PRICE $30.00 U.S.

LIGHT AND MATTER: THE DANGEROUS ROMANCE

Applied Quantum Physics Theory for Museum Illumination

RESEARCH REPORT

by:

Jack V. Miller

NoUVIR RESEARCH

U.S. HIGHWAY 13 & LOOP 532
PH. (302) 628-9933
RR4 BOX 748 SEAFORD, DE 19973
FAX (302) 628-9932

PRICE $30.00 U.S.

LIGHT AND MATTER: THE DANGEROUS ROMANCE

Applied Quantum Physics Theory for Museum Illumination

RESEARCH REPORT
by:

Jack V. Miller

LIGHT AND MATTER: THE DANGEROUS ROMANCE

Applied Quantum Physics Theory for Museum Illumination

by Jack V. Miller

PHOTON: THE ELUSIVE DEFINITION

Conservators and museum exhibit designers know that light damages art work and historic artifacts. But there aren't very many people around who have any idea what light actually is.

The basic element of light is the photon. If you ask most lighting experts what a photon is, you usually get a lot of arm waving about corpuscles and wave theory that was abandoned by quantum physicists around 1910.[1] Now they say that photons are particles that sometimes act like waves. If you look up the term "photon" in the latest lighting handbooks, chances are you won't find it defined. However, if you don't know know what photons are, how they are born, how they live and how they die, it will be impossible to light a museum effectively without damaging art work.

The writer has sifted through a maze of confusing (and often contra-dictory) information on light to present a theory of *quantum physics:* the study of light *particle*s and their interactions with matter.[2] This theory is based on observations, calculations and experiments from Claudius Ptolemy (140 A.D.) to modern Nobel physicists like Richard Feynman. Most technical papers are written by scientists and *for* scientists. This one is different. It has been written for working museum professionals, the people who must exhibit and protect art and our historic heritage.

For the first time, the mysteries of quantum physics are explained in a clear, simple and interesting narrative adventure. Now you can understand light. You can visualize what it is and what happens when it hits something. This theory appears to conform to the observations of other investigators, to known information in the real world of lighting, and it has survived real world tests through many experiments that directly apply to museum lighting and photochemical damage control.

You will note numerous footnotes. They might be ignored on the initial first reading, but should be carefully studied in a second reading. The footnotes include quotations to document the concepts in the theory presented. If something later is learned about the world that contradicts the theory, it will have to be changed. But now, as *Hunter* said, "It works for me". You will find this story fascinating... and it will work for you too.

DANCING WITH ELECTRONS

A bright tungsten atom was randomly placed among billions of similar atoms in the filament wire of an electric light bulb. This was a fine, stable, tungsten atom. It had an almost infinite life expectancy. The atom was kind of a community, made up of 74 electrons swirling about in loosely-arranged concentric rings around a nucleus like dancers at a ball.[3] The nucleus at the center of the dancing electrons was called NucleAnna. Because tungsten is a very heavy metal, NucleAnna was a powerful nucleus, with a strong attraction that held all her electrons in gyrating orbital dances.

In the middle of the electron rings was an electron named Victor because of his spin velocity "v".[4] Like all electrons, Victor had an electrical charge and magnetic polarity that were the opposite of NucleAnna's. Since opposite fields attract, Victor and NucleAnna were strongly attracted to each other. NucleAnna's powerful field held Victor in orbit with his magnetic field aligned in exactly the opposite polarity to hers, just like a compass needle stays in North-South alignment with the earth's magnetic field. Therefore, Victor not only couldn't get away, he was stuck in a magnetic straight-jacket, so he couldn't even turn. But in spite of his attraction for her, Victor couldn't approach NucleAnna. Her magnetic attraction was balanced by the centrifugal force of his spinning orbit. This was also true for all the other electrons orbiting around NucleAnna.

As Victor looked outward, he saw his outer neighbor electrons, circling him in a slower-moving crowd with slower spin velocities. Beyond those electrons there was the slowest of all electrons, circling in an orbit called the "valence" ring.[5]

Looking inward towards NucleAnna, Victor observed more of his neighbor electrons in an orbit just a little closer to NucleAnna than Victor was. They danced around her faster than Victor, as their closer orbital path followed a smaller circle. As the orbital circles had smaller and smaller diameters, the electrons were spinning faster and faster. Finally, very close to NucleAnna, there were 32 frantically spinning electrons dancing around her in a very tight circle, faster than any of the electrons in rings further out, and many times faster than Victor could move around his ring.[6]

Victor also saw that as the nearest electron tried to approach NucleAnna his spin increased like an ice skater pulling in his arms. As he moved a little closer his faster spin caused centrifugal force to always be increased just enough to move him back out again. NucleAnna somehow seemed to know that as long as the spinning continued, centrifugal force was a very effective way to keep all those persistent electrons in their places.

Like magnetic poles (and like electric charges) repel each other. All electrons in an atom have the same magnetic polarity and the same negative electrical charge. Therefore, none of NucleAnna's dancing electron suitors liked each other. They kept their distance from each other... and from Victor. In each ring, the electrons stayed spaced around a circle, as far away from each other as they could get. As a matter of fact, Victor knew he shared his ring with other electrons, but the unfriendly fellows always stayed away from him. Victor also felt a slight repulsion from their presence and he could never approach any of them.

As the closest electrons circled NucleAnna, their repelling fields formed 32 invisible speed bumps in the paths of each of the electrons in the other rings. Since every successively larger diameter orbit had slower speeds, they were passed by the faster-moving inner orbits. Like speedboats racing around in circles, each electron was disturbed by the electrostatic and magnetic wake of every other passing electron.

Those bumpy orbital paths caused all the electrons to bounce around a lot, so it wouldn't take too much additional energy to boot any of them out of their orbits. But every time one got knocked out a little further, he moved out to a larger radius, which slowed him down. That weakened his centrifugal force just enough for NucleAnna's attraction to pull him back into orbit. Thus, she carefully guarded her spinning suitors from straying off.

Next door to NucleAnna's atom resided other tungsten atoms in the tungsten wire. Each of the other atoms also had a strong nucleus with powerful magnetic forces. Their nuclear magnetic and electrostatic fields automatically adjusted themselves to form a combined magnetic field that held the atoms of the wire together. Their powerful mutual attraction made the filament wire strong enough to hold together, even under severe heat and stress. However, the *electrons* of the atoms next to NucleAnna's had polarities and charges identical to those of NucleAnna's electrons. Thus, all the electrons in all the atoms were equally unfriendly, bouncing around their respective orbits, trying to avoid each other as much as possible. This assured NucleAnna of proper spacing with respect to her neighbor atoms.

Although the tungsten metal seems to be a very rigid material, at the microscopic level, it is really a swirling, jiggling, bouncing structure that is very elastic. It appears that each electron is held in place by "rubber-band" shackles just strong enough to keep him captive. Victor and all the other electrons were trapped in the prison of the tungsten filament. Without some outside help they could never escape.**[7]**

THE SHACKLES ARE BROKEN

Then a fateful thing happened. Someone turned on a switch that caused electrons to flow through the switch, along a copper wire and into the tungsten filament wire. The voltage (or electromotive force) caused an instantaneous barrage of speeding electrons to flood into every ring of NucleAnna's atom.

Victor was astonished to find a speeding electron right behind him as it zipped into his orbit. This new electron was called Victoria. When the switch was thrown the electromotive force pushed Victoria into Victor's orbital path, instantaneously accelerating him to a dizzying velocity he had never achieved before; and injecting a quantum of energy into the atom by raising the orbits of the outer electrons to make way for her presence in the orbit. This new stranger also shunted off a little of NucleAnna's magnetic strength, which caused NucleAnna to loosen her grip on Victor just a little... but it was enough.

Victoria was much closer to Victor than any electron had ever been. As Victoria approached Victor's magnetic field, which was identically polarized and parallel to hers, she now found that she was close enough to Victor that her magnetic effect on Victor was stronger than the magnetism of NucleAnna's distant poles. Victor thought, "Ugh! One of those repulsive electrons is on a collision course with me!"

But before he could panic and run away, Victoria did something that was amazing. Without the slightest amount of slowing, and with the skill of a movie stunt driver, she instantaneously did a skidding 180° turn. Since electrons are polarized like tiny bar magnets, if two of them get close enough, one can flip around in exactly the same way just as a bar magnet will flip around if pushed too close to another parallel magnet. Suddenly Victoria's magnetic field, after her pirouette turn in orbit, was the same polarity as NucleAnna's field. Thus, Victoria was not captured as another electron. Instead, she was actually *repelled* by NucleAnna.

However, Victoria's polarity was now *opposite* to Victor's field, so she felt an attraction towards him. Since they were close together, and because their mutual electron field attractions increased by $1/R^2$, Victor's magnetic field ignored NucleAnna's weaker attraction and he instantly coupled with Victoria's field. "Hmm, this electron is really different... and *very* attractive." he observed as she waltzed around him.

Of course, after her 180° magnetic flip turn, Victoria now felt a magnetic repulsion from NucleAnna. She had no desire at all to stay in orbit. Instead, NucleAnna's magnetic field pushed Victoria right out of Victor's old orbit. She left and she pulled Victor away with her.

As Victor and Victoria left the atom, the raised orbits that were above them returned to the previous energy state. That energy quantum was applied to the acceleration of Victor and Victoria, spitting them out like watermelon seeds and restoring the energy balance of the atom.**[8]**

NucleAnna really did not miss Victor either. Victor's replacement had arrived in the stream of electrons. A clone, an exact duplicate, had taken his place and NucleAnna had all the electrons she could handle. She was completely stable with her suitors, all 74 of them, just as before.

However, Victor was now no longer an impotent drone circling NucleAnna. Even though Victoria had spent only an instant in the orbit ring at Victor's spin velocity, their spins were perfectly matched. It was a marriage made in heaven.

But how could this be? Victor hated other electrons. He stayed as far away from them as possible. He kicked at them and pushed them away when they passed anywhere near him on orbit. But here he was, now strongly attracted to this unusual electron! Victoria's secret was the 180° turn. It suddenly made her irresistible to Victor. The polarity that had previously attracted Victor to NucleAnna *was now Victoria's polarity*. Victoria had become an "anti-electron", also known as a *positron*, **[9]** which combined with the electron, Victor. That combination was now a photon!

From Victor's viewpoint, he knew he was an electron. He was born, raised and had spent all of his life as an electron. Victoria was of the same electron species, but after her 180° flip turn, she was spinning in the opposite direction and had the opposite magnetic polarity. So Victor thought "Wow! Victoria is a very attractive positron."

But from Victoria's viewpoint, *she* thought *she* was an electron. After all, didn't she spend a lifetime orbiting the nucleus of a copper atom before someone threw the switch that happily forced her to enter Victor's orbit? But Victoria saw Victor spinning in the opposite direction from her. Thus, Victoria thought Victor was the one who was the powerfully-attractive positron... and that was good enough for Victoria. After all, everything is relative in physics.

Now Victor and Victoria were free! Their mutual attraction held them spinning together as a pair of particles (an electron and a positron) joined together as one particle (a photon)**[10]** traveling in a straight path through space at the speed of light of 186,282 miles per second.**[11]** Their spinning centrifugal forces were just strong enough to exactly balance the combined field forces holding them together. Since they had emerged from a middle orbit around the atom they danced through space together now as a green photon requiring about 560 nanometers at the speed of light to make one revolution.

PAST THE GUARDS

Once free from their atomic captivity, Victor and Victoria, whom we now identify as a green photon, faced other perils; for their filament home was in a tungsten/halogen lamp. Their speeding dance together was slowed a little by hot halogen gas atoms in a pressurized bulb. The halogen atoms were *huge* compared to the photon's size. Those guards had a smell of iodine that Victor and Victoria found disgusting.

However, the halogen atoms were frantically bouncing off each other and everything in sight. Even if one got right in front of Victor and Victoria, the halogen atom was be too sparselymade to stop a photon. They slipped through without difficulty. In fact, those giants couldn't even see the tiny spinning photon zipping right through them.[12] The halogen atoms were there to guard whole atoms like NucleAnna's and her neighbors' atoms, to keep them in the filament where they belong. "Amazing!" thought Victor, "NucleAnna and those other powerful nuclei were captives just like we were... and *they* are still prisoners!"

AND THROUGH THE WALL

The final obstacle to the photon's freedom was a thick wall made of hard, hot, temperature-resistant quartz. It was made of billions of molecules of silicon dioxide. It was thick and strong enough to contain the high-pressure halogen gas atmosphere in the bulb.

The halogen gas atoms also wanted to get out, because guard or captive, a light bulb is still a hot prison. But every time a halogen guard atom approached the quartz wall, it was bounced away by spinning electrons of the frantically-jiggling atoms of the heated quartz surface.

Occasionally a tungsten atom would make a break for freedom. But it usually was bounced back into the filament by a collision with a halogen atom. If a really quick tungsten atom made it to the wall, it was almost always repelled by the jiggling atoms of the hot wall... and it was then chased back to the filament by a circulating halogen atom as part of his guard duties.

The quartz wall looked quite solid to Victor, until he noticed that all the silicon dioxide molecules were lined up in precise rows that crossed each other in geometric crystalline patterns. Physicists call those rows "invariant" because they are consistent for the entire crystal structure of the quartz, even throughout the entire wall thickness.[13] In between the rows were tunnels large enough to easily permit the green photon to spin through. However, the tunnels were far too small to allow any atoms to pass, so just like the tungsten filament atoms, the halogen guards couldn't find a big enough tunnel. They remained captives too.

THE GREAT ESCAPE

Although Victor and Victoria didn't notice during their escape, when that fateful switch was thrown, there were a lot of other electrons that the electromotive force of the supply voltage injected into NucleAnna's atom. Since the valence electron ring was filled, it caused a freeway jam-up in that outer ring. Other electrons in the current flow had to take off-ramps into smaller and smaller orbits, pushing their way into the bouncing orbits of the swirling occupants of the inner electron shells.

Unlike Victor and Victoria who combined into a 560 nanometer wavelength green photon, other arrivals did their flip turns and coupled with electrons that were spinning in different orbits at different diameters. Some took away slow-moving outer electrons to form IR (infrared) photons and others moved into the next faster, smaller orbit, forming red photons. In a yet smaller orbit, yellow photons were born. Then other electrons entering Victor and Victoria's previous orbit formed more green light.

Photons of smaller diameters with shorter wavelengths were formed closer to the nucleus as blue and then violet light. Since the tungsten atom was a very heavy metal, NucleAnna had 32 of her 74 electrons in the closest possible electron ring. Therefore, when the flood of incoming electrons charged near NucleAnna, they spirited off her closest suitors. From these small diameter orbits, they took away electrons that formed UV (ultraviolet) photons with very short wavelengths. In a fraction of a second, the whole spectrum of light, from infrared heat, through the visible range to invisible ultraviolet rays, erupted from NucleAnna's atom and those of her neighbors in the tungsten filament.

Just as Victoria had done, billions of EMF (Electromotive Force) driven electrons were injected into atoms by the applied voltage and turned into positrons. Some of them took NucleAnna's electron partners at every orbital diameter and eloped with them, forming photons of different wavelengths. As a matter of fact, things got a little confusing. Many incoming electrons saw their own predecessors in the electron flow ahead of them and thought they were resident electrons. Well, actually they were. But the residence time was extremely short... just long enough to acquire the right spin diameter and frequency.

Clouds of electrons and 180° flipped electrons (now positrons) joined with electrons to elope out of the tungsten atoms as photons. At that point it really didn't matter whether the resident or the injected electron did the flip. The pairing was an ongoing process that produced the photons. Thus, *all the photons, of every wavelength and frequency, were created out of nothing but a flow of electrons* through the filament.

Since the outer electrons were the easiest targets for elopement, the filament produced most its energy (over 90%) as infrared photons. Fewer and fewer photons were produced at shorter and shorter wavelengths until only about 5% of the photons had UV wavelengths.

All the photons emitted by the filament were identical... except for wavelength (spin frequency).**[14]** Thus the entire spectrum was emitted from NucleAnna's atom, from IR through visible light to UV radiation.

As the voltage was increased the lamp "color temperature" increased to 3100K°. That put great strain on the filament and the seals in the quartz envelope that housed the filament, shortening the lamp life. It also increased the number of visible violet photons at 400 nm and

UV photons at 300 nm.[15] NucleAnna was not really disturbed by the mass exodus of her electrons that paired up to form photons. Every departing suitor was replaced in kind in each electron shell. As a matter of fact, replacements arrived before the departing electrons left, so the same waltzing around went on as usual. There was a lot of bumping and shaking going on in the transition, but NucleAnna's magnetic force and her inherent electrical and magnetic properties stayed in balance. Of course, if in all the excitement of a voltage surge when the switch was thrown, she did try to jiggle loose from the filament, there were always those halogen guards to keep her in place.

Victor and Victoria, as part of the great jailbreak, had close-up views of some interesting escape techniques used by other photons. Since all photons are the same, except for their diameters[16] they looked very much like bolo stones at either ends of different-length cords.

An electron named Ulysses (who was exactly the same as Victor) was one of the innermost-ring electrons. Victor had seen him orbiting very close to NucleAnna. Ulysses was tightly coupled to a positron named Ursula (who was exactly the same as Victoria). They were so closely held together, they formed a tiny UV photon. That tightly-coupled UV photon buzzed right through the halogen guards and the lattice work of the quartz wall. It went through the tunnel without even a close approach to one of those invariant walls of the quartz. The ease of getting through the quartz permitted an abundance of ultraviolet energy to radiate from the halogen lamp.

The visible spectrum photons also moved through quite readily. But they found they had to dip downward a little in refraction, as they entered the quartz. Then they re-assumed their original courses upon emerging from the outer wall surface.

Victor had learned something about probability in feeling and counting the electron-wake bumps he had lived with day after day. He noticed that the photons who approached the lens-like quartz at exactly right angles, were equally affected by the combined fields of quartz atoms on every side. Thus, their paths went straight through the quartz with no refraction (bending). He also saw that those photons who approached the surface at an angle were attracted by the pull of a statistically larger number of close-by quartz atoms on the near side of their trajectory. That caused them to dive in at a steeper angle than their approach path. Then, after traveling straight through the quartz, they emerged to find the same statistically larger number of close-by quartz atoms now on the *opposite* side of the trajectory. This re-corrected the flight path to be parallel to the original entrance trajectory. The amazing thing about the process was that it was so precise! It almost appeared that the refraction he observed followed some law of physics.[16]

Victor also noted that the tunnels were a bit of a "sticky wicket" for some of the long wavelength infrared photons. These photons had a variety of very long cords connecting the respective electrons and positrons. He saw an electron named Ira (again, exactly the same as Victor) spaced a long distance away from, but still spinning with a positron named Irene (who was exactly the same as Victoria). Victor saw that their timing was just about right. Ira went through a tunnel head-first, and he then simply pulled Irene through like she was on the end of a tow-rope. "Cool" Victor thought.

But what was definitely *not* cool were those other IR photons that were 90° out of phase. They literally got crossways in the tunnel entrances. They went "splutch" into the quartz, broke apart and contributed their energy to the quartz atoms. That raised the lamp envelope quartz to even hotter temperatures, up to 300° Centigrade. "Of course," he remembered, "that's what's keeping the filament tungsten from condensing and blackening the bulb surfaces... and it's also keeping the tungsten atoms from plugging up the tunnels, so they remained clear for the rest of the escapees to flow through and flee from the lamp."

THE PHUNCTION OF THE PHOTON

There was a good reason the switch was thrown. It made current to flow through the filament and caused an amazing electromagnetic spectrum to erupt from the light bulb as photons. Someone in a museum wanted to illuminate a valuable watercolor painting so visitors to the museum (also known as paying customers) could see and enjoy it. Thus, the stream of photons from the halogen lamp, ultraviolet through infrared, was aimed at the artwork to illuminate it.

It was a watercolor landscape painted centuries ago when artists made paints themselves... and from anything that looked about the right color. Therefore, some of the colors used were quite "fugitive". They had a tendency to disappear or turn into some weird color in a relatively short time when illuminated. The pigments were organic molecules made of long chains of simple atoms that were rather loosely held together. Such organic materials are not nearly as stable as the molecules of heavy metals like NucleAnna's tungsten filament.

The painting was a landscape with trees and grass painted with a lot of sap green pigment. Sap green, made from Buckthorn berries[17], is often a bright, almost fluorescent yellow-green color that reflects light very efficiently at a wavelength of 560 nm, the exact wavelength of green photons.

Victor and Victoria were a green photon emitted by the lamp. But life is never easy for a photon. They discovered a glass barrier in front of the painting. "Piece of cake", thought Victor, "this stuff looks just like that quartz lamp envelope, and Sweetheart, we had no trouble getting through that barrier." And he was right.

However, some of his fellow escapees from the lamp didn't fare so well. The glass quality contained some imperfections in its molecular structure. These are called crystal "dislocations" caused by impurities in the glass[18] in which atoms don't line up to make perfectly smooth tunnels in the glass crystal lattice.

Many of the ultraviolet photons, being more closely-coupled and spinning faster than visible-light photons, were too self-centered to stay away from the grasping walls of the tunnel dislocations. They wouldn't bend, so they were surprised by a dislocation and were caught in the glass. Thus, some of them never made it to the painting. Ulysses and Ursula did indeed hit the painting, and they hit the painting like a small-diameter, high-speed drill. Their momentum screwed them deeply into the paint, through thousands of atoms. Each such UV photon wreaked havoc with one or two pigment atoms deep within the structure of the paint. Thus the paint was damaged all the way through, even into the paper.

Some of the infrared photons like Ira and Irene, made it though the glass over the painting by diving though the tunnels head first, and dragging their tails through afterwards, as they did at the quartz lamp surface. But many of the infrared photons were simply victims of probability. Their timing was off. and they got cross-wise with the tunnels of the glass crystal matrix. The result was infrared "splutches" of the cross-wise photons.

These IR photons at the glass surface raised the glass temperature very slightly. As with the UV photons, some of the IR photons made it to the painting. Their large diameter, slowly rotating, orbits covered a shallow, wide circle. So they broke apart into electrons that affected only the surface of the paint, leaving deeper layers intact. The damage was real, but not as visible as that produced by the UV photons.

The IR photons had two effects. The immediate effect was to upset the electron balance of some of the paint surface atoms, changing their chemical bonds. That broke up a few paint atoms. But the second effect was thermal. Many IR photons, like Ira and Irene, raised the temperature of the paint surface. Ira recalled stories about how some of his cousins came out of a Bunsen burner in a laboratory to double the rate of chemical reaction by raising the temperature 10° C. Thus, the entire surface of the painting faded a little faster.

In addition to the UV and IR, light of every light color entered the surface of the ancient paints used by the artist. Victor and Victoria encountered an atom in a sap green pigment molecule. It was like meeting an old friend. They paid their admission by adding a little quantum of energy to the electron shell of the pigment atom as they entered. Then they instantly found a centrally-located ring of electrons spinning around the nucleus of the atom 5×10^{14} Hz (cycles per second).

This electron ring perfectly-matched the spin frequency of the Victor/Victoria photon, with its characteristic 560 nm green light wavelength. As the photon approached, the electron ring was resonant at that same 5×10^{14} Hz spin frequency of the photon's 560 nm wavelength.

The electron ring in the atom instantly aligned itself with the incoming photon trajectory, as if the electron ring was on a weightless gimbal. Then, acting much like a mirror, the resonating electron ring bounced Victor and Victoria back out of the atom. The atom accelerated them on their way, booting them out like a tennis ball being hit with a volley shot at the net. They were accelerated by the same energy quantum they paid on admission to the atom. As they left, the atom was unchanged in any way by their passage through the neighborhood. It simply punched their quantum dance ticket, refused their entry, gave them a full refund... and sent them on their way. **[19]**

Victor and Victoria, now a *reflected* green photon, left the painting by the same mechanism used for its arrival. They found a convenient tunnel through the crystal lattice of the glass covering the painting, and emerged into the viewing area of the museum. Since the photon was reflected by the pigment, it did not age or damage the painting in any way.

The green photon fulfilled its purpose by illuminating the watercolor. But the UV and IR photons did nothing to show the museum visitors that artwork. They merely added their quanta of energy to the paint atoms, producing fading. Some went all the way into the paper, yellowing it by causing oxygen to join the cellulose molecules.

BEAUTY IS IN THE EYE OF THE BEHOLDER

In order for someone to see all of a painting, the person must see the light reflected from each color in the painting. Therefore, the illumination of the painting *must* include light of each specific wavelength, reflected by resonant electron rings in an atom of each respectively-colored pigment molecule... including sap green.

There's a fundamental law in lighting: *an object can't reflect a color that isn't present in the light illuminating the object*. That means typical red-yellow light produced by dimmed incandescent lamps (even if they are halogen lamps) fails to show the subtle lavender hues artists use to paint distant hills. If there is no lavender in the light spectrum, the lavender pigment looks grey; and the painting loses all of its depth. That also means if Victor and Victoria hadn't arrived with the proper matching 560 nm wavelength spin frequency that could be reflected by an atom in the sap green molecule, *no one could ever see that sap green color* in the painting.

Fortunately, a visitor to the museum was standing right in the path of the 560 nm photon as it was reflected by the sap green pigment. The reflected green photon (yes, even that same photon that was born in the filament) passed right through the cornea and lens of the visitor's eye.

The optics of the human's eye are softer than quartz or glass. But they are still made of crystals known as "amorphous crystals" and have invariant atoms in a regular geometric pattern.[20]

Victor and Victoria easily found a tunnel entrance into the lens and cornea. Once again following Snell's Law[16] (as was applied to the photons passage through quartz lamp envelope) there was a preponderance of atoms nearer the thick center of the lens; and fewer atoms near the edge. The difference in atomic density distribution provided a statistically-accurate asymmetric attraction that bent the photon's path just enough to focus it onto the retina. It struck a cone photoreceptor sensitive to green light.[21]

When the photon entered the cone, it was absorbed by the organic "chlorolabe" of the cone. But nothing happened. That is because there could be no signal until a sufficient quantum of energy was accumulated by the cone. When 5 or 6 green photons finally struck the same cone they collectively produced a quantum signal that traveled through the visitor's optic nerve to his brain. Then the visitor thought: "Wow! What beautiful green trees that artist painted!"

THE LIGHT PIRATES

There are always pirates around who are destructive and rarely, if ever, accomplish anything good. In a museum, the pirates are the light wavelengths that <u>do not match</u> any of the colored pigments. If photons are not reflected from a pigment molecule, they are absorbed. That changes the valence electron patterns in the atoms. In turn, that changes the molecular structure of pigment molecules, fading and degrading the pigments.[22]

Some of the light pirates are invisible ultraviolet photons having wavelengths *too short* for the human eye to see. Other light pirates are infrared photons with wavelengths *too long* to be seen. But many light pirates are actually photons of <u>*visible light*</u> that found no matching pigment color to reflect them. Without the required matching pigment colors in the painting to reflect each wavelength, photons of all non-reflected colors are absorbed.

Organic pigments, such as were used in the antique watercolor, are made up of hydrocarbons. These are molecules consisting of hydrogen, oxygen and carbon. Even the largest atom in a hydrocarbon molecule, which is oxygen, has only 8 electrons. Such atoms lack the close-in rings required for short-wavelength ultraviolet reflection. They also lack large outer rings required for long-wavelength infrared reflection. Since the organic materials cannot reflect either UV or IR radiation, all those invisible photons are absorbed to cause fading and photochemical damage.

In the example museum painting, in addition to the green photons like Victor and Victoria, a large number of red photons were emitted from the quartz halogen light bulb. Those red photons also arrived at the green painting surface. When the green photon hit a green pigment atom it was 100% reflected. However, when a light pirate in the form of a red photon hit an adjacent green pigment atom, the red photon was 100% absorbed. The green pigment molecule was destroyed in the raid.

This is a critically important mechanism in photochemical damage.
There was no resonant electron ring in an atom of the green molecule to reflect the red photon. Since it couldn't reflect, the speeding red photon approached close enough for its positron of the electron-positron pair to be caught and be flipped 180°. This was exactly the reverse of the process that had made an ordinary electron into a positron like Victoria.

So one wavelength-mismatched photon injected two excess electrons into atom of the green pigment molecule. Electrons are electrons. The rest of the gang in the atom did not want any new additions. As the recent arrivals couldn't find a matching orbit to reflect them, they elbowed their way into other orbital spin diameters. Each of the successive outer rings had to expand to absorb the incoming red pirate photon's quanta of energy. That forced electrons to rearrange themselves, upsetting the outer valence ring that determined the atom's chemical properties (and the organic molecule's "green-ness").

The atoms of the green pigment molecule then re-combined to share valence electrons with other adjacent atoms (such as ubiquitous and always-attractive oxygen atoms). This "oxidation" of the pigment molecule altered the internal electron ring orbits so they no longer resonated with (reflected) green light. In sap green pigment the damaged molecule turns from green to white. But in many green organic pigments light damage causes an electron ring (one that reflects yellow photons) to be shifted to another diameter. The yellow reflectance is no longer present. The formerly-green pigment can never again reflect green light, but instead looks quite blue.[23] As a result, the absorbed light has severely distorted the visual appearance of the artwork.

THE CENSUS TAKER

There comes a time when it is necessary to count photons. This often happens when a museum conservator discovers that something has faded. Then he (or she) must take a census of how many photons have been used to illuminate the artifact. Once the fading has been noticed the damage has been done, not by just footcandles (or lux) but in footcandle-hours. Footcandle hours (or lux hours) then represent the total number of photons that have illuminated the artifact over a period of time. Of course, the exhibits were designed with the light adjusted to the "correct" recommended light level of perhaps 10 footcandles. But since then, many hands have been at the dimmer controls. Somebody had better take a census of the current light levels! Also, the census taker must understand there are gross errors in the count.

Measurement of light level is done with a lightmeter. that instrument simply converts photons into electrons. It is the exact reverse of the process described in the beginning of this adventure, where electrons were converted into photons in the light bulb. Thus, it is only logical to end the story by converting the photons back into electrons.

Victor and Victoria went through a lot of trouble to become a free photon. Now, to be counted, they have to again become electrons that the meter can read as current flow. This is done by connecting a photovoltaic cell to a meter that measures the number of electrons flowing through the meter.

The photovoltaic cell is also a "semiconductor diode" that will only permit the flow of electrons in one direction and not in the other direction. The photocell has a crystalline pattern of billions of atoms (usually of pure silicon) that are oriented to create the semiconductor effect.

As in the quartz light bulb and the glass cover over the painting, the photocell atoms are also lined up in invariant geometry that forms a pattern of tunnels. But the rows of atoms in the photocell are aligned and spinning the same way. The electrons on the same face of each silicon tunnel cell are all orbiting in the same direction. Thus, any electron that enters the crystal will have to go in one direction... and then through the meter.

There is enough room in the invariant tunnels for most photons to enter the crystal. Victor and Victoria slip into one quite nicely. However, the combined fields of the array of oriented silicon atoms, which were all rotating clockwise, draw Victor close to a tunnel wall. Inevitably, one of the silicon atom nuclei snags him into a clockwise orbit much like the one he left in NucleAnna's atom. Victor is now the new "stranger" electron in the silicon atom. He may be relayed from atom to atom, to end up passing through the meter, or he may force a valence electron out of the atom, which, in turn, becomes part of the circulating electrical current through the meter. Thus Victor's presence in the cell is ultimately measured.

As for Victoria, she is on her own. When Victor was drawn towards his tunnel wall it bled off some of his energy that coupled him with Victoria. She then was yanked away from Victor's weakened field attraction and was drawn to the opposite side of the tunnel. The electrons in those wall atoms are orbiting in the "same direction" as the clockwise ones that captured Victor. But Victoria is now looking at the *back sides* of a wall of spinning atoms. She sees that their orbits are *counter-clockwise* from her positron viewpoint. By a happy coincidence, that <u>matches</u> her spin direction perfectly. Therefore, Victoria is drawn into one of the silicon atoms and she fits right in... not as a positron, but as an electron! If the atom Victoria entered is just viewed on it's other side from the next tunnel over, it is seen spinning clockwise, and so is Victoria. Remember? Everything is relative in physics! Just like Victor, Victoria now may be relayed along the silicon atom valence rings as a free electron, or may remain in an atomic orbit, kicking out a valence electron that then contributes to the current flow and indicates her arrival.

THE HIDDEN POPULATION

Both Victor's and Victoria's presence in the cell are quite accurately measured by the meter. But is that true for all the photons? Certainly not! The photocell is *literally blind to the vast majority of photons* that strike it. Remember all those speedy little UV photons that zipped right through the invariant lattices of the quartz (silicon dioxide) lamp envelope? Well, the same-size silicon atoms make up a silicon photocell. Thus, the lattice tunnels are nearly identical and invariant. It's a no-sweat passage for most of the UV photons passing through. Since they never lose an electron to the tunnel wall, that no-sweat passage is also a *no data* passage. Any UV photons in the light beam are simply undetected by the photocell.

And how about those IR photons? Of course, a lot of them showed up to be counted at the lightmeter. They fall all over the photocell; but the meter simply ignores them.

The silicon photocell in a lightmeter is entirely capable of measuring both UV and IR, but to make sure that meter can't read anything that can't be actually seen by human eyes, the photocell has a "C.I.E. filter" in front of the photocell. That filter is basically a thick, green-colored window that "corrects" the photocell to the spectral response of the human eye. It transmits almost zero light at either end of the visible spectrum and lets nearly all of the green light through to the photocell.[24]

Therefore, the lightmeter itself sees almost *none* of the UV light, only about 3% of incident violet light, about 10% of blue light, by calibration 100% of the green light, about 10% of the red light and 3% of the carmine red light... and almost *none* of the IR light. But that infrared comprises the *vast majority (over 90%) of the energy* from the halogen lamp.

The C.I.E. filter thus corrects the photocell so the lightmeter has about the same relative spectral efficiency (the same sensitivity to each color) as the average college student's eyes. But the lightmeter *does not indicate the number of photons* in the light. It *only* indicates the number of photons perceived by the eye. Further, the C.I.E. curve was derived from testing young people. Older eyes, those of most museum members, contributors and sponsors, have an entirely different response curve that must be considered.[25, 26]

Keep in mind that the lightmeter reads only what the eye can see. It is not a reliable indicator of what an artifact sees. Every light source has its own spectral distribution. The more the distribution curve of the light differs from the sensitivity curve of the lightmeter, the more the meter lies to you.

THE MALEVOLENT METAMERS

The incandescent tungsten lamp filament emits a smooth, continuous spectrum of light from ultraviolet; through the entire visible spectrum of violet, blue, green, yellow, orange, red; to the infrared. But gas-discharge light sources do not emit all those wavelengths of light.

Gas discharge lamps concentrate the light in narrow color lines that are very efficiently produced by specific gasses and phosphors in a gap between two electrodes in the lamp. Electrons are made to flow across the gap, exiting specific atoms that emit specific spectral lines. This is the principle behind the high efficiencies of fluorescent and HID (high-intensity-discharge) lamps. HID lamps include metal halide, mercury vapor, sodium vapor and even xenon light sources.

In the quest for more efficiency, tri-stimulus lamps have been developed. These lamps emit the three colors matching the primary photoreceptor enzymes in the human eye. They are cyanolabe (red), chlorolabe (green) and erythrolabe (blue).**[21]** Your eye can sense these three colors equally and actually see white as a "metamer", a color the eye actually creates from different color components. That is why you can see a complete spectrum of color on a TV or computer that has only RGB (red, green, blue) pixels on the screen.

All gas discharge lamps, including fluorescent lamps, are metameric. They add various elements that produce individual color spectral lines. They do not produce a continuous spectrum. Artifacts having colors in the spaces between the spectral lines of the lamp are washed out and distorted. That's why women use daylight or incandescent light to apply cosmetics. That's also why their lipstick turns black under streetlights and parking lot lights. The measure of a lamp's ability to show true colors is called CRI (Color Renfition Index).**[27]**

Now look at what the lightmeter does under a tri-color lamp having equal stimulation of RGB (red, green, blue) light. The meter sees 100% of the green light and only 10% of the red and 10% of the blue light falling on the meter. How, then do you get an equal RGB stimulus? You simply make the red and blue content of the light 10 times greater than the green. There you go! A tri-stimulus source that metamerically gives you white light. That's great for working or reading, but what does it do to artworks?

Now let's put that light on the watercolor painting with photosensitive green organic paint. We set the light level at 10 fc, using a lightmeter matching the 555 nm (green) sensitivity of the eye. The C.I.E. filter is thus green, and that's where most of the meter reading is obtained. **[24]** The green light is efficiently reflected by the green paint pigments and is seen by the observer. What happens to the blue and red light components? With no blue or red pigments to reflect them, those colors are absorbed by the photosensitive green pigment.**[22]**

THE SNAP QUIZ

At this point a museum conservator has faithfully followed the recommended light levels, using halogen lamps that are reported to be less damaging than gas-discharge (fluorescent or metal halide) lamps. Now that he (or she) is sure everything is done "by the book", let's have a snap quiz.

Question #1: Mr. (or Ms.) Conservator with your trusty lightmeter in hand, if the light level on an artifact is too high at a measured 20 footcandles, (200 lux) what do you do about it?

Answer: Easy! I turn down the dimming control until the lightmeter reads 10 fc at the artifact. That's what the book says to do.

Question #2: What does that mean to you as a conservator?

Answer: That's also easy! It means there are now only 10 fc striking the artwork as measured by the photocell, instead of the original 20 fc. That's what the meter reads, and the eyes see. Since the total exposure in footcandle-hours is cut in half, the artifact should last twice as long.

Question #3: Now that you have reduced the footcandle level by 50%, have you reduced the number of *photons* by 50%?

Answer: Oh... that's not so easy! Uh, um, er, ah... I think so. At least I always thought so. It seems only logical.

Question #4: Here is a multiple choice question to make it a little easier. Just pick the answer *you* think is most correct. When you reduce the footcandle level by dimming the light by 50%, you reduce the photon number by: a) 75%; b) 50%; c) 25%; **d) 10%**. You can even peek at the answer.[28]

Answer: Is this a trick question? OK, I'll *guess* d) 10%.

Question #5. So now we know that the number of photons was reduced by 10%, but the lightmeter dropped by 50%. Where did the other 40% of the photons go?

Answer: Gosh, uh, I guess 40% of the visual spectrum was shifted into red (where the meter only saw a small part of the light) and infrared (where the meter couldn't see the photons at all). Is that actually possible?

Question #6: I ask questions; you give answers. Here is the next one:
If a painting has a lot of green trees, purple mountains and blue skies, would shifting the whole light spectrum towards the red during dimming increase the spectral mismatch of the light with respect to the pigments?

Answer: Yes, but I think I want a lawyer. I believe my 5th amendment rights are being abused here.

Question #7: You know the C.I.E. filter in front of the lightmeter's photocell filters out much of the energy from the light falling on the photocell. Thus, the number of photons impinging the artifact (with no filter in front of it) is much, much, **much** greater than the 10 fc reading of the lightmeter. Here is another multiple-choice question: If you remove the C.I.E. filter from the photocell reading 10 fc, the *equivalent* footcandle meter reading of the total energy measured by the meter will be approximately:

a) 50 fc; b) 100 fc; c) 500 fc; d) 1,000 fc; **e) 3,000 fc**.**[29]** OK, you can peek at the answer again.

Answer: You've got to be kidding! *3,000 equivalent footcandles?*

Question #8: What is likely to happen to that priceless green watercolor painting in the next ten years of illumination at 3,000 efc (equivalent footcandles)?

Answer: Now that you put it that way, I suspect it's going to look a lot like a blank sheet of old, yellow paper.

Question #9: Now that you understand the basics of quantum physics (the interaction of light and matter) what should you do to avoid that?

Answer: First, I should remove all UV and IR from the light. Then I should remove all possible absorbed light through reflected energy matching, without distorting the colors of the painting.**[30]** Finally, I should set the light levels just bright enought so visitors of all ages can see the painting.**[31]**

CONCLUSIONS

Light and matter are indeed a dangerous marriage, particularly when the matter is a priceless work of art. But the danger can be controlled and virtually eliminated when the nature of photons and their interactions with the structure of the artifacts is understood. Once the conservator and exhibit designer know what light actually is, illumination and the preservation tasks become simple and obvious. The basic element of light, a photon, is without question a particle.**[32]** In order to avoid fading and photochemical damage, photons must be treated as the energetic, specific-size particles they are. That working definition of photons, applied to practical lighting, provides three basic rules:

1) Reflected light cannot be absorbed;
2) Absorbed light cannot be reflected; and
3) Only absorbed light can cause photochemical damage.

• The first step in controlling light damage is to eliminate the invisible UV and IR photons from all of the light illuminating artifacts.

• The next step in controlling light damage is to eliminate those visible wavelengths of light that are mis-matched with respect to the colors of the artifacts.

• The final step is to understand and predict the effects of total photon illumination, both visible and invisible, resulting from the use of each light source used for museum exhibit lighting, considering the spectral distribution of each source that is used.

FOOTNOTES:

1. "American physicist Arthur Holley Compton (1893-1962) named such a speeding quantum a photon, from the Greek word for 'light.' It was fitting that Compton invented the name, for in 1923, he showed that radiation *did* act as particles, not being just separate pieces of something, but by *behaving* as particles did."
Asimov, Isaac, *ATOM Journey Across the Subatomic Cosmos*, pages 82-83, Penguin Books, (1991)

2. "We scientists are always checking to see if there is something the matter with the theory. That's the game, because if there is something the matter, it's interesting! But so far, we have found nothing wrong with the theory of quantum electrodynamics. It is, therefore, I would say, the jewel of physics - our proudest possession."
Feynman, Richard P. *QED The Strange Theory of Light and Matter*, page 8, Princeton University Press, (1985)

3. Tungsten has the element symbol W, and an atomic number of 74, with an electron configuration of 32-12-2.
HANDBOOK of CHEMISTRY and PHYSICS, 48th Edition, Periodic Table of the Elements, inside back cover, The Chemical Rubber Company, (1968)

4. "If the energy content (*e*) of a quantum of radiation is proportional to the frequency of that radiation (*v*), we can say that : $e=hv$ where *h* is a proportioanlity constant, commonly called *Planck's constant*. The best currently-accepted value of *h* is --- 6.6256×10^{-27} erg-seconds."
Asimov, Isaac, UNDERSTANDING PHYSICS, Volume II, page 131, Walker and Co. (1966)

5. "The chemical properties of different atoms (or elements) are determined principally by the uppermost filled energy levels, since those higher-energy electrons, being less tightly bound to the atomic core, most easily share themselves with other atomic cores for the formation of chemical bonds in molecules and in solids."
Fromhold, Albert Thomas, Jr., *QUANTUM MECHANICS for Applied Physics and Engineering*, page 132, Dover Publications, (1981).

6. "Valence electrons are readily excited by ultraviolet or visible radiation or by electron impact and can be removed completely with relative ease."
I.E.S. LIGHTING HANDBOOK, page 2-5, Illuminating Engineering Society of North America, 1981.

7. "If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic *fact,* or whatever you wish to call it) that *all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling when squeezed into one another.*"

Feynman, Richard P. *QED The Strange Theory of Light and Matte*r, page 15, Princeton University Press, (1985).

8. "...bound energies are not arbitrary. The atom must have one or another of a set of allowed values... Now let us call the allowed values of energy E1, E2, E3. If an atom is in one of these excited states, El, E2, etc., it does not remain in that state forever. Sooner or later it drops to a lower state and radiates energy in the form of light."
Feynman, Leighton & Sands, *The Feynman Lectures of Physics*, Vol III, page 2-7.

9. "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."
Herbert, Nick, PhD, *FASTER THAN LIGHT Superluminal Loopholes in Physics*, Penguin Books, (1988).

10. "For Feynman's own developing theory, a breakthrough came when he confronted the ticklish area of antimatter. The first antiparticle, the negative electron, or positron, had been born less than two decades earlier as a minus sign in Dirac's equation - a consequence of asymmetry between positive and negative energy. --- The collision of an electron with its antimatter cousin released energy in the form of gamma ray(s) ,--- nothing more than high-frequency particles of light ---."
Gleick, James, *GENIUS The Life and Science of Richard Feynman*, page 253, Pantheon Books, (1992).

11. "All forms of radiant energy are transmitted at the same speed in a vacuum (299,793 km/s, or 186,282 mi/s). However, each form differs in wavelength and thus in frequency."
I.E.S. LIGHTING HANDBOOK, Illuminating Engineering Society of North America, 8th Edition, page 4, (1993).

12. "The nucleus has anywhere from 99.945 to 99.975 percent of the mass of an atom of which it is a part. --- Despite its mass, the nucleus is tiny in size, with a diameter only 1/100,000 that of the atom." Asimov, Isaac,
ATOM Journey Across the Subatomic Cosmos, page 96, Penguin Books, (1991).

13. "Solids are most likely to be found in the crystalline state, although amorphous forms are not uncommon. Crystalline solids are characterized by a regular three-dimensional pattern for the location of the atoms making up the solid" --- "The perfect crystalline solid (viz., the single crystal or monocrystal) has the property known as transitional invariance, ---"
Fromhold, Albert Thomas, Jr., *QUANTUM MECHANICS for Applied Physics and Engineering*, page 334, Dover Publications, (1981)

14. Feynman [discussing color-selective interference filters]: "The cycles of reflection repeat at different rates because the stopwatch hand [measuring spin velocity] turns around faster when it times a blue photon than it does timing 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."
Feynman, Richard P. *QED The Strange Theory of Light and Matte*r, page 34, Princeton University Press, (1985).

15. "Energy in the region from 300 to 400 nm is emitted from most light sources, but in a much smaller amount per lumen than daylight. This spectral region apparently produces more fading per unit of energy than an equal amount in the visible spectrum. Filters which absorb much of the near ultraviolet, but very little visible light, have been found to reduce fading somewhat, but not as much as sometimes suggested."
I.E.S. LIGHTING HANDBOOK, Illuminating Engineering Society of North America, 8th Edition, page 165, (1993).

16. "Claudius Ptolemy made a list of the angle in water for each of a different angle in air. The...table was made in 140 A.D., but it was not until 1621 that someone found the rule connecting the two angles! The rule, found by Willebrord Snell, a Dutch mathematician, is as follows: If *Oi* is the angle in air, and *Or* is the angle in water, then it turns out that the sine of *Oi* is equal to some constant multiple of the sine of *Or*. For water the (constant) number is approximately 1.33... according to Snell's Law."
Feynman, Leighton & Sands, *The Feynman Lectures of Physics*, Vol I, page 26-2.

17. "During the 13th century suitable substitute greens were discovered and rapidly developed. The most important of these were Sap and Iris Green. Sap Green, prepared from Buckthorn berries gave a fairly versatile, but impermanent color."
Wilcox, Michael, *The Wilcox Guide to the Best Watercolor Paints*, page 135, Artways, (1991)

18. "A variety of point defects are found experimentally, such as impurity atoms, misplaced atoms and vacant positions. There are also extended defects known as dislocations which represent microscopic atomic configurations made up of atoms which have been misplaced in some appropriately regular manner."
Fromhold, Albert Thomas, Jr., *QUANTUM MECHANICS for Applied Physics and Engineering*, page 336, Dover Publications, (1981)

19. "...we know that the atom is going to arrange itself to make some kind of compromise so that the energy is a little as possible."
Feynman, Leighton & Sands, *The Feynman Lectures of Physics*, Vol III, page 2-7.

20. "Solids are most likely to be found in the *crystalline* state, although amorphous forms are not uncommon... The energy of the solid is generally higher for the amorphous state, so there is a thermodynamic tendency for the amorphous state to change into the crystalline state. However, the viscosity of the amorphous state is generally so large that for all practical purposes this ordering process takes an infinitely long time. The amorphous state is thus frozen (or 'quenched in') with respect to a *laboratory* time frame."
Fromhold, Albert Thomas, Jr., *QUANTUM MECHANICS for Applied Physics and Engineering*, pages 334-336, Dover Publications, (1981)

21. "Cones are divided into three known classes, each characterized by the photopigment it contains: erythrolabe, chlorolabe or cyanolabe" *I.E.S. LIGHTING HANDBOOK*, page 3-2, Illuminating Engineering Society of North America, 8th Edition, page 73, (1993).

22. "A law proposed by Grotthus at the surprisingly early date of 1817 states that only light actually absorbed by the molecule can produce the chemical change. At a later date it was recognized that this law means the wavelengths of light must overlap an absorption band of the compound before it can produce a chemical reaction."
Brill, Thomas B., *LIGHT Its Interaction with Art and Antiquities*, Plenum Press, page 175, (1980).

23. "Most artists will say that green is a combination of the primary colors of blue and yellow. --- This is typical of many green dyes in old scenic tapestries that now have blue foliage. Yellow molecules have been destroyed first, turning the originally-green leaves to blue." Miller, Jack V. and Miller, Ruth Ellen, *Fading of Fugitive Colors by Museum Light Sources*, page 22, NoUVIR Research, (1993).

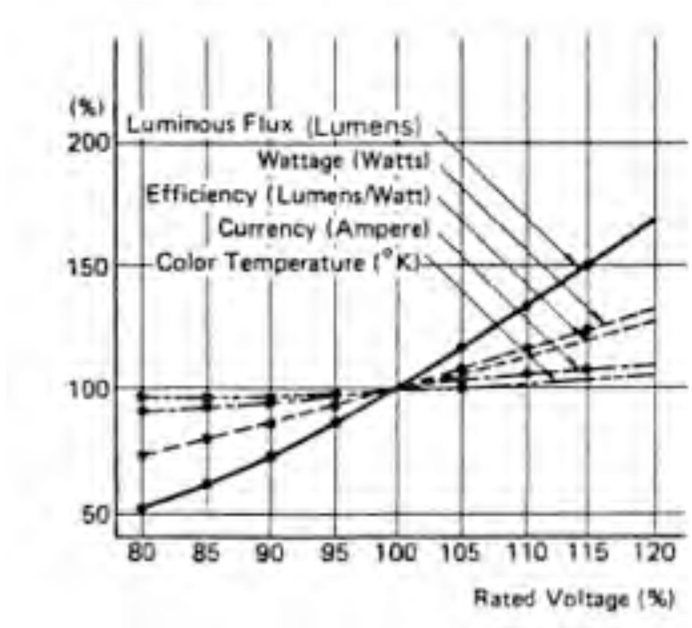
24. "The eye is not equally sensitive to energy of all wavelengths, i.e., to all colors. Tests on a large number of observers have established a *spectral luminous efficiency curve* which gives the response of the average eye to equal amounts of energy at various wavelengths of light. The maximum efficiency is in the yellow green, at a wavelength of about 555 nanometers, and the efficiency of the blue and red ends of the spectrum is very low by comparison."
Westinghouse Lighting Handbook, Westinghouse Electric Corporation, 1976.

25. "Youth doesn't last forever, nor does youthful vision. A person's eyesight usually begins to degrade by age 40. It continues to degrade until at age 60 the iris diameter control range becomes less flexible. The range in an older person's eye in only from 5mm to 3mm diameter. That means an older person has an f-stop range of only from f:3.6 to f:6. Thus, instead of the 20-to-1 light-control range of a young person, an elderly person has a light-control range of only about 3-to-1. --- The older you get the more sensitive you become to poor lighting design and the more often you will complain when you can't see.
Miller, Jack V., *Optics and Physiology of Reading Signs in a Museum Environment*, NoUVIR Research, (1994).

26. "As one ages, there is a general reduction in the transmittance at all wavelengths combined with a marked reduction (greater than four times) in short wavelength transmittance due primarily to the yellowing of the crystalline lens."
I.E.S. LIGHTING HANDBOOK, Illuminating Engineering Society of North America, Reference Volume, page 3-2, (1984).

27. "The color Rendering Index (ideal value 100) is a measure of how well the full spectrum of colors is reproduced in the light of a given color temperature. --- Generally speaking, the more continuous the spectral distribution, the higher the color rendering index; the more gaps in the spectrum, the smaller this value."
Special Discharge Lamps for Technology and Science, HTI Metal Halide Short-Arc Lamps, page 9, Osram, (1988)

28. The light is generated by the electron flow through the filament. The number of electrons flowing is the product of volts times current, the number of Watts consumed by the lamp. The total number of photons produced (at all wavelengths) is then directly proportional to the lamp watts. The chart at the right shows lumens in only the visible portion of the spectrum. As a lamp is dimmed, more and more energy is shifted into the infrared, where the C.I.E. corrected meter cannot detect its presence. Thus, reducing lumens by 50% only reduces Watts (total photons) by only 10%. [Author's note regarding reference]



USHIO Halogen Lamps, USHIO AMERICA, INC. chart on page 2, (1988)

29. The author removed the C.I.E. filter from a Gossen Panlux®2 Electronic lightmeter, mounting the filter in a removable bezel, leaving the silicon photocell covered by only a 0.0005" thick frosted mylar film for protection. The cell was placed under a lamp at approximately 2200K° and the lamp-to-cell spacing adjusted to read 10 fc on the meter with the C.I.E. filter in place. Then the C.I.E. filter was removed. The meter then read 3,000 fc.
NoUVIR Research (1994)

30. "Increased exhibit life is dependent on two factors. First, the invisible UV and IR energy must be removed from the illumination. Second, the visible illumination color should be matched as closely as possible to the reflected color of the artifact. --- The simple test for color matching is to illuminate a small area --- with full-spectrum "white" fiber optics light. Then a second similar light source may be fitted with a selected --- filter --- that precisely matches the unfiltered light reflected ---. It is common to find that the color-matched light produces equal or superior visibility with less than half the measured footcandle level used for "white" light illumination of an artifact."
MIller, Jack V., EVALUATING FADING CHARACTERISTICS OF LIGHT SOURCES, NoUVIR Research, page 14 (1993)

31. The author illuminated a rare and photosensitive paper document on loan from the National Archives for a traveling exhibit. The document was yellowed, and was written in faded sepia ink. Fiber optic illumination was provided through a sepia filter at 2.5 fc, less than the 3 fc limit established by the conservator. It was found that the document was clearly readable, even by elderly viewers wearing bifocal glasses.
NoUVIR Research (1992)

32. "Newton thought that light was made of particles - he called them "corpuscles" - and he was right (but the reasoning that he used to come to that conclusion was erroneous). We know that light is made of particles because we can take a very sensitive instrument that makes clicks when light shines on it, and if the light gets dimmer, the clicks remain just as loud - there are fewer of them. Thus light is something like raindrops - each little lump of light is called a photon - and if the light is all the same color, all the raindrops are the same size... I want to emphasize that light comes in this form- particles. It is very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves. I'm telling you the way it does behave- like particles. You might say it's just the photomultiplier that detects light as particles, but no, 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."
Feynman, Richard P. *QED The Strange Theory of Light and Matte*r, pages 14- 15, Princeton University Press, (1985).