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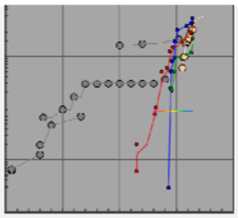

The New World of Engineered SSL

Past & Present, but mostly Future (5 SSL Grand Challenges)

Jeff Tsao

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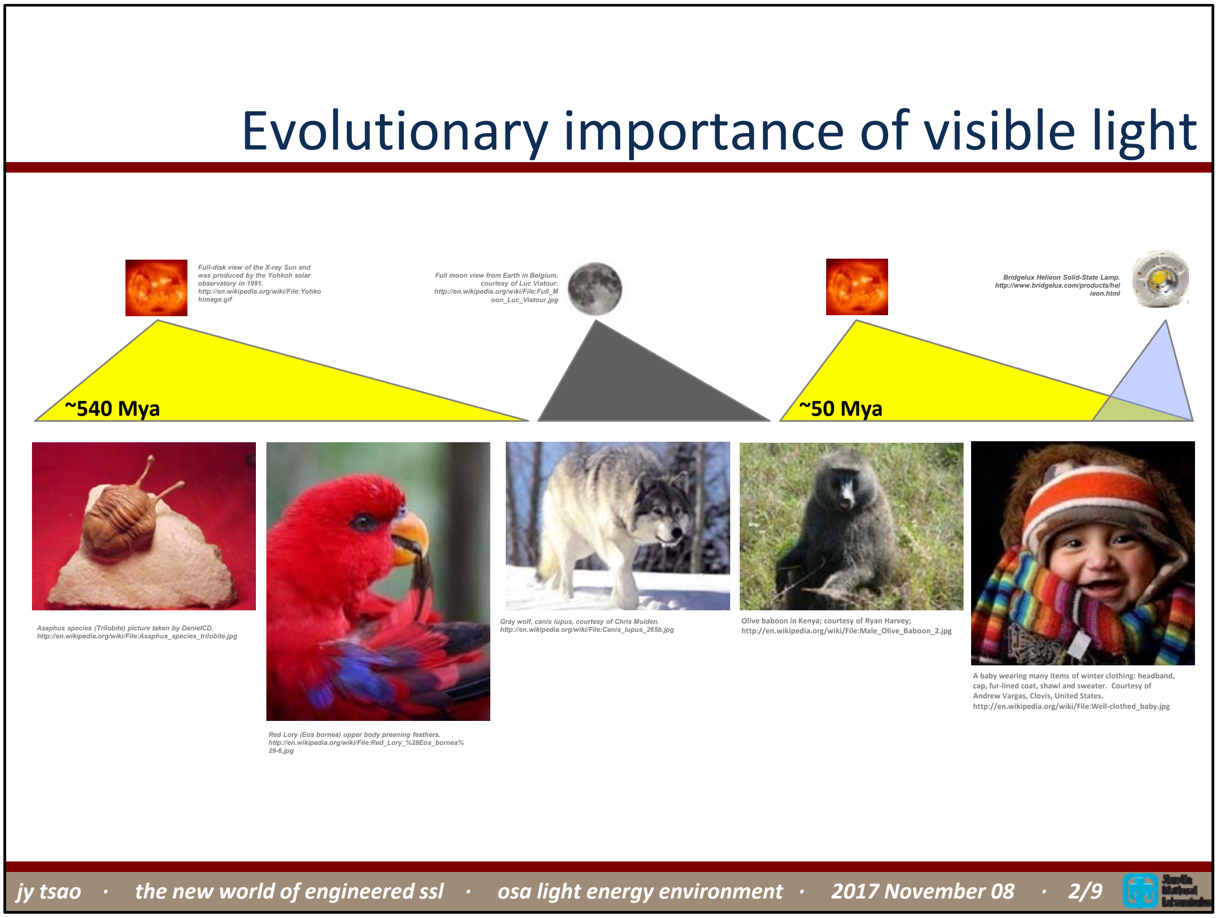
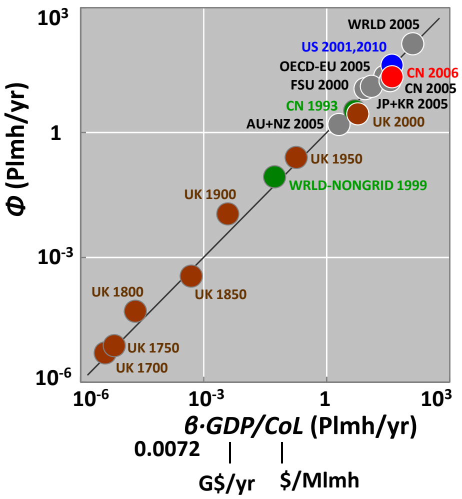
- HELLO. Good morning. Thank-you, Barry and the program chairs, for the invitation to speak.
- FUTURE, NOT PAST. What I'd like to talk about this morning is what some of us are calling the New World of Engineered Solid-State Lighting, in which light is engineered in space, time and spectral content to enable new functionality and new applications beyond basic illumination. So, I'll say a few words about the past and present (about 1/3 of the talk), but mostly this will be a somewhat speculative talk about the future of solid-state lighting (about 2/3 of the talk), organize around what I see as five forward-looking grand challenges in solid-state lighting.
- ACKNOWLEDGEMENTS. Before I start, let me acknowledge a lot of people whose insights and collaborations I have benefited from over the years, and for this talk especially let me acknowledge insights developed in collaboration with Morgan Pattison of the DOE SSL program management team.

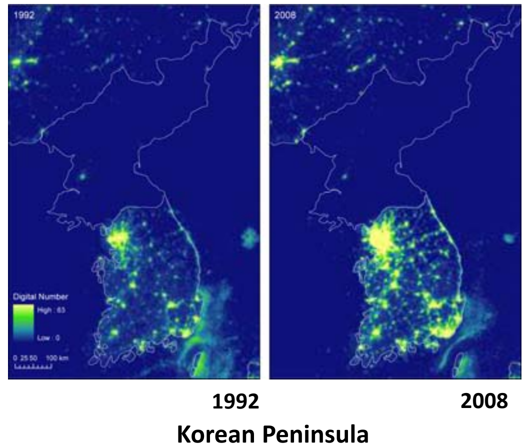


- EVOLUTIONARY IMPORTANCE OF VISIBLE LIGHT. Let's start with the past. Solid-state lighting is of course all about visible light, and is important to us because visible light is important to us. And visible light has been important, not just at this instant in time to us humans, but over evolutionary time to all species. To illustrate that, here I show a one-slide history of key evolutionary events driven by visible light.
- TRILOBITES. Let's start at the far left, where you see a fossil of a trilobite, one of the first known animals with imaging eyes – eyes that could image objects illuminated by visible light from the sun. The invention of such an animal eye was a very big deal, and some evolutionary biologists believe that it was this invention that helped fuel the so-called Cambrian explosion, 540 million years or so ago, in which all of the currently known 36 animal phyla appeared in a blink of geological time. Once an animal could see, it could became a predator, other animals could become prey, and the resulting predator-prey arms race could provide a powerful source of evolutionary selection pressure.
- BIRDS. As evolutionary time went on, animal eyes began to take advantage of the fact that sunlight is white and contains a spectrum of colors, and evolved the ability to see those colors. Birds are a well known example of a species that sees color extremely well: many of them actually have four kinds of color sensors, not just the three that humans have, so they are tetrachromats, not trichromats. As tetrachromats they can distinguish color differences that our poor trichromat visual system can scarcely imagine. This isn't so surprising – after all, birds are very colorful, and they use that color for one of the most important of all biological functions: to attract mates!
- MAMMALS. Mammals, interestingly, are altogether different. As some of you may know, evolutionary biologists believe that the ancestor of mammals was trichromat, but because mammals went through a very long period of evolutionary time when they were nocturnal, and lived under the moon's light, they lost one kind of color sensor and became dichromat. So this grey wolf, the ancestor of modern dogs, was dichromat. And the grey wolf's descendant, the modern dog, is also dichromat.
- PRIMATES. Only later, about 50 million years ago or so, when primates (like you and me) came out from the night and became active during the day, did they re-evolve a third kind of color sensor and become trichromat again, so that they could more effectively hunt and forage for food. And of course now as humans we not only make use of our color vision to see natural colors, but also to see artificial colors, like in the clothes we wear. An alien from outer space wouldn't need to know the details of our physiology to know, just by looking at our clothes, that visible light is fundamental to humans as a species.

Economic importance of visible *artificial* light



J.Y. Tsao and P. Waide, "The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents," LEUKOS **6**, 259-281 (2010).

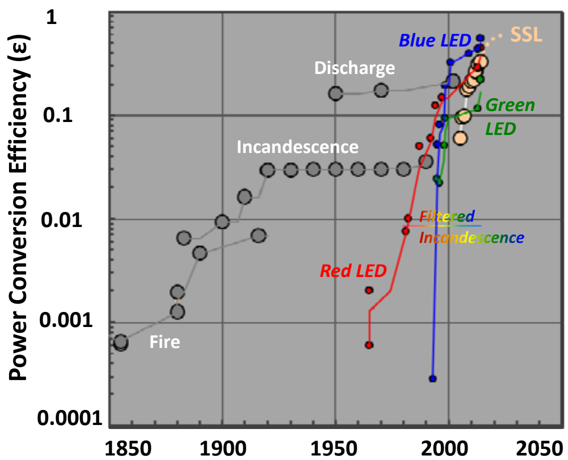


J.V. Henderson, A. Storeygard, and D.N. Weil, "Measuring Economic Growth from Outer Space," Amer. Economic review **102**, 994-1028 (2012).

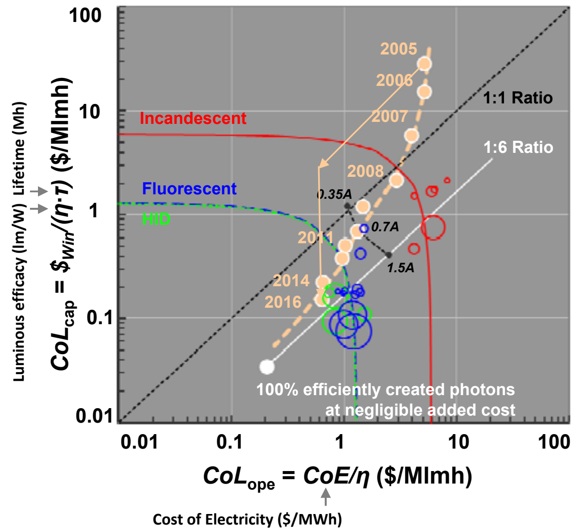
- ECONOMIC IMPORTANCE OF VISIBLE LIGHT. Let's continue with the past for two more slides. Because visible light has had such large-scale evolutionary importance to us (as homo sapiens), it is natural for the artificial production of visible light to also have had major economic importance to us (as homo economicus).
- APPETITE FOR LIGHT. To see that, here I show a plot of the last three hundred years of artificial light. You see various countries or sets of countries, like the UK, the US, China, at various times in history. The vertical axis of the plot is total consumption of light, with the units Plmh/year. The horizontal axis of the plot is a fixed constant, β, times the ratio between gross domestic product, GDP, and cost of light, CoL. If we use as our units for GDP billions of dollars per year, and for cost of light $/Mlmh, we see that this ratio has the same units, Plmh/year, as the units of the vertical axis. And, if we choose the fixed constant, β, to be 0.0072, you can see that the empirical data fall very closely along a line of slope unity and zero offset. This has two implications. The first implication is: as GDP has increased, consumption of light has increased, linearly. That is, the wealthier we are the more light we consume. The second implication is: as cost of light has decreased, consumption of light has increased, also linearly. And because cost of light is inversely proportional to the efficiency with which it is produced and used, the more efficiently we have produced light, the lower its cost and the more we as a human society have consumed.
- NOT SUCH A BAD THING. Now, this also seems to suggest that, with the advent of solid-state lighting, which will be more efficient and less expensive than traditional lighting, we may consume even more artificial light in the future. That may very well be the case. And if it is the case, that's actually a good thing. We don't consume light for no reason. We consume light because it has benefits. We can see at night, we can see when we are indoors – we can do all sorts of things that we could not do if we did not have light. In short, consuming light enables us to be more productive as a human society. There is a link between GDP and light consumption, and it's not just one way (higher GDP means more light consumption), it's the other way as well (more light consumption means higher GDP).
- KOREA. You can see this visually for the case of South Korea, in which the consumption of light, as measured by the light leakage seen from outer space, increased markedly from 1992 to 2008, just as its economy was also taking off. That was not the case for North Korea, of course – you see that it's lights became somewhat dimmer during that same period.

Coming importance of solid-state lighting

White & blue photons are now delivered by commercial devices at 30 & 60% efficiency, with 50% & 80% on the horizon



And the cost of the devices that produce those photons is becoming negligible



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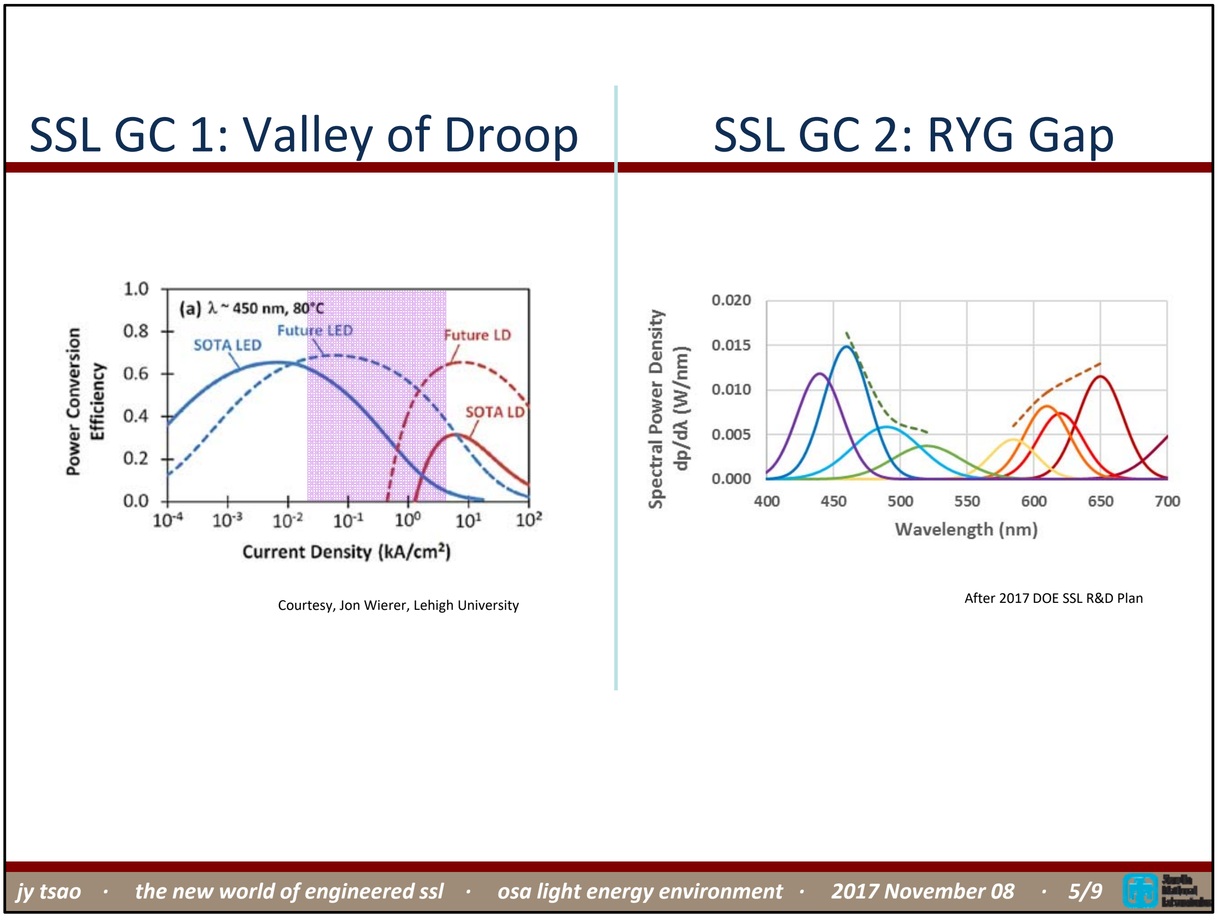
- PAST PROGRESS. Let's continue with the past one more slide, but now turn to solid-state lighting, and the astonishing progress it is has made relative to traditional lighting.
- EFFICIENCY. Here on the left you see a 150-year history of lighting efficiency starting with fire, then incandescence, then discharge lamps, then the astonishingly rapid increase in efficiency of the red LED, the even more rapid increase in efficiency of the blue LED, and of the closely related warm white LED composed of a blue LED and phosphors. At this point, white photons are being delivered by commercial devices at 30% efficiency, with 50% on the horizon; while blue photons are being delivered by commercial devices at 60% efficiency, with 80% on the horizon.
- COST. Here on the right I plot the two important costs of light. On the left axis is the capital cost of light: the purchase cost of the lamp divided by the efficiency, η, with which the lamp converts electricity into light, amortized over the life of the lamp, τ. On the bottom axis is the operating cost of light: the cost of the electricity divided by the efficiency, η, with which the electricity is converted into light. Both of these costs have the same units, $ per Mlmh.
- MARKERS. The black diagonal line represents capital and operating costs; the white line represents capital costs that are 1/6 of operating costs.
- SSL. I've also drawn a trajectory of solid-state lighting, starting up here in 2005. It's steadily moving downwards, so decreasing in purchase cost, but also moving to the left, so decreasing in operating cost. I won't go into the details of this trajectory, except to point out two "critical points."
- CRITICAL POINT 1. The first critical point is the one, in 2008, when the ownership cost of SSL crossed that of incandescence, in red. That's when it became clear that SSL was on its way to replacing one big chunk of traditional lighting technology.
- CRITICAL POINT 2. The second critical point is the one, in 2011, when the ownership cost of SSL crossed those of fluorescent and HID lighting, in blue and green. That's when it became clear that SSL was on its way to displacing *all* traditional lighting, not just incandescent lighting.
- REST OF TALK. Let's turn now to the future. I've structured the remainder of my talk around five forward-looking grand challenges. The first two have to do with continuing to narrow the gap between where we are now, this 2016 dot here, and perfect 100%-efficient SSL, this white dot here. The last three have to do with new opportunities for engineered SSL that go beyond the raw economic costs illustrated here.



- TWO GRAND CHALLENGES. The first two grand challenges many of you have seen before, because they've been with us for a while.
- VALLEY OF DROOP. The first grand challenge is efficiency droop. When you drive a blue LED harder and harder, efficiency increases at first, then decreases. This is a problem because continuing to drive down chip cost means getting as much light out of a chip as possible, which means driving the chip as hard as possible. One solution is laser diodes, which can be driven extremely hard – but absolute efficiencies of blue laser diodes are only half that of blue LEDs. To get laser diode efficiencies higher, it is likely that one will need to lower their drive current densities, in order to reduce one of their principle loss mechanisms, ohmic loss. So one could think of droop as being a valley. These intermediate current densities are the best: if you could either get your LED efficiency curve to move to the right while *maintaining* efficiency, or get your laser diode efficiency curve to move to the left so that you could *increase* efficiency, we could eliminate this valley of droop.
- RED-YELLOW-GREEN GAP. The second grand challenge is the red-yellow-green gap. As we all know, InGaN LEDs are very efficient in the purple and blue, but not very efficient in the green, yellow and red. AlInGaP LEDs are very efficient in the deep red, but not very efficient in the yellow and green. To make white you want photons of all visible colors, and you'd rather have the photons come from LEDs than from phosphors that had to be excited by photons of higher energy.
- THREE FORWARD-LOOKING GRAND CHALLENGES. As I said, these two grand challenges have been around for a while, everyone knows them, and they continue to be important. But there are also three more-forward-looking grand challenge that are just emerging, so let me spend the rest of the talk discussing these.

SSL GC 3: Expanded Functionality

Sony's *Multifunctional Light*

Actuation
- **Color-Tunable and On/Off/Dim Light**
- **Speaker**

Communications
- **Wi-Fi**

Sensors
- **Temperature, Humidity, Presence**
- **Microphone**

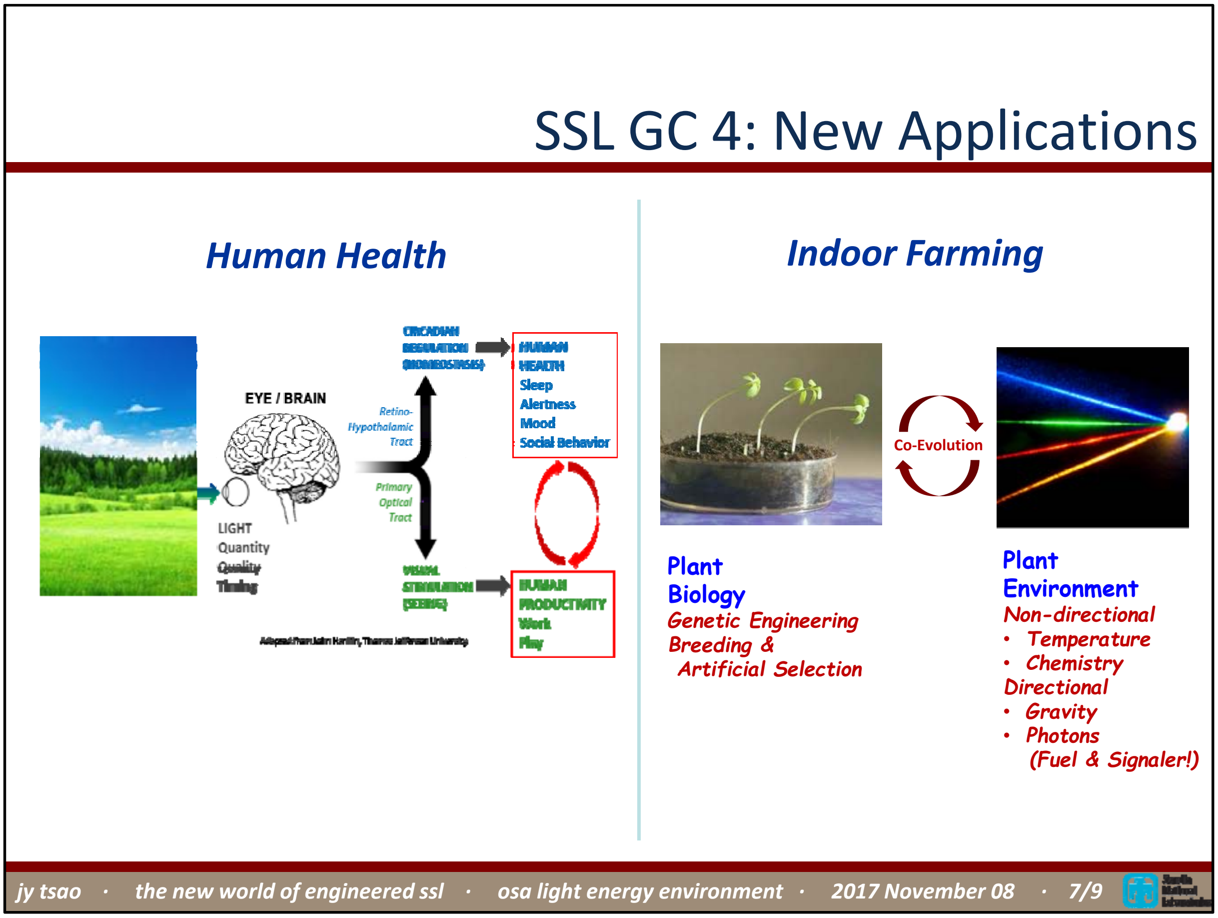
To Come?
- **Local Intelligence and Alexa-like Interactivity**
- **Cameras**
- **Structured Light and 3D Mapping**
- **Chemical/Biochemical Sensing**

Augmented Reality and Illumination/Display Convergence

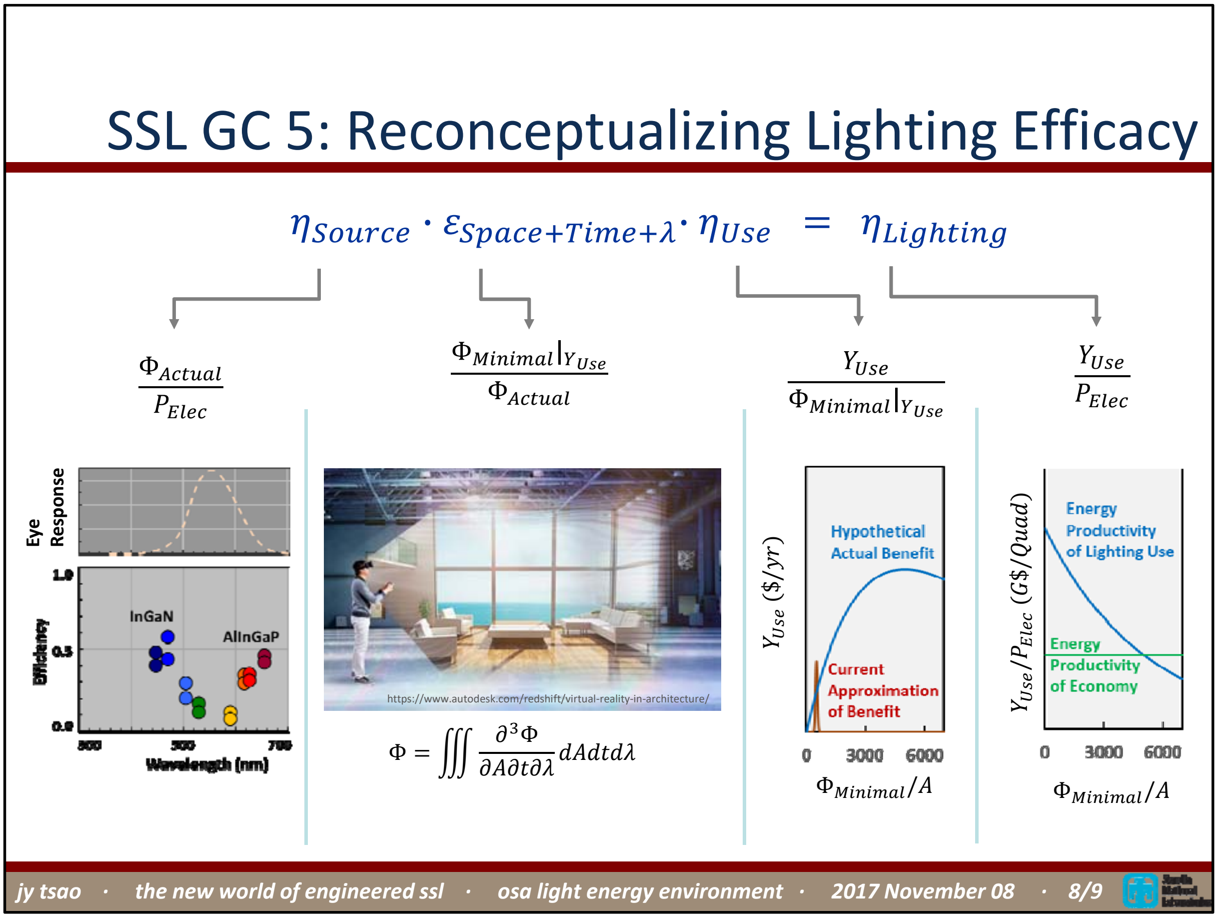
From Corning's "A Day in the Life"

After Extreme Tech (April, 2016) https://www.extremetech.com/extreme/193402-what-is-night-vision-how-does-it-work-and-do-i-really-need-it-in-my-next-car

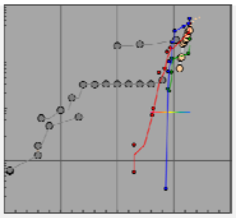
- EXPANDED FUNCTIONALITY. The third grand challenge might be loosely called expanded functionality.
- UBIQUITOUS LUMINAIRES. The reason expanded functionality is interesting is partly related to lighting, but also partly related simply to how ubiquitous lighting *fixtures* are. Lighting fixtures are everywhere humans are because humans need light to go about their everyday lives. In fact, they are the most ubiquitous of all grid-connected appliances on the planet. What that means is that the lowly lighting fixture has the potential to be *the* conduit to the Internet of Things. It's already there, it already has grid power, why *not* turn it into a hub for all sorts of other Internet-of-Things functionalities?
- SONY. Indeed, Sony was probably the first company to take a baby step in this direction, announcing last year, in Japan only, its so-called "Multifunctional Light." This is a fixture with a ring that emits smart light -- that is, light that is color-temperature tunable and has on/off/dim functionality. But, most importantly, it has a disk in the middle that contains additional functionality that has nothing to do with light. It has a speaker. It has Wi-Fi. It senses temperature, humidity and the presence of people so it can help optimize the heating and cooling of your home or office. It has a microphone. Ultimately, with the addition of more local intelligence, this light fixture will listen and talk to you just like Alexa does. One could imagine additional features: cameras, structured light and 3D mapping of the room and the objects in it, sensing of more than just temperature and humidity, but of chemicals or biochemicals that one either wants or doesn't want.
- AUGMENTED REALITY. And, perhaps farthest into the future, but in a way potentially the most interesting expanded functionality, is augmented reality. This is where you use lighting to enhance some feature of the environment – like the way this BMW headlamp is enhancing the visibility of this deer in the roadway. Of course, you can only do this kind of thing when you've pixelated your beam, so that some parts of your beam are doing one thing, and other parts are doing other things. That means you've turned your beam into a projection display of sorts, and, if you could get the resolution up, you could imagine using your illumination source sometimes for illumination, sometimes for simple augmented reality, and sometimes as a full-up display. This is what some folks, including Bob Karlicek at RPI, are calling illumination/display convergence.



- NEW APPLICATIONS. The fourth grand challenge is new applications – especially applications enabled by the new ability to engineer light in space, time and spectral content. Let me mention two examples.
- HUMAN HEALTH. The first example is human health. As many of you know, and as illustrated here, there are two photoreceptor channels in the eye and brain.
  - IMAGING VISION. There is the primary optical tract in green. This is the one we've known about for a long time – the one that starts with the rods and cones in the fovea of our eye, and that provides the imaging color vision whose peak sensitivity is in the green at a wavelength of roughly 555 nm, approximately the color of green foliage. This is the photoreceptor channel that feeds into our human visual productivity.
  - CIRCADIAN REGULATION. Then there is the retino-hypothalamic tract in blue. These are non-imaging photoreceptors whose peak sensitivity is in the blue at a wavelength of roughly 464 nm, approximately the color of the blue sky, and that trigger a chain of photochemical and chemical events that regulate our Circadian rhythm. And that Circadian rhythm, in turn, influences all sorts of other processes -- sleep, alertness, mood, social behavior. So this is the photoreceptor channel that feeds into our human health.
  - GOOD AND BAD. What's interesting about this channel is that the influence is both positive and negative. Exposure to too much blue light in the evening can disturb one's Circadian rhythm. But exposure to a lot of blue light in the morning can help entrain one's Circadian rhythm. Indeed, it is very possible that the daylight levels of sunlight that we evolved under would be ideal, which means indoor illumination levels would need to be a factor 10x higher than they are currently. Needless to say, it will be very interesting to see how artificial light will be engineered in the future to benefit human health.
- INDOOR FARMING. Example two is indoor farming, potentially on an industrial scale. Some of you know about this trend. The idea is that humanity is moving to cities, so let's bring farms closer to those cities to reduce food transport and spoilage costs, and lets bring the farms indoors to extend the growing season and create a more protected environment. But then you need artificial light, and just in time here comes super-efficient solid-state lighting. Who knows how this will end up, but however it ends up, it is almost for sure just the beginning of a long-term story in which plant biology and plant environment are artificially co-evolved in complex and beneficial ways.
  - PLANT BIOLOGY. On the plant biology side of things, plants themselves can be engineered – either through direct genetic engineering or through breeding and artificial selection – beyond the ways they have already been for outdoor farming.
  - PLANT ENVIRONMENT. On the plant environment side of things, we can now engineer the environment – both its non-directional components (like temperature and the chemical environment of the roots and leaves), and its directional components (like gravity and photon flux) – with much more precision than previously possible.
  - PHOTONS. Photons are particularly important, in part because they play dual roles. First, they are the fuel that is converted, along with carbon dioxide and water, into carbohydrates and oxygen. But, second, they also provide signals that inform the plant how to grow – what kinds of morphologies to adopt. Normally, these two functions aren't independent, because sunlight isn't tunable, it comes as it is. But with solid-state lighting, these functions *might* be separately tunable. One might even imagine tailoring the directional components of the environment to produce morphologies optimized for robotic harvesting. And if robotic harvesting could be perfected, it could reduce or even eliminate one of the most expensive inputs to farming, human labor, and perhaps revolutionize the economics of indoor farming, especially of leafy and fragile vegetables.



- UNDERSTANDING APPLICATION EFFICACY. The fifth grand challenge is "re-conceptualizing lighting efficacy." In the new world of engineered light even something so basic as lighting efficacy is not as simple as it used to be.
- SOURCE EFFICACY. Before, lighting efficacy took into account only the first term on the left -- the efficacy of the source in actual optical lumens produced per electrical Watt consumed. The emphasis was on the power efficiency of solid-state lighting sources at wavelengths that fit within the human eye response and therefore could be translated into lumens.
- SPACE+TIME+λ EFFICIENCY. But in a new world in which light can be engineered in space, time and spectral content, it's incomplete. In particular, we need at minimum to take into account one more efficiency: this second efficiency that we might call the space+time+spectral-distribution efficiency.
  - Imagine you start with your actual lumens, distributed in some way in space, time and spectral content. In space, the lumens are distributed according to how the lighting architect positioned the luminaires and selected them for their beam patterns. In time, the lumens are distributed according to the on/off or dimmer switches that the user controls. In spectral content, the lumens are distributed according to the CRIs and color temperatures that the lighting architect thought best for the typical use case of the room. These actual distributions of light are of course reasonable, we make use of them all the time, and if you integrate those distributions up over space, time and spectral content, then you get some overall amount of lumens.
  - But surely there are also more minimal distributions of light: distributions which preserve the usefulness of the light while making use of much less light. If I'm in my office working at my desk, maybe the lights in back of me don't need to be on. If I turn around to grab something from my bookshelf, maybe the lights at my desk now don't need to be on. In 2010, about seven years ago, Roland Haitz, one of the pioneers of solid-state lighting, estimated that the ratio between the actual light we use and the minimal light for the same usefulness might be a factor two or three, which means that this space+time+spectral-content distribution efficiency might be as low as ½ or 1/3.
  - But how would we know what this minimal distribution is, so that we could figure out what the efficiency of our actual distribution is, so as to motivate the continuing development of technologies for engineering those actual distributions?
  - Here I speculate on one way, perhaps not practical now, but perhaps possible in the future. And that would be to use computational simulations in a virtual reality environment. In virtual reality, there are no limitations except on computational power that would keep us from arbitrarily redistributing light in space, time and spectral content. An algorithm could be used to distribute the light to preserve productivity while minimizing total amount of light used. The algorithm might be designed by a lighting architect, or might be artificial intelligence based. And it would only be a starting point. You could then vary the algorithm and compete algorithms against each other. The result would an optimal algorithm for minimizing light while preserving the usefulness of the light.
- USE EFFICACY. Note that preserving the usefulness of the light is critical, because otherwise it isn't a fair comparison. You could always save energy by simply decreasing the amount of light and making it less useful. But this raises the notion that light usefulness itself should be more subject to quantification than it is now. Right now, we often tacitly make the assumption that, if you were to plot usefulness versus light level, the 500 lux illuminance that is standard for offices is best – less is too little, more is too much. But of course it is probably not like that at all. Maybe, if we were to plot human productivity versus illuminance it would increase rapidly up to 500 lux due to the benefit to human vision, and continue to increase, just at a lower rate, up to some illuminance comparable to that of a cloudy outdoor day due to the benefit to human health of entrainment of Circadian rhythm. Maybe only beyond that would the human benefit decrease as the light becomes so bright as to cause discomfort.
- APPLICATION EFFICACY. You can see now where this is going. If you multiply all three of these efficacies or efficiencies together, you might get a lighting efficacy in units of $/Wh, or G$/(TWh), which is starting to look like the energy productivities used by energy economists to measure the contribution that energy makes to economic activity. One could imagine choosing the best operating point for the use of lighting in a particular application based on if the energy productivity of the lighting use is greater or less than the energy productivity of the economy as a whole!
- RECONCEPTUALIZING LIGHTING EFFICACY. In any case, there is a lot to be done in reconceptualizing lighting efficacy, as we enter this new world of engineered solid-state lighting, combined with a new world of computational light simulations.


Solid-State Lighting Grand Challenges for the Future

1. ***Valley of Droop***
2. ***Red-Yellow-Green Gap***
3. ***Expanded Functionality***
4. ***New Applications (Human Health, Indoor Farming)***
5. ***Reconceptualizing Lighting Efficacy***

- THANK-YOU. With that, thank-you very much. Here are the 5 grand challenges I discussed, happy to have questions and discussion about these or any other aspects of solid-state lighting.