Requirements. People see well under these low light levels. But they have to be light adapted. However, change one light bulb and suddenly the other LED lights are dim. Patrons will not only loose their light adaptation. But the gallery will be dark. Footcandle levels cut in half is a big shift.

The point to remember is that all LEDs are “blue pump phosphor” sources. They have a blue bias no matter what the color temperature. They blend blues into more singular blues, add contrast to the blacks and dull complex reds. All of them!

Understanding LED Color

Your how-it-works know-how gives you a big hint about color rendition and color temperature. Why is that so important? Because LED manufacturers are publishing data that is changing how lighting is specified.

Remember the rule-of-thumb for any LED is that the more phosphors, the “yellower” the light gets and the more expensive the lamp. The more phosphors the lamp has, the less energy efficient it is.

Some manufacturer state that, “All you need to know about LEDs” is the Kelvin temperature which is a “decisive measurement.” But Kelvin assumes no phosphor. And in the last 20 years, look what has happened to the definition of white light and Kelvin temperature. It is hardly a decisive measurement.

Color Temperature Kelvin Style

Here are the industry’s new, shifted standards. Light now comes in:

1. warm white (from 2000°K to 3000°K),
2. natural white (from 3300°K to 5300°K), and
3. cool white, also called “daylight white” (from 5300°K up).

This is a good change for LEDs. It’s a good change for fluorescent lamps using less phosphors. It’s a good change for the U.S. Department of Energy. But let’s put this in perspective.

The entertainment industry’s standards haven’t changed. “White” light is still a very specific number of 3250°K. In practice, you do not have to be exacting. So from 3200°K to 3300°K or 3400°K is acceptable. Even in a world with photo editing and digital visual effects, white light’s definition to match computer generated images with pure white pixels is still 3250°K.

The range above is from 2000°K to the “super bright” LED at 8200°K. Now that you know how these lamps work, what should you immediately think about 8200°K? Right. There will be no to little phosphor. The lamp is a really, really, really “cool white” like in blue-blue.

This new range is 6200 degrees. It is from 2000 to 8200. That is a huge span.

For cinematographers, theater stage lighting experts and professional photographers (add in technically skilled artists), light has to render color realistically and make the visual arts appealing. Light is:

1. not useable light except for very special rendition (below 2800°K) as it’s too yellow,
2. warm white (from 2800°K to 3100°K),
3. ~~natural~~ white (from 3100°K to 4000°K, preferable at exactly 3250°K),
4. cool white (from 4000°K to maybe 5200°), and
5. not useable light except for very special rendition (above 5200°K) as it’s too blue.

This range, which was used by lighting for generations until several years ago, is from 2800°K to 5200°K. The range is 2400 degrees. Compare that to 6200.

The entertainment industry’s cool white is in the new standards included as part of natural white for the lighting industry’s new chart. This is very different. This is a huge change.

Both cannot be true. A color temperature of 5300°K in the new standard cannot be “natural white” and a color temperature of 5200°K be “cool white” at the same time. You will also still find fluorescent lamps marked as cool white that are 5200°K. The lighting industry has added 3000 degrees, more than doubling the whole 2400 degree range, in this new definition. And frankly, it is confusing consumers.

Compare both lists and look deeper. “Natural white” is a new term. This white light starts at a white of 3300°K and goes clear past a cool white fluorescent at 5200°K up to 5300°. Notice that the new “cool white” light is 5300°K and up. Cool white is also being redefined as “daylight”.

Daylight ranges from the morning well past sunrise at around 3000°K to mid-morning, climbing to 3300°K (maybe 3500°K) to 4500°K. As the sun climbs to zenith at noon, the color temperature is 5500°K (with a possible peak of 6500°K). At afternoon the color temperature goes back down to 4500°K to 3500°K to 2000°K and then dims to dusk. These are numbers for the equator. The peak of 5500°K is less at different locations on the globe. Things tend to average about 3200°K which should be a familiar number.

The light is data filled. All the colors exist. It is balanced. The distribution is tp hat. But sunlight usually does not have an over abundance of blue color even though the sky is blue.

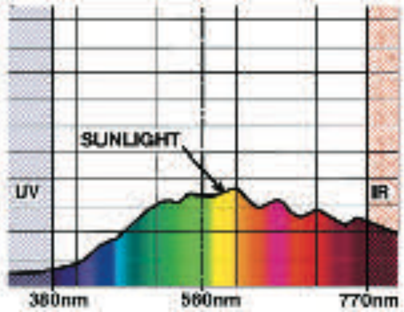
In photography or film, when color is critical, white sheets, reflectors, screens and shades are used to filter the light to around 3250°K. Filming is often a morning or afternoon event. Look at the shadows, rather than high noon. If the sun is not bright enough, manmade lighting is supplemented to balance to 3250°K.

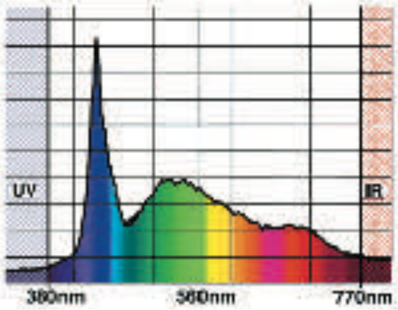
A blue sky can be 6500°K or 7000°K. That is not daylight. It is the color of the sky. We call it a “brilliant blue” sky for a reason. Yet some special LEDs are now offered at 8200°°.

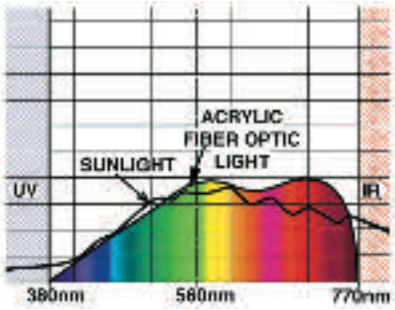
LEDs have redefined daylight to be above 5300°K. That is blue even for a cool white fluorescent lamp. For LEDs that high color temperature is the blue spike of color. It is the color driving the phosphors. What was once thought way too blue for indoor living (fluorescent lamps come in warm whites from between 4000°K to 4800°K for a reason) is now “daylight”.

Could this change in definitions be a response to how a LED works? Seems likely. Does it also support LEDs as better energy saving lamps. Yes. Less phosphor means the most energy efficient LEDs are now “daylight”. That is much more acceptable as a specification.

Here is sunlight’s spectral output compared to a white LED compared to NoUVIR® fiber optics. Study the shapes of the curves. Check out the blues and the reds.





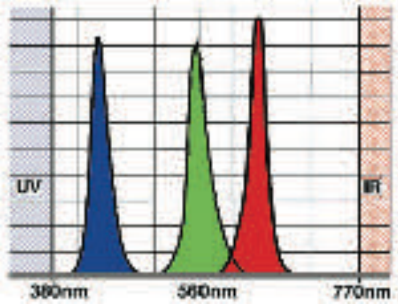


Look at the output of each color. A popular LED company states “no light source is as close of a duplicate to sunlight as a LED.” Obviously NoUVIR fiber optic lighting is closer. Remember the LED used is an excellent quality LED with a color temperature of 3300°K. It is not a LED at daylight at 5300°K and up. As LED color temperature goes up, the curve gets further and further away from sunlight. Yet the industry has redefined these very blue lights as daylight. So do not lean on terms like daylight. Instead, when in doubt, get a spectral output curve.

The RGB LED

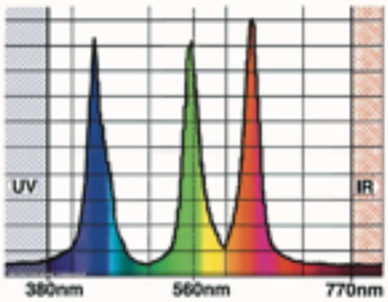
Go back to the basics. A LED diode is made of two thin pieces of semiconductor material doped with a very thin layer or layers of chemicals in the middle. One half of the circuit easily conducts electricity. The other half resists. At the middle intersection of the sandwiched material, electrons from both sides of the material combine into photons at the PN-junction.

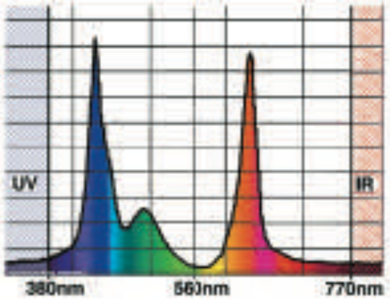
Different semiconductor materials with different physical distances in the gap and different coatings (chemistry) with even different layering techniques make different wavelengths as a single probability curve of color. Some LEDs are designed with three diodes as emitters. Blue, green and red are blended to feign white light. We read left to right with spectral charts portrayed as blue to red. But these lamps are RGB. Change the electron flow into the emitters, so the color spike shortens or lengthens and thousands of colors are simulated.



Often the industry simplifies these spectral output curves and shows the data on the left. This is usually, but not always, the heart of LED programmable lighting system called "smart" lighting. LEDs can shift color at will. The more LEDs and the more technically sophisticated the controller, the greater the range in blended colors.

Fortunately, this curve is not the real output. The spikes are monochromatic as each emitter's material combinations and manufacturing techniques dictate a specific color. But the PN junction spins out photons in a probability curve. The color is more random due to the orbital mechanics of the electron rings in the materials and the doping. So, for example, the red puts out a red band, but in different red wavelengths over a tall, spike-like probability curve. The spectral output generally looks like one of these two curves published by two major leaders in the industry.





Note how there is a better range of color. The orange, yellow and magenta are often in the tailings of the probability curve. But the colors exist in the output to reflect weakly instead of appear as gray. There is not very much of many of these other colors. But they are present.

These curves are all red-green-blue. Different manufacturers combine different materials to try to produce a more perceived whiter light. Since the source is already a group of three emitters, many companies build whole arrays.

There are two major facts you need to be aware of with a RGB LED.

First, the emitters are physically clustered. But the chips cannot be mounted on top of each other. A white LED already has problems with focus, because of the gap and the slot. A RGB LED triples these optical errors. RGB lamps scatter light. They have a fuzzy aim and uneven beams from edge to edge.

Close to the source, even the better light sources will show streaks as the emitters cannot be mounted physically close enough to produce smooth beams. Less well designed RGB LED lamps and paneled arrays will break emitters' light into color at the very edge of the beam as the distance is not far enough away to blend the colors out into a simulated white light. They can have severe chromatic aberration, not caused by a lens; but because the emitters are spaced next to each other with a triple focus. It is an engineering limitation of the lamp.

A poor beam can be quite problematic in a single RGB LED required to project a tight beam. The color at the edges are objectionable. There is a lot of glare in scattered light outside of the beam. Think squinting.

Did you catch that? RGB lamps are energy efficient. Put in an integration sphere and measured for lumens per watt, they display good numbers. But the test factors in ALL of the light output. What light is useful in the beam?

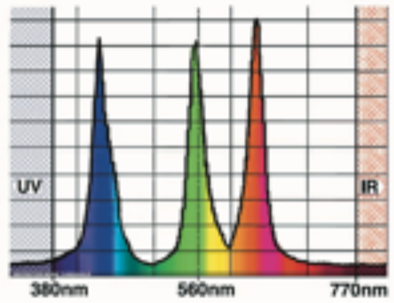
These lamps by nature are out of focus. Many are intentionally defocused further. So always measure the beam. *For producing footcandles in a beam, other light sources can be **superior** in energy savings.*

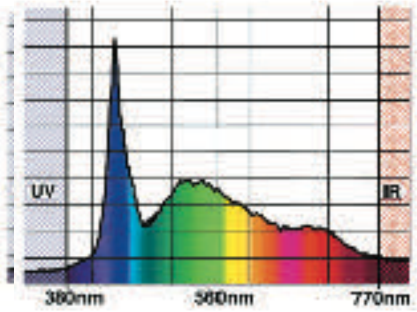
Lack of beam control is why arrays are popular. The array makes the multiple sources blend into an overlapping wall washer or area light. Still, the beams are not smooth. Here is a photo of the beam output of one of the best and most popular LED arrays offered. Notice how uneven the beam is from edge-to-edge and the inconsistent color.

Second, there is a color rendition problem that is hard to describe. Colors go missing. But how is that possible since the spikes of color blend into thousands if not millions (television language) of colors?

These are colors in a light source, not a monitor. We see reflected light as data. If the color is not strong, there are not enough photons to reflect. The color grays. The dominant RGB colors dominant shifting near colors to the spike color of the light.

For example, a red apple is “red”. It reflects red light and absorbs other colors. The spiked red output will turn the apple to the dominant shade of red in the LED. The nuances of the red color get muted. The dark red of deep ripeness disappears into a more general red.





Colors in the valleys between the three dominate gaps are not there to reflect as well. At least they are not completely missing as is represented in so many simplified spectral charts. The apple has yellow freckles or slight rose-orange streaks. These colors are turned towards a shade of red. If the apple has a deep green leaf attached to the stem, the green will turn to a gray green. So color rendition is different depending upon the manufacturer.

In a monitor or screen, the RGB is viewed as direct output. There is no reflection. So the RGB can be manipulated to make a fairly accurate simulated red apple.

The trouble is that LED lights skew color. But the colors are still present. RGB LEDs not just skew color, but turn some colors into a different hue and other color go quite gray.

For example RGB LEDs can be great for theater backdrops and lighting walls or sets. But they can make costumes and people look ghastly. The spread can also be a horrible source of glare, because the beam control is poor. So the talent and the audience should not see directly into these sources

Put another way, a jewelry store can set a variety of moods with RGB LEDs as up lighting on the ceiling or even light cascading off walls. But if the whole store is LED lit, the cases will look better it with LEDs. Using RGB LEDs may be programmable to set a mood, but will further mute the fire of opals, dull sapphires, etc. The gemstones will not look as appealing. Using all LEDs save the retailer energy. But they can have unrealized consequences as the jewelry retailer three stores down stayed with halogen lighting. So what if the competitor pays a higher electric bill. The competitor’s inventory moves two or three times faster.

A new trend in RGB LED lamps is being pioneered by specialty manufacturers stacking emitters all with slightly different outputs to fill in the gaps. Things look promising. Focus (lots of emitters), heat (lots of circuitry) and lamp life (consumed phosphors) are challenges.

Human Sight Verses Blue Light

Search the internet and you will find contradictory studies and science. So what is the concern over blue light? And why is it tied to LEDs?

Humans are really good at light adapting. Our minds mentally turn a yellow or blue world into a white one. This is why we can wear colored sunglasses without being distracted. But this also means we are terrible at identifying problems with light without a comparison.

LEDs can be very, very blue without us really noticing. LEDs (fluorescent lamps too) above 5200°K force the brain to constantly convert the world to white. Our brain gets tired. But all we know is that we are not as productive. The world isn’t as interesting. (We miss color.) We are bored. And we need some coffee to wake up. What is actually wrong is our lighting is too blue.

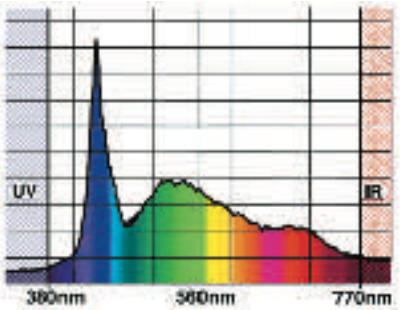
With these very blue LEDs, we have entered new territory. The brain uses the color green as feedback to control the size of the iris. When the world is blue, the iris is too large for the footcandle exposure. The retina gets too much light. Over a long period of time, the nerves can wither and the enzymes secreted by the retina dry up. This cause is well known. Seamen that stare across the blue ocean with no green to control the iris have had blindness problems for centuries. So the new question is if the blue in certain or even all LEDs is so dominant that the eye over time will be overexposed and harmed. So far studies have had contradictory results.

However, we do know ultraviolet light causes retinal blindness, cataracts and skin cancer. So long term exposure to bare LED emitters is a bad idea. Most unfiltered LEDs have as much UV as visible blue light. If we want our eyes to last into old age, we probably should not work or live under unfiltered fluorescent lamps either. Consider this a modern challenge. Halogen tungsten lamps have very little UV content.

Today most eye damage studies have been focused on LED displays. How harmful is a phone's screen or a computer monitor? Again, there has been some very contradictory studies. But it looks like the footlamberts are so low that the exposure is limited enough not to cause blindness. Footcandles in a room are a lot more. Quietly the lighting industry is very concerned about LEDs. Therefore, always use filtered LEDs with an acrylic lens.

LED Photochemical Damage Known as Notching

A detailed discussion of notching is beyond the discussion of how a LED works. The reason is that light damage caused by notching is universal *for any lamp* with a heavy, spiked output in any color, UV or IR wavelength. This means all LEDs, most fluorescent lamps, all high-intensity discharge lamps, all mercury and sodium vapor lamps, and all lamps, regardless of type, that are RGB, if mismatched with an artifact's molecular structure will cause notching.



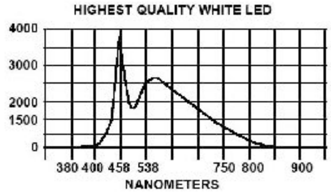
Put simply, the spike of color or spike of UV or spike of IR hits the object the same way over and over again. The dominant wavelength skews the probability curves for interaction with the atoms. Since a molecule is hit repeatedly in exactly the same wavelength, the chance of quantum change increases. The molecule is more likely to break into two smaller molecules to stabilize its atoms. Photochemical change occurs.

Think of it as a drip of water on a rock. That deep blue light strikes the object in the same place and same way. The constant, near-identical encounter between the photon with the same wavelength is like the drop of water.

It breaks the rock (molecule). The light is not random enough. All that blue is one wavelength. The "rock" of the artifact is "notched" by slow, continual wear like the constant flow of individual drips of water. Drip. Drip. Drip. Testing proves that LEDs can be very destructive, if the notch matches a fragile link in the artifact's structure.

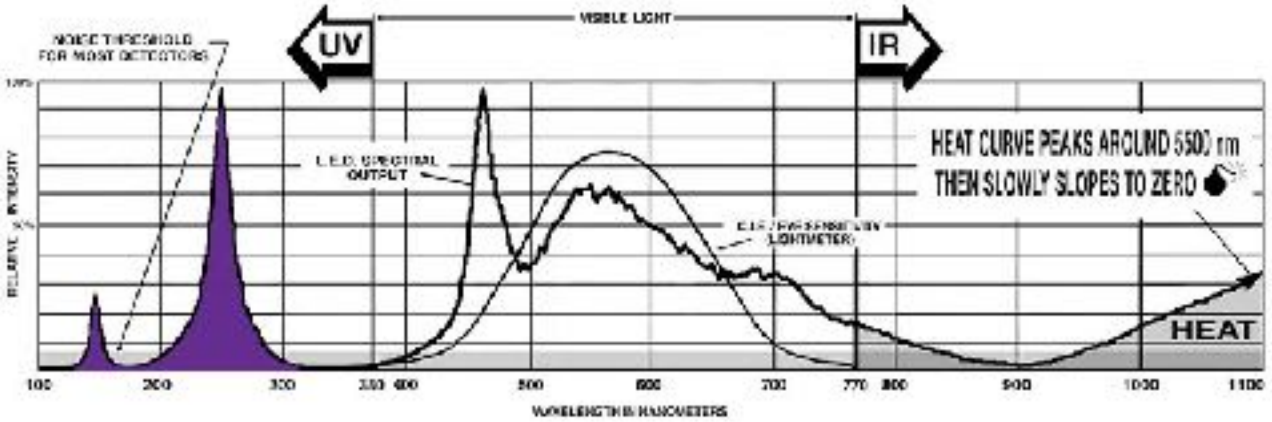
LED Ultraviolet Content

As you know LED output is often shown as spectral output. The graph never shows ultraviolet light. The graph never shows infrared.



This graph is *used everywhere.* Salespeople, lighting experts, designers, sales representatives, architects, builders, electricians… have been told over and over again that LED lights have no UV.

It’s not true. Producing visible blue light through a diode generates ultraviolet. The word “ultraviolet” is not by accident. It is “ultra”, meaning extreme, blue “violet” light that is so deep in color we do not see. It is light below 380 nm.



Now just because someone reading this will say, “This can’t be right. LEDs do not have UV. I know they do not. They can’t!”

Here is an array lamp of white LEDs originally specified for a museum installation to light rare artifacts being tested for UV content. **The meter does not read zero.** But you say you have seen zero readings. Some LEDs are without UV. Some have UV. But reading UV through all the different nm is difficult. Most commercial-grade meters, as opposed to scientific instruments, will fail to register the UV content of a visible light source. Some meters have thresholds that are too great and are do not read below 200 nm. Other meters are designed to check only UV sources, not lighting.

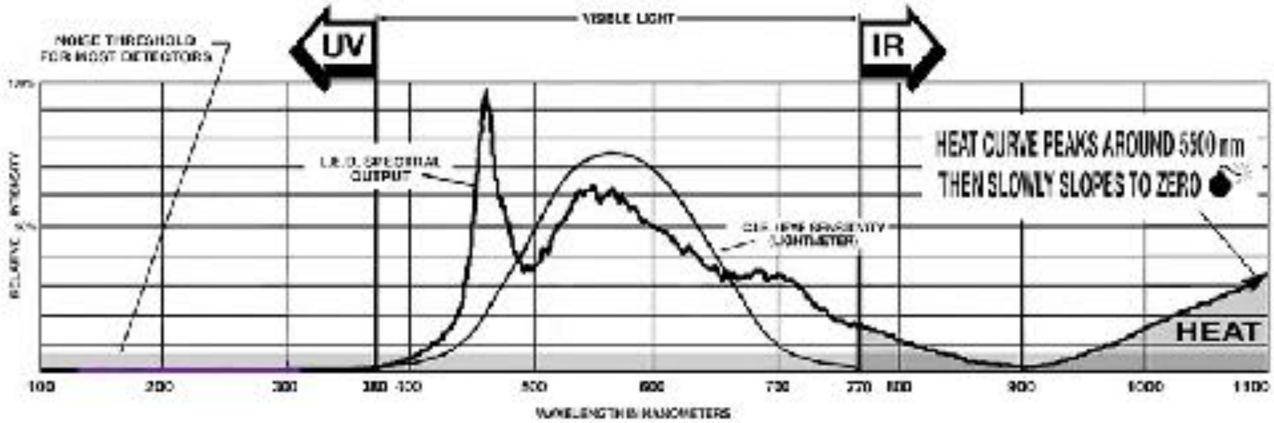
So unless you see physical filtering, automatically know there is significant UV content. It is in the nature of the LED. And if you cannot identify the filter material (the light source in this photo had what looked like a substantial filter), assume there is UV.

UV harms objects. It causes fading, embrittlement, cracking, spalling, yellowing and splitting. It breaks up objects at a molecular level deep inside. It is one of the key factors in causing photochemical damage.

All LEDs produce UV. Did you notice in the graph above, the UV content is about the same volume as the blue visible light that drives the phosphors?

The phosphors used in LEDs do respond to some of this UV content. The UV does help some LEDs make more visible light. But most of the UV bleeds through. It goes right between the phosphor atoms. The UV is mixed in with the visible light.

That is not to say there are not LEDs that have little to no UV content. But the emitter must have a lens made specifically out of acrylic that is a minimum of 1/32 inch thick to filter the UV.



The output will look like this. Many arrays do not have the correct plastic to filter and then on top of that, the lens is not thick enough to fully filter. What is interesting is that there are several MR-16 and MR-11 LED type lamps that often do have acrylic lenses and will test without UV.

Are you looking for a LED that does not have UV?

Make sure the LED has a great lens. Acrylic tends to be harder than styrene. It has no odor as compared to some butyrate plastics. Tap. Feel with a fingernail. It should sound hard and be very clear.

Check for a nice heatsink with well formed cooling fins. Manufacturers that are concerned about IR often pay attention to UV. Operate unenclosed if possible. The lens increases the operating temperature of the diode circuitry cutting the lamp life. Remember for treasures, NoUVIR fiber optic lighting has absolutely no UV.

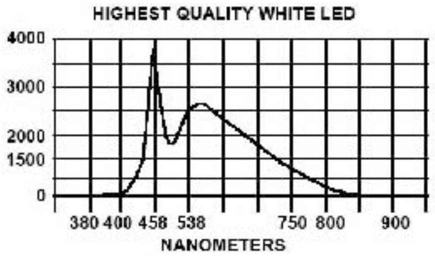
LED Heat Content

To repeat, a LED output is often shown as spectral output only. The graph never shows ultraviolet light. The graph never shows infrared.

Again, this simplified graph is *used for marketing everywhere.* Salespeople, lighting experts, designers, sales representatives, architects, builders, electricians…have been told over and over again that LED lights have no IR.

It's not true.

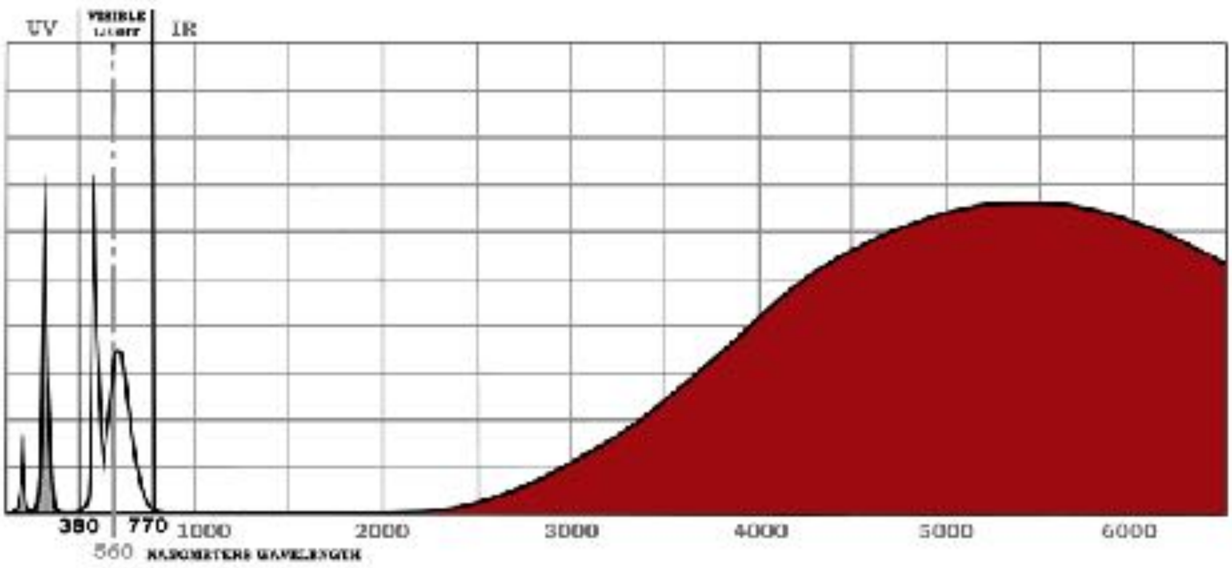
Even this favored graph of visible spectral output shows infrared from 770 nm to 800 nm. That is heat. And to be fair, this graph is based on data taken with an instrument that cannot read the infrared sketched into the chart.



Most data at the bottom near zero is below the threshold of the meter. Sometimes the curve will look like this one with green lines to compare. The data just hangs. But there is infrared…a lot of it. LEDs average 75% of their output as heat.

Need to confirm? First, look at the LEDs construction. A lamp without heat does not need heatsinks as cooling fins. Next, see if the lamp's instructions require open free-air use. A lamp without heat can be buried in anything. It does not have to radiate to the surrounding air. Finally, turn the light on and seal it in a box. The temperature of the air in the box will climb. So much for no IR.

The heatsink protects the electronics from overheating and failing. Some of the lamps contain small muffin fans within the lamp base. Place you r hand behind the heat sink and you will feel blowing warm air. These are critical for extending lamp life. If a LED does not have some form or surface for dissipating heat, pick another product. The lamp will not be reliable.



IR is photons above 770 nm. This is the almost black red where humans cannot see drifting into invisible. Again LEDs sketch in data to zero. Yet look at all the energy past 1000 nm where some LEDs start and at 2500 nm where all LEDs emit IR.

Because heat is not good as a selling point, it's hard to find a full spectral output. Usually a full spectral output is only available from the manufacturers of the actual chips. And part of the data supplied will be specifications for cooling the semiconductor. When you do get graphic data, check the scales. It is not uncommon for the scale to condense to ever smaller bars so the infrared visually looks to be less than it really is. One the above graph, compare the visible to the UV in gray and the IR in deep red. The volume of UV and IR is eye opening.

Why do these sources and even filaments generate so much heat? IR are photon pairs that are widely spaced coming from the outer rings of the atom. These are the valence rings that combine or drop to make chemical reactions. They link or break apart molecules.

When electricity is used to create light, the first and easiest conversions of electrons happens in the cloud's outer perimeters of the atoms. This is the most active orbit. So it follows that physics predicts IR is the most abundantly produced light. As more photon pairs come from orbits closer to the nucleus, the spacing of the diameter in nanometers gets smaller; because the orbits kicking out photons are smaller. The really tight orbits nearer the nucleus output ultraviolet.

Every high school chemistry student learns a 10°C rise in temperature excites atoms in molecules and doubles the reaction rate. Want chemistry to happen faster? Add heat.

The science is the same for objects, artifacts, food, merchandise, furnishings, even the oceans of our world. Chemistry is accelerated by heat. The IR drives and accelerates the photochemical processes. Infrared also drives photomechanical damage.

LEDs sealed in a case will rise a case's temperature. LEDs aimed through a glass ceiling of a case or through the front window of a case will increase the temperature. We deal with many museums. Field work has found temperatures of 10°C or more compared to gallery ambient temperature. So museums have cut exhibit life for their artifacts in half without knowing.

Changes in temperature also impacts relative humidity. Control of a constant RH is part of artifact care. If the lights introduce IR, every day the RH of the artifacts is changed as they are warmed. Every night the RH changes again as the lights are turned off and the artifacts cool. The artifacts physically grow and contract. Dry and wet. This adds to the damage.

LEDs start with less energy than halogen tungsten lamps. So the IR exposure is less. But LEDs and fluorescents use the same phosphors to convert one set of photon types into more useable visible photons.

They output roughly the same infrared. Therefore, if fluorescents are too hot for your application, LEDs will be also. Those heat sinks are there for a reason.

LED Lighting Is "Smart" and "Stupid" Lighting

LEDs are marketed as "smart" lighting. The light's output can vary. The color can be changed. The user has lots of choices by controlling the electrical input.

Indirect "Artist" Sunlight

Good Quality LED

But the cost of smart is stupid presentation. With an average CRI of 72, the light misidentifies 28% of the colors. These are not subtle shade differences. Colors are perceived to be different shades and hues. The light quality is marginal enough, it is an impossible task to sort a big box of crayons by color and get them in the correct order. Colors look like different colors.

Because it is so important, remember the painting. With halogen lights you get a CRI of 100. With fiber optic lighting you get a CRI of 100 plus the energy savings. For collections, excellent color is the way objects and artifacts communicate their value.

The lighting industry over the last twenty years has focused on electronic drivers, computer software, power supplies, WiFi and worked hard to make

LED systems not conflict with each other. LEDs were suppose to maintain their 40% profit margin. Other lamps were abandoned, because of legislation and their 4% profit margin. The smart building was the wave of the future. Unfortunately, lighting products became more and more tied to those same building controls that were to support the industry. With the focus not really on light fixtures and the efforts in lamps centered on energy savings, the industry has shifted much of it products into be sold as generic lights.

Products are bought based on price often picked by a contractor or a low-level designer. No one thinks about presentation. So the industry suffers. And so do consumers, because they have to live with marginal CRI.

The economic question awaiting smart lighting is the entrance of cell phone companies and other computer based tech which is better prepared to control LED lighting systems. Or any lighting systems. And tie the lighting to HVAC, security, smart televisions, etc. The lighting industry has been pulled outside of its expertise. It is not part of the computer industry. So now others are offering more friendly solutions.

Smart phones and smart houses have been further confused with terms like “intelligent LEDs” and AI controlled lighting (think LEDs). But smart or intelligent or basic, the irrefutable truth is how the hardware makes photons. That means ugly is part of the quintessence make-up of a LED.

There are advancements. There are new inventions. There is a lot of exciting development. But LEDs at the core will never change. They will always be a light emitting diode. For white light, they will always be a **blue** pump phosphor lamp. They will always have the advantages and disadvantages for how the quantum physics works.

Therefore, LEDs work very well in certain applications. LEDs work okay in other applications. LEDs are marginal and cost more compared to better lighting solutions in yet other applications.

And LEDs can flat out stink and be dangerous in speciality applications. Ignore sales talk. Pick product based on how lamps work. And if you are lighting something beautiful, valuable and rare, be smart. Be intelligent. Use halogen or fiber optic lighting.

How an OLED Lamp Works

Photons are created at the atomic level where the PN-junction meets. So it wasn’t long until some inventors started playing with thin layered coatings instead of semiconductors as hard chips. Stack the right types of film layers together. Carefully control the flow of electricity just right through these layers. And the sheet of material will glow as the interfaces create PN-junctions within the film and its choices in materials.

At the beginning, the science only worked with organic materials. The layers are carbon-based (like living things) compared to the rare earths of LEDs. The new LEDs where called “organic” light emitting diodes or OLEDs. The organic stuck even though later improvements added materials that

Science on the Side

Organic is a term used to describe the carbon-based chemistry used in OLEDs found in organic matter as compared to the metallic salts and other caustic materials mined out of the earth used by LEDs. The organic in OLEDs can be unnatural (meaning they do not exist in nature), synthetic and polymers (think plastic). Some manufacturers claim an OLED is safer for the environment, because some day in the future an OLED will degrade in a landfill whereas a LED will not were not organic. Organic has nothing to do with being more natural or safer or better for the plant. It is just chemistry.

In OLEDs photons are created in tiny PN junctions dispersed throughout the key layers. Certain materials have the perfect molecular structure with gaps between the key molecules. The atoms branch off and stick out from a core atom. Those branch atoms have holes.

Sandwiched between a N-type layer and P-type layer, the branches will flip electrons into positrons. Stripe in red, green and blue strips as doping, the RGB makes white light.

Inside the matrix, buried in layers, is a diode structure. The sheet are tiny multiple diodes. The photons are still made by the electron attracted to a hole which you now know is a positron.

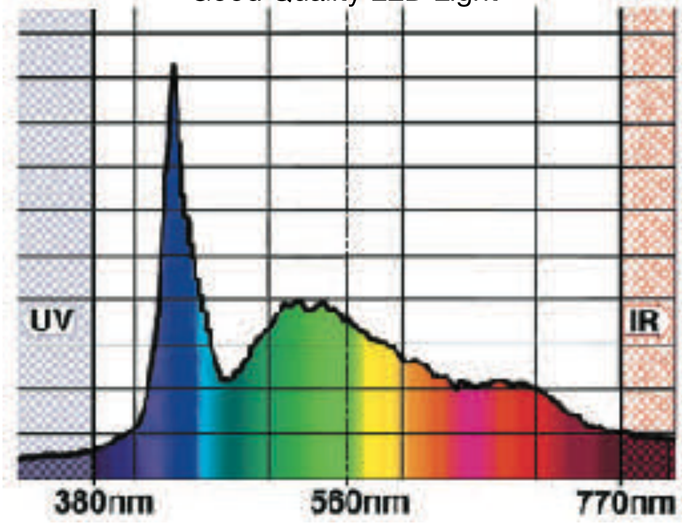
Just like in LEDs, different layers of chemicals produce very different results.

The layers are so thin, they are usually vacuum deposited or (an OLED manufacturer's dream) printed onto a backing. How the striations are lined up can control the electrical inflow and the photon output. So can the backing which may only to mechanically support the layers or can further influence the OLEDs ability to output light. The final "layer" or "coating" is a protective cover.

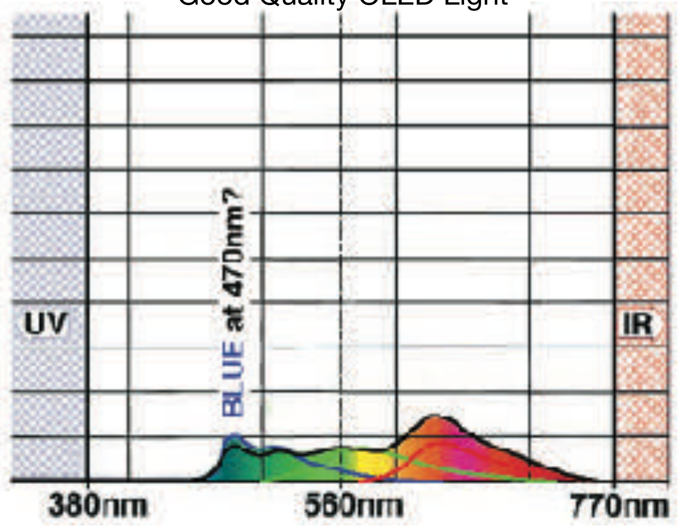
The OLED internal ribbons or bands produce red, green and blue. These tiny bands are sandwiched between a lattice of multiple, ultra-thin coatings that include a super thin N-layer and P-layer. Some manufacturers will identify the PN junction driven by the layers on each side and some will not.

But the OLED has many exacting electrical paths for the free flow of electricity. It is part of the vacuum coating pattern or determined by the printing. Combined with patches of dead end paths that resist and electrons will stack up just like in a LED. It is all about numerous patches of PN junctions. It is a lattice work of interfaces using a pattern to make the circuits.

Good Quality LED Light



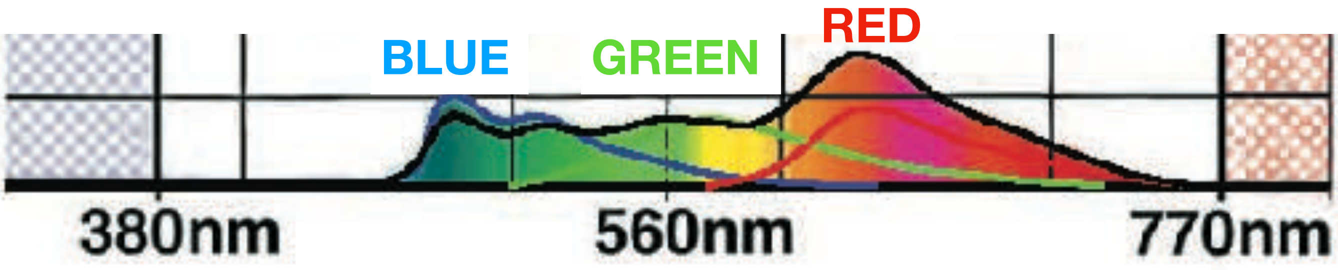
Good Quality OLED Light



The output is less, because the emitters cannot be driven as hard. And these ribbons are manufactured differently from manufacturer to manufacturer. The spectral output can greatly vary depending upon the manufacturer. But OLED output is an overlapping of RGB.

To make what the output is clear, here is an expanded view of the RGB with the superimposed blue, green and red curves of the spectral chart.

The overall light averages as the black line as output. Note how the blue drops and feeds the green color and the green feeds the red to make the OLED more of a warm white light.



Because the electrical circuit is a deposited or printed pattern, the electricity can be turned on and off at each and every junction. It is a matrix. For screens this is revolutionary.

For lighting the deposit mechanically limits the amount of electricity the lines will carry. Fewer electrons means fewer pairings into photons at PN-junctions which limits the footcandle output. Even with all the interfaces actively generating photons, OLEDs tend to be a low footcandle source. Volume of panels are needed to do most task lighting jobs.

What is a dramatic change in technology is that a black pixel is not powered. The junction is dead. It has no flow of free electrons.

A red pixel is a flow through a red ribbon. A green pixel is flow through a green ribbon of material. A blue pixel is a flow through the blue ribbon. Route electricity through all three ribbons and the panel produces RGB making white light. Again, cut the electron flow, and there is black.

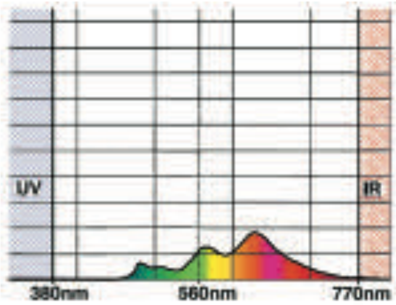
The panel can shift color or stay white depending upon the complexity of the patterns imbedded into the film's materials and how the paths are either powered or turned off.

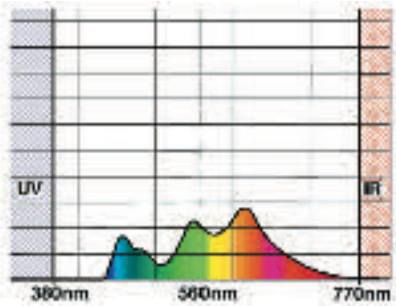
For lighting our focus is on producing white light projected onto an object or into a room. The OLED does not have any phosphors. So the spectral output is designed through the choice of materials to be warmer and an effort is made to remove the aggressive blue spike of color. Without phosphor, the aggressive blue output is not needed to convert blue into white light.

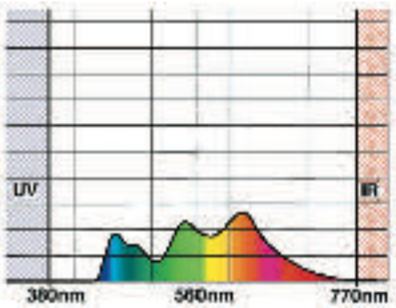
OLED manufacturers will claim light at 500 nm is blue. And it sort of maybe can be. But this is right at the very edge of blue green and sort of is cyan. But it is not really as a good cyan is below 500 nm. Above 500 nm is so not much blue. As a matter of fact, 500 nm is the data cut-off for documents required to NOT be exhibited under any blue light.

So the color (the CRI) is a little odd in an OLED. To preserve the vacuum deposited or printed materials, the manufacturers tend to trim the ends of the color spectrum to boost and increase footcandle output. The OLED depends upon brightness and contrast to warm and cool colors instead of adding a stronger blue or a stronger red. And the colors are built RGB just as any other RGB light, but the colors act more CYMK as cyan (little intense royal blue light), yellow (with a green bias), magenta (not really red, but orange-pink) and an intense black.

The point is that the manufacturer of OLEDs will greatly manipulate specific colors. The OLED changes its configuration and materials based on Kelvin temperatures. Shown are the spectral outputs of three OLED lamps **made by the same manufacturer**. These are all from the same line of high-quality OLEDs. But each lamp has a different color temperature.


OLED 3000°K


OLED 3500°K

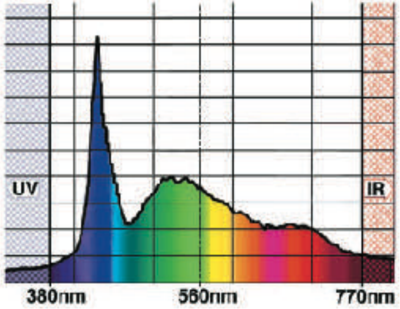

OLED 4000°K

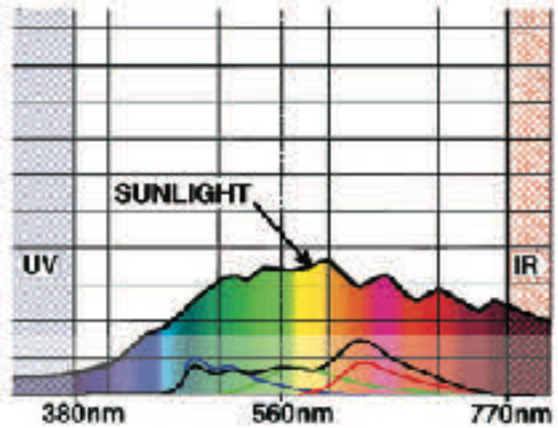
The overall output in lumens per watt grows as the blue-cyan-green is added to the RGB mix. This is not the same lamp adjusted for color. These are three separate OLEDs. From the spectral output, you can see a significant difference in the blue-cyan-green and how the color never has a true red.

Color rendition is an important quality to life. Again, compare the above curves to a LED.

The blue is a light blue, not the strong dark blue of a LED. And the blue is not in great volume. This is why the footcandle output of an OLED is about half of a LED. The close to UV blue content is not there to drive a phosphor that is not there either.

Add in the lack of optical direction and though LEDs work like LEDs using PN-junctions, the OLEDs do not light up like LEDs. They work identically. But OLEDs have a lot of visible light missing. There is a lot of volume in light that disappears.


Good Quality LED Light



This might be more obvious if the OLED is compared to the curve we have been using throughout this paper for sunlight. Again note the three curves representing the RGB of the light. But note that an LED would be twice as high in output.

One curve is red. One curve is green. One curve is blue. Blended together this white OLED forms the black line.

Can you see the missing colors? Can you imagine what a seascape with blue water will look like? A color must be in the light source to be seen. If it is not present in the light, the color will distort and most likely turn gray. A gray world is a boring world.

Can you imagine what a pair of Ruby Red Slippers would look like? The deep reds do not exist. The red peaks at orange-pink instead. Would they be ruby? If you said, “No,” take a bow. You have learned how to read spectral output curves. Yu can now predict presentation based on data curve if that curve is accurate.

One last fact to look for when dealing with OLED data. Often the scales in the spectral output charts are different than those used for LEDs. Having compared curves, increasing the y-axis as a scale is good marketing. It makes the footcandle output look better.

OLED Advantages

OLEDs are flat, flexible sheets that glow. The photons exit at random out the front surface of the structure. Because the light is distributed from a surface, the glare is less.

The back of the panel can be a reflector, but it is usually only a support for the chemistry of the layers. Because the photons are created, including the IR, over the area of the layers, overheating is not as much of a problem as it is in LEDs.

For lighting the flexibility and thin structure makes building light fixtures with curves or hidden behind structure like cabinets a new design choice. But OLEDs have the same color bias and distortion as RGB LEDs. Because of the color mix, the distortion can be greater. It is hard to represent blue and red when the blue and red are not intense enough. The light is soft and usually chemistry is picked to make a warm white.

Most OLEDs cannot bend too sharply or the lamp breaks the vacuumed deposited or printed patterns. To protect the patterns within the layers, companies can and do add plastics or sometimes glass to make the OLED rigid and more durable. Therefore, a new look in lighting are shelves, ceilings, wall and floor panels that glow. However, cleaning an OLED surface without harming the lamp causes problems in the field.

Today effort is focused on having a really foldable light source. Wouldn’t it be neat if an OLED could condense like a fan and then fold out to give light? Wouldn’t it be exciting to have a folding television? You can see where the research is going.

Since an OLEDs pixels are without power, they are very dark. Screens, monitors and televisions have a sharper black. There are also power savings as a LED screen backlights its black pixels.

The other advantage is size. RGB LEDs place three emitters as close together as possible and then must electrically connect them as individuals to control each emitter. Signs require a lot of wiring. OLEDs control color by the patterns built within the layers directing the electrical connections.

The goal is to drop the price of OLEDs by printing the circuits instead of using vacuum deposit. The RGB pixel will be smaller, cheaper to manufacturer and more exacting. But it will still retain all of its physics and color limitations.

OLED Disadvantages

The big advantage is that OLEDs are flat, flexible sheets that glow. The big disadvantage is that OLEDs are flat, flexible sheets that glow. The photons exit **at random** out the front surface of the structure. Because the light is distributed from a surface, OLED panels are not very bright. That does not mean that the footcandles in an integration sphere are not impressive. But in the field, getting useable footcandle to light something can be difficult. Because they are panels, a lot of panels are needed to light over any significant throw distance. When a panel is a few feet away, the light is scattered and still not all that concentrated. Size matters. So OLEDs are great for small screens.

But brightness matters. Even television screens, monitors and signs revert back to RGB LEDs to overcome higher ambient light levels in a room. That need for brightness is worth the cost of wiring the LEDs.

The other important OLED disadvantage is that dozens of manufacturers are still experimenting with what layers produce what light. Therefore, it is not just the quality and performance that varies. The basic spectral output varies too. Performance is less in useful lumens than a LED. But OLED footcandles verse OLED footcandles are very, very dependent upon which manufacturer produced the OLED.

Then add in the controllers, software and other equipment. Drivers can quickly become obsolete or fail to interface with other lighting. That means OLEDs can have a very short, useful life. The calculated lamp life might be a decade or more. But reality can be a system that lasts a shorter period than a basic halogen lamp in a light socket. The technology is still in great flux.

Dead Pixels

Our focus is on lighting, not screens or monitors. The layers are film thin. The electrical paths vacuum deposited or printed. Photons are created as heat. Photons are also created and then absorbed back into atoms.

The panel experiences its own photochemical damage.

The electronic industry calls this damage “burn in” or “degrade” often attributed to non-radiated heat. Simply it means the IR photons were absorbed into the structure. They caused chemical change.

The large single molecules used to spin electrons into positrons accepts enough electrons into orbiting rings that the molecules breaks apart and becomes two smaller molecules. The atomic structure is different and no longer works. The molecules needed to be whole to convert electricity into light. That tiny part of the panel goes dark. It is a “dead pixel”.

Enough photochemical damage and the light gets dimmer and dimmer. The matrix stops working well enough to specifically direct the electrons. The electrons stop being crowded enough to spin into positrons. More and more parts of the OLED go dead.

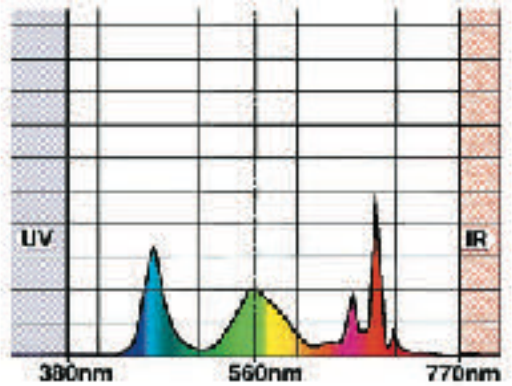
But there is also dead pixels caused by impact. The OLED is made of films. A sharp tap, a scratch, a mechanical jab, any impact that reaches past the layers and breaks the mechanical pattern used for feeding electrons will cut the connections. It is a dead pixel. Or a dead area in the panel.

Therefore, OLEDs have a shorter lamp life than LEDs. Both manufacturers of LEDs and OLEDs publish identical predicted lamp life expectations of 30,000 hours. But OLED manufactures will contradict by stating an expected 5 years for the life for the product verses the LED manufacturers predict 10 years. Warranties for dead pixels can be as short as 90 days. So what happens in the field can be much, much shorter.

How a PLED Lamp Works

The PLED is a “phosphor” light emitting diode. Now do not get confused. Many LEDs have phosphor. We have gone over this. All light emitting diode lamps (LEDs) that produce white light instead of a single indicator color (but a white light that is not RGB) are “blue pump phosphor” sources. **All of them.**

Phosphors are how a good quality LED lamp converts blue light into white. The more phosphors, the better the lamp’s color rendition and the more practical it is to use in spaces we live and work in. We also know that the less phosphor, the more energy efficient the LED is as a lamp. It produces more watts per lumens. But it becomes even more blue as a blue pump phosphor lamp.



But now there is a twist. The latest direction of research and development is to take an OLED. Then add a layer of phosphor or cap the OLED circuits with tiny cells of phosphor like the phosphors used in LEDs. These phosphor are a different blend as you can see from the spectral output. The blue is not as deep blue or strong. Phosphors add in green-yellow and a stronger red compared to the typical OLED.

If the PLED is for screens, monitors and televisions, stay with the materials that produce move further away for that damaging blue which has people concerned about blindness.

If the PLED is for light, try to move the output of the OLED’s photons into a deeper blue or maybe even an ultraviolet to get the phosphors to produce more lumens per watt.

Right now PLEDs are experimental. They are expensive. And they might or might not work.

In Summary

LEDs, OLEDs and PLED are not the panacea for all lighting jobs or for energy savings. Sometimes a LED is a great choice. Sometimes a LED is a marginal choice. And sometimes LEDs are the worse light you can use. It all depends upon the application.

But if you let the architect pick your lighting, chances are you will end up with LEDs. If the architect wants to impress, maybe a few OLEDs will be addd into the mix rather they are reliable or not. And hopefully as a good architect, the manufacturer(s) will be specified; so yu get reliable products.

If you let contractor pick the lighting, you definitely will get LEDs. There are convenient. They meet energy codes. They are hard to argue that the latest in lighting was not provided. As to reliability and performance, the profit margins have already persuaded the contractor to buy LEDs. Hopefully the products won’t be too cheaply made.

If you let the exhibit builder pick, you may or may not get LEDs, because exhibit builders and museum designers know LEDs have less heat. Some exhibit builders understand blue light damage. Some know all about UV filtering. Some have a working know-how about presentation. They have learned presentation is essential to a museum’s long-term success and impacts everything from attendance to fund raising. Some will research and buy the best in LED quality.

But some exhibit builders will not. You will spend more time discussing case finishes than lighting. Yet the safety of your collection is tied to the lights.

There is a reason there are many different types of lamps from regular light bulbs to fiber optic lighting. Each is a superior solution for certain jobs. Others can absolutely fail when used for the wrong purpose in the wrong installation.

Pick what works well, not okay. Pick what truly saves energy and resources. Pick the type of lighting that fits the job at hand. You pick. Not the architect. Not the contractor. Not the exhibit builder. Not even the maintenance staff. You pick with knowledge.