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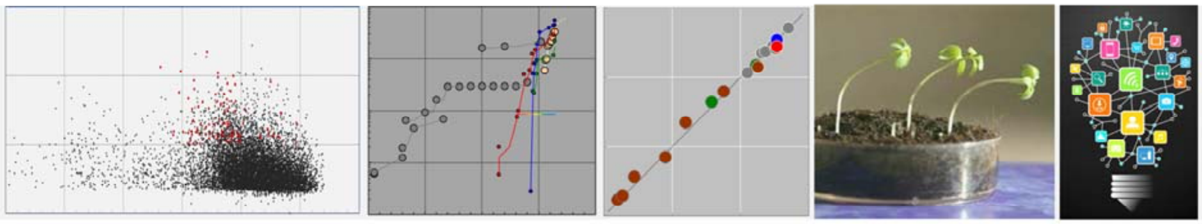

The New World of Lighting: SSL and Beyond

Past; Present; Future (SSL, Beyond SSL, Beyond Lighting)

Jeff Tsao

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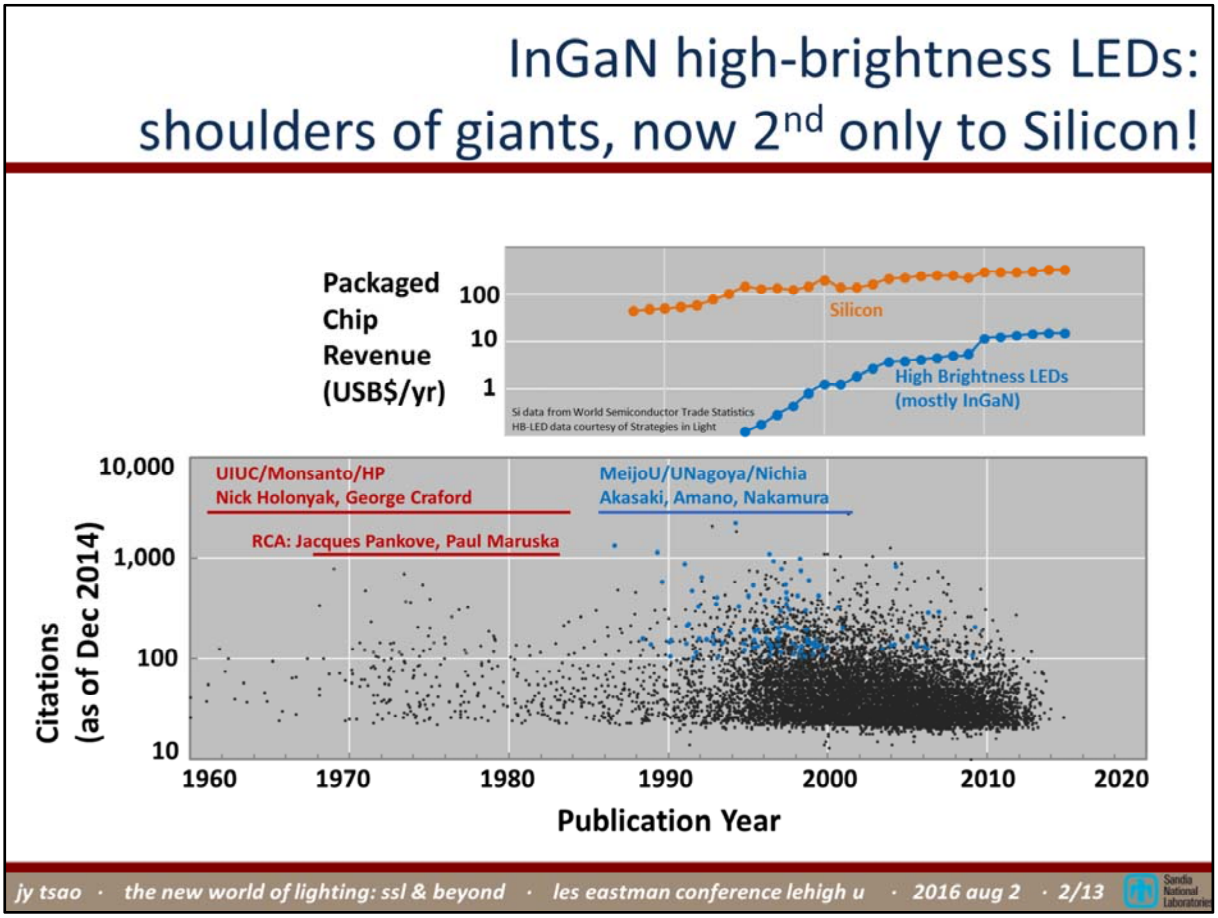
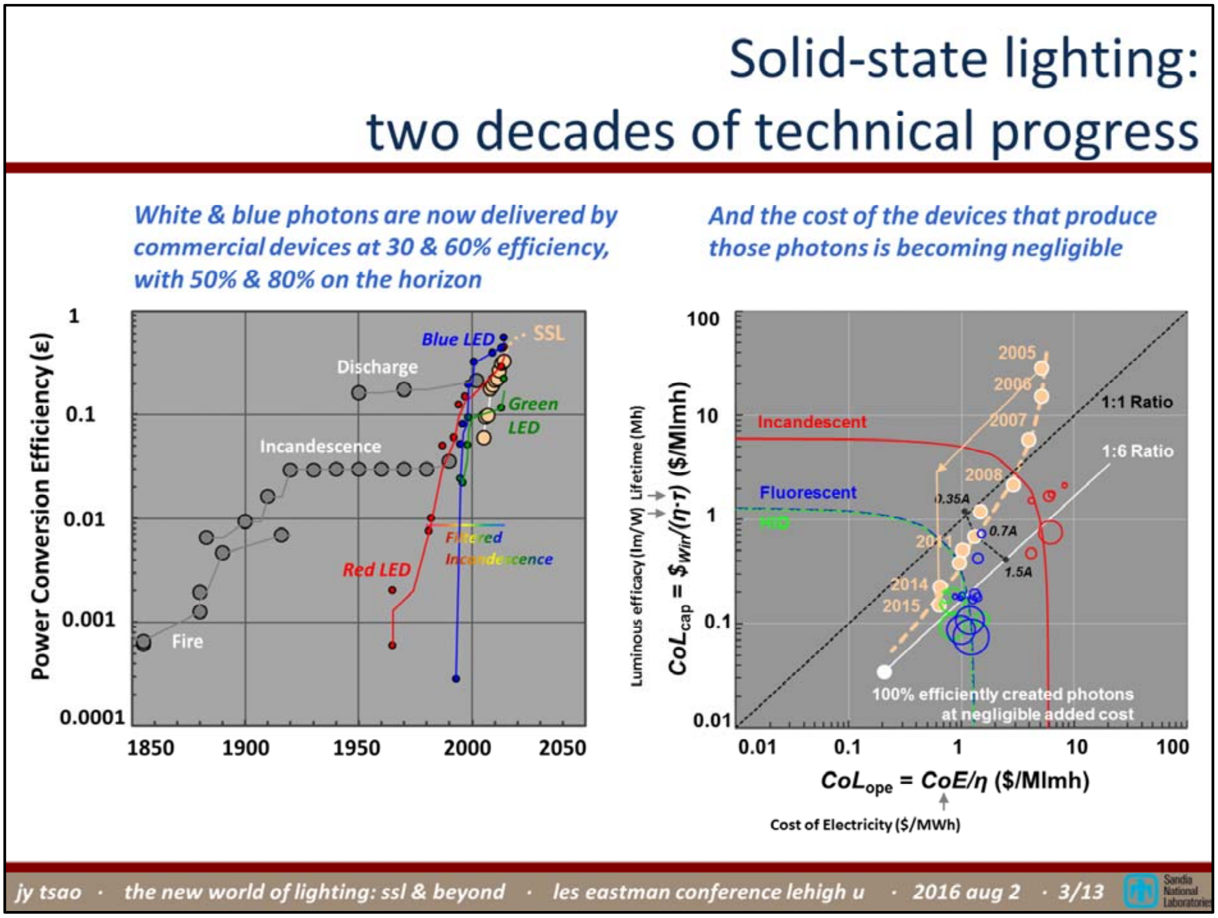
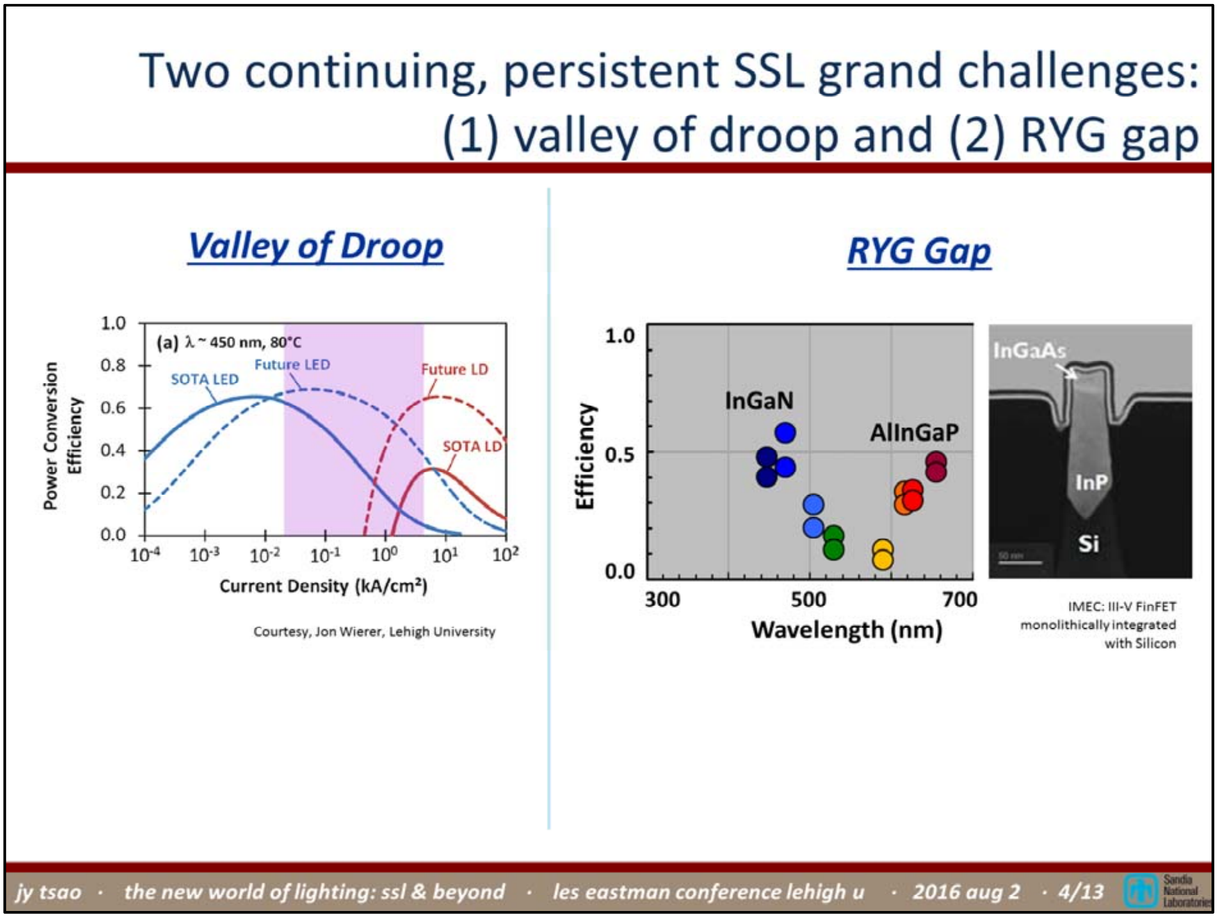
- HELLO. Good morning. Thank-you, Jon, Siddharth and Grace, for the invitation to give this talk. As Jon knows, I was a bit apprehensive at first about this talk, as I've been inching away from solid-state lighting per se for the last couple of years. Instead I've been thinking more about what's next *after* solid-state lighting. So if it's OK with you, that's what I'd like to make the focus of my talk: the new world of lighting that solid-state lighting enables, but that goes beyond solid-state lighting.
- OUTLINE. I will talk a little about the past and a little about the present, to set the context. But mostly this talk will be about the future – one piece of which intersects solid-state lighting, a bigger piece that goes beyond solid-state lighting, and possibly an even bigger piece that goes beyond lighting itself.
- 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.



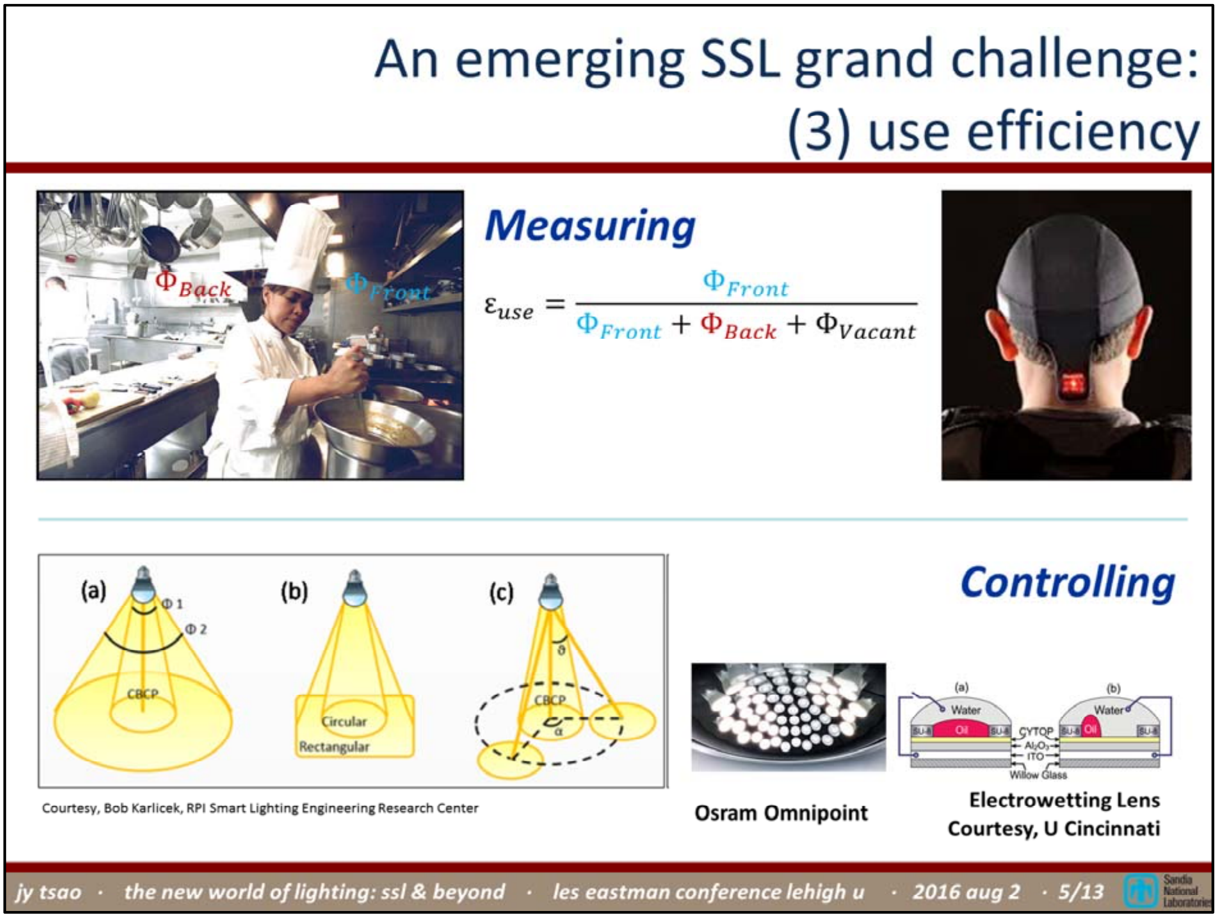
- SHOULDERS OF GIANTS. Let me start by paying tribute to the past. High-brightness LEDs, of which InGaN blue LEDs are the most important, have as we all know been amazingly successful. The work at the University of Illinois of Nick Holonyak and his many students, the work at Monsanto and HP of George Craford and his many colleagues, the work at RCA of Jacques Pankove and Paul Maruska, and the work of countless others – all of that work paved the way for these successes.
- ANN. And of course the Nobel-Prize-winning work of Akasaki, Amano and Nakamura in the late 1980's and early 1990's changed the game completely. To put their work in context, here I show a citation history of research in the wide-bandgap nitrides. Each of these dots represents an article, and you can see that the Akasaki, Amano and Nakamura work, color-coded blue, was singular, and catalyzed an explosion of research.
- ECONOMIC SUCCESS ALSO. At the same time, the blue LED also became a huge commercial success. Here I plot a history of packaged chip revenue. High-brightness LEDs, which in the early 1990's generated essentially zero revenue, now generate about $15B/yr, second among semiconductor technologies only to Silicon, and even a non-negligible fraction, something like 5%, of Silicon, which is amazing considering the reach that Silicon technology has into modern society.



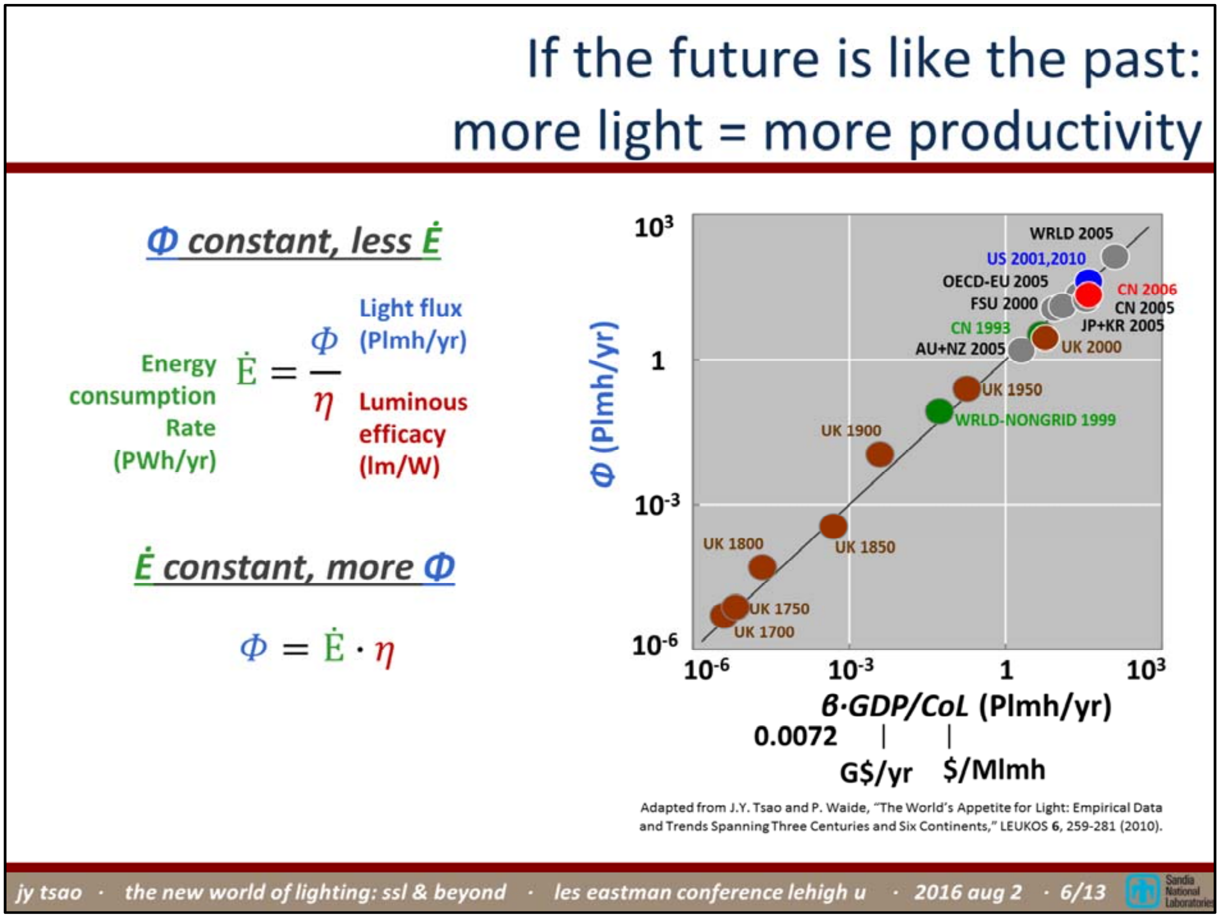
- WHAT WERE THE ENABLERS? What was the technological progress that enabled that commercial success? Here I show the two most important overarching metrics of that progress: efficiency, and cost.
- EFFICIENCY. Here on the left you see a 150-year history of lighting efficiency starting with fire, then 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, or purchase, cost of light: the purchase cost of the lamp divided by the efficiency with which the lamp converts electricity into light, amortized over the life of the lamp. On the bottom axis is the operating cost of light: the cost of the electricity divided by the efficiency with which the electricity is converted into light. Both of these costs have the same units, $ per Mlmh. The black diagonal line represents purchase costs that are the same as operating costs; the white diagonal line represents purchase costs that are 1/6 of the operating costs.
- SSL. You can see now the trajectory of solid-state lighting, starting up here in 2005, steadily moving downwards, so decreasing in purchase cost, but also moving to the left, so decreasing in operating cost. Note that increases in efficiency lower both capital and operating costs, so the movement downwards in purchase cost is due about half to increases in efficiency and about half to decreases in actual LED lamp cost. What's most astonishing is that the purchase cost became lower than the operating cost in 2008, and is on its way to becoming lower than the operating cost by a factor of 6. In other words, the cost of the packaged devices that produce these photons is becoming negligible. That's exactly what has been the case for traditional lighting – the red, blue and green circles that correspond to incandescent, fluorescent and high-intensity-discharge lighting. But there was definitely doubt in the early years of solid-state lighting whether this would happen or not.
- FREE PHOTONS. What's different about solid-state lighting than traditional lighting is that this cost structure is taking place at an electricity-to-light efficiency that in the long run is heading towards 100%. That end-game would be this white dot: where you have 100%-efficiently created photons at negligible added device cost. I call this a world in which photons and electrons cost the same, so you can choose to use either depending on what task you are trying to accomplish.
- MORE TO DO. I'll have more to say about what that kind of world might imply, but in the meantime, you see that there is still a gap between where we are now and this world in which photons and electrons cost the same. There's a gap diagonally down and to the left, meaning in efficiency. But there's also a gap directly downwards, meaning in lamp cost. And here I want to emphasize that there is much more room for a decrease in lamp cost than appears. I'll talk later about the importance of lamp functionality beyond lighting – here I'll just say that this functionality won't come for free, so the lower you spend on lamp functionality associated with lighting, the more you can spend on lamp functionality beyond lighting.



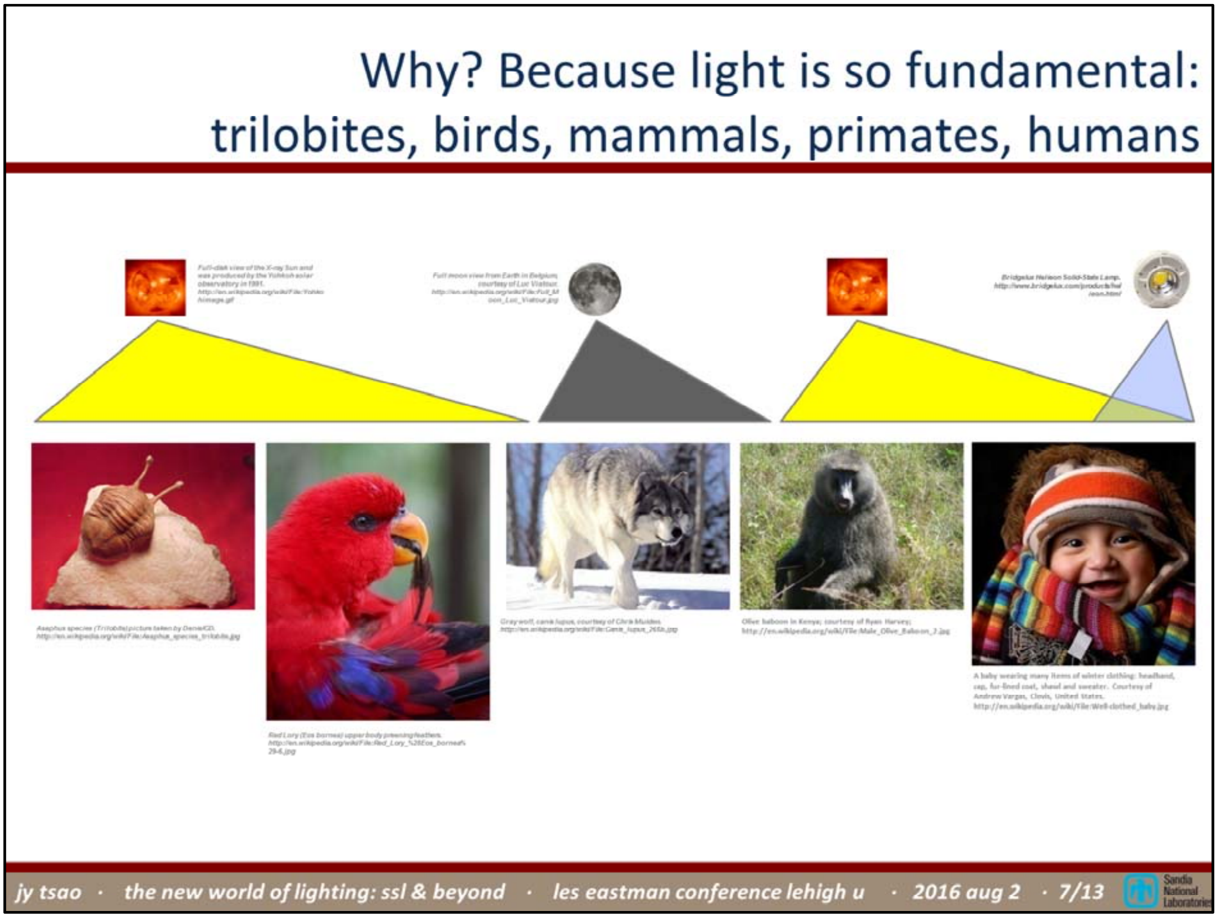
- TWO GRAND CHALLENGES. To continue to increase efficiency and decrease cost, there are two continuing grand challenges, grand challenges that much progress has been made towards, but that still persist.
- GRAND CHALLENGE 1. The first grand challenge is so-called efficiency droop: when you drive a blue 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 the 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 can *increase* efficiency, we could eliminate this valley of droop.
- GRAND CHALLENGE 2. The second grand challenge is the red-yellow-green gap. InGaN LEDs are very efficient with just a little bit of Indium, in the purple and blue, but not very efficient when you add a lot of Indium, in the green, yellow and red. AlInGaP LEDs are very efficient with a little bit of Aluminum, in the deep red, but not very efficient when you add a lot of Aluminum, 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. Now there are all sorts of materials and physics issues associated with this RYG gap, and I show this figure on the far right to suggest that it is at the nanoscale that the solutions might be found. This is a figure from IMEC in Belgium, in which they have monolithically integrated with silicon a nanoscale region of InGaAs to be the active region of a FinFET. When it comes to mixed materials integration, there are all sorts of nanoscale phenomena, like strain compliancy, or aspect-ratio trapping, that, if controlled, could be helpful.
- PERSISTENT. As I said, these two grand challenges have been around for a while, and everyone knows them, and I'm optimistic that progress will be made. But, in the meantime, there is another challenge that is emerging, one that I feel is also grand challenge like.



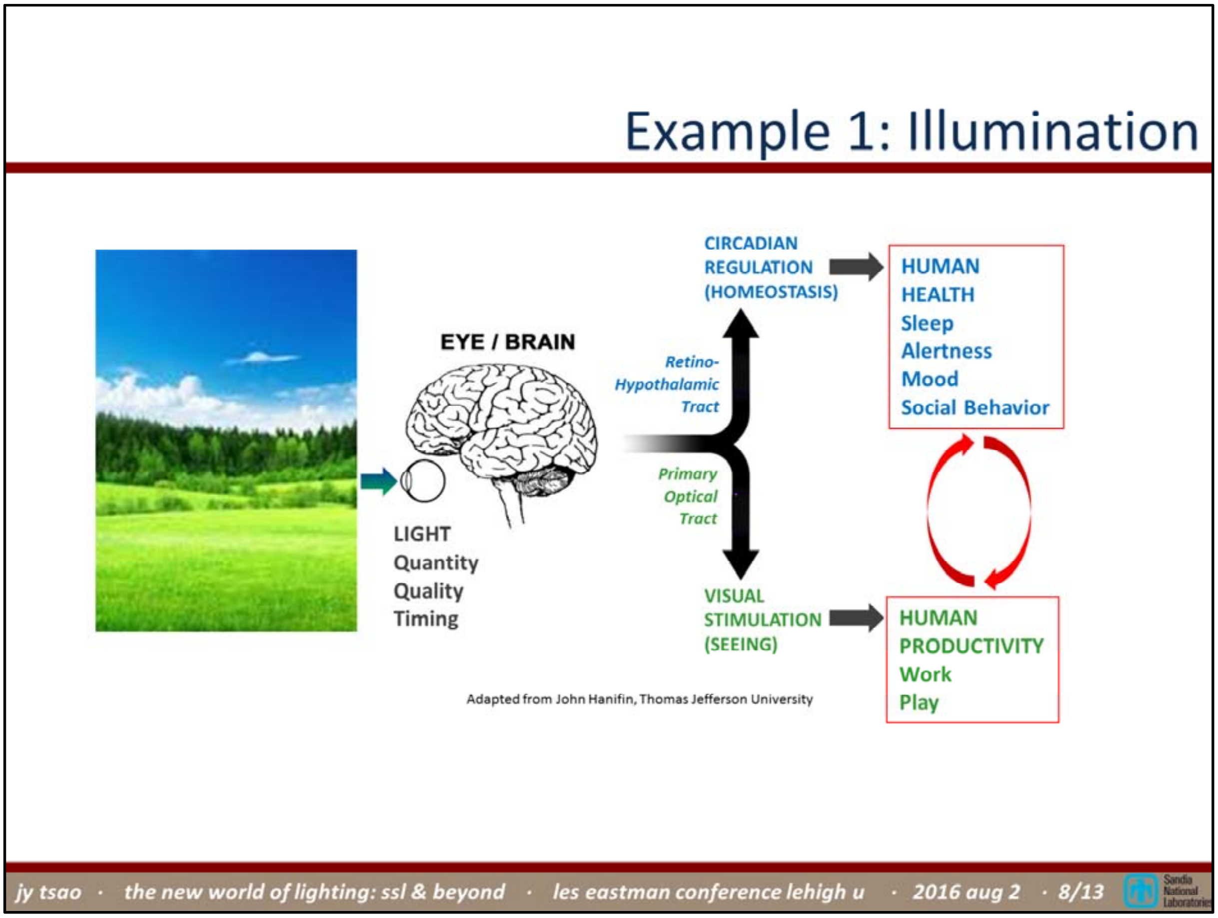
- GRAND CHALLENGE 3. This grand challenge might be called use efficiency. When SSL was at efficiencies of a few percent, the biggest gains to be made were in increasing those efficiencies. Now that SSL is at efficiencies of 10's of percent, the biggest gains to be made may very well be in the efficiency with which light is used, not the efficiency with which it is produced. Think about it: how often are lights on in an empty room; and how often is an entire room lit but most of that room you aren't even facing? There may be as much as 2x or 3x to be gained in use efficiency. To improve use efficiency, though, there are two things we need to be able to do.
- MEASURING. The first thing we need to do is measure. Suppose Φ_{Front} is the light flux that you see, the light flux coming from in front of you in the room you are in. Suppose Φ_{Back} is the light flux coming from in back of you in the room you are in, light flux that you can't see. And suppose Φ_{Vacant} is the light flux in rooms that are vacant in the house or building you are in. Then a rough measure of use efficiency might be the ratio: the light flux you can see divided by all of the light fluxes. The challenge is to measure all of these fluxes: the light fluxes in the rooms that are empty and the light fluxes in the room you are in. And you want to separate out the light fluxes in the room you are in between the flux you can see and the flux you can't see. I don't think one would want to do it in as obtrusive a way as this, but perhaps one could using a sensor or camera like this one on the back of one's head.
- CONTROLLING. The second thing we need to do is control. Here I've borrowed a figure from the RPI Smart Lighting Engineering Research Center. It shows a hypothetical dream lamp whose spatial light flux pattern can be changed in three ways: the size of the pattern; the shape of the pattern (square or round); and the position of the pattern. If every lamp had this kind of spatial control, plus you could measure use efficiency in real-time, you would have the basic hardware tools to optimize that efficiency in real time.
- CONTROL SCHEMES: Now, people are exploring different ways for doing this kind of control, and I'll just mention two. One is to use an array of LEDs, each with a fixed but different spatial light pattern, and to switch them on and off depending on the kind of overall pattern you'd like, like this Omnipoint lamp from Osram. A second is to use a single LED, but to shape and steer it using some kind of electromechanically controlled optical element, like this electro-wetting lens from the University of Cincinnati.
- EARLY DAYS. It's very early days, and I'm not sure how many others would at this point call this a grand challenge, but my guess is that it will soon become one.



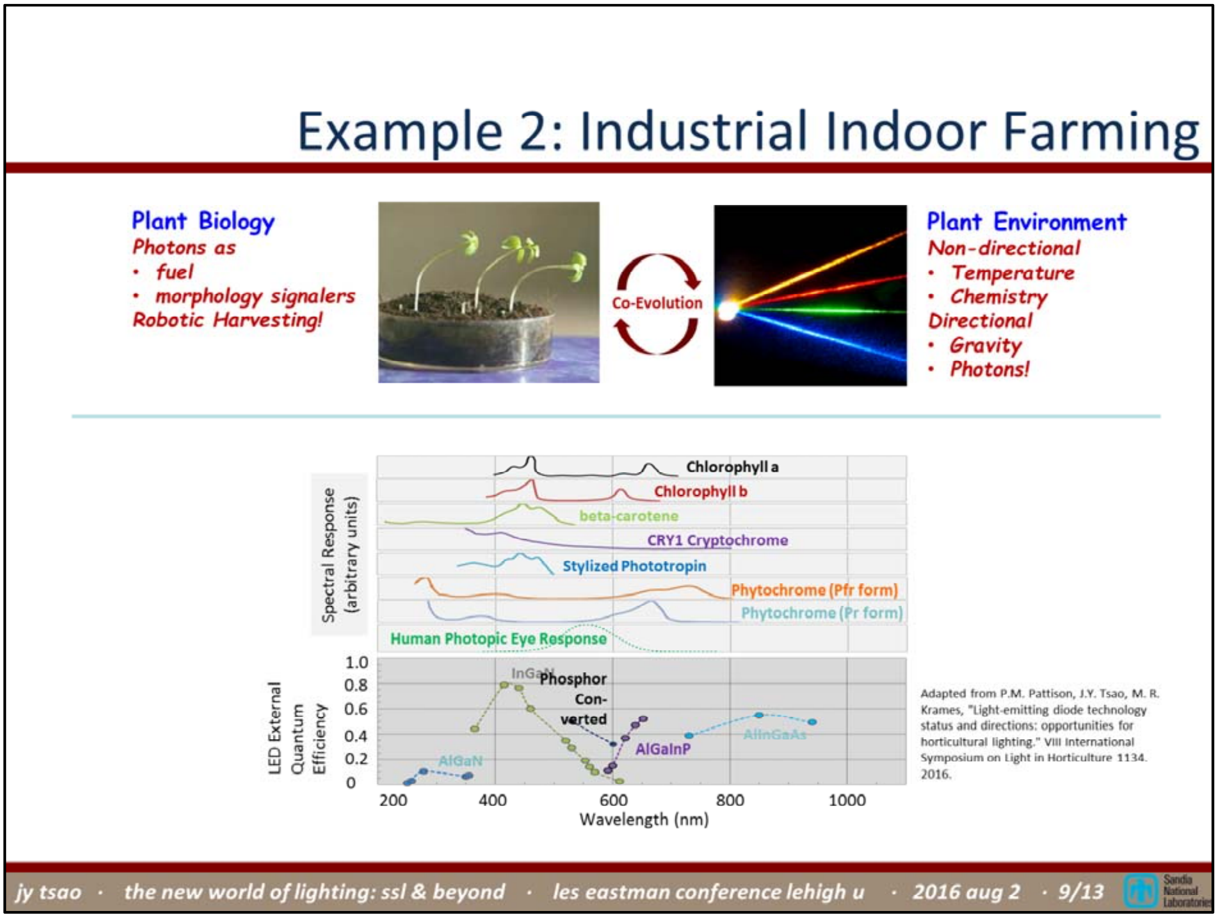
- ENERGY SAVINGS. Let me switch gears a little now. Up until now, I've talked about efficiency: the efficiency with which white light is produced, and the efficiency with which it is used. The unstated assumption was that if we're more efficient at producing and using light, and if the total light flux we as a human society consume, Φ, is approximately constant, then we won't need as much energy to produce that light. In other words, as efficiency increases, the rate at which energy is consumed, which is just light consumption divided by efficiency, decreases.
- LIGHT CONSUMPTION INCREASES. But there is another scenario, which in its extreme form would be that it isn't light consumption that is approximately constant, it is energy consumption that is approximately constant. In this scenario, light consumption increases as efficiency increases.
- APPETITE FOR LIGHT. In fact, this is exactly what has been observed in the past. The vertical axis of this 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, we don't know what the future will be, whether it will be like the past or not. But the main point I want to make is that with respect to lighting technology in the big picture it doesn't matter, and probably there will be some of both scenarios. Solid-state lighting will enable us to consume the light we already consume more efficiently, and in those situations we will save energy and that is a good thing. But solid-state lighting will be so much lower in cost and higher in functionality that it will open up opportunities to consume *more* light, and that is also a good thing because 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). But why is this? What is so special about light that when it becomes more affordable and available it always seems to be open up new opportunities for consumption?



- INTERACTION BETWEEN THE SUN AND THE EVOLUTION OF COLOR VISION. Here's one possible reason: it's because light really is *very* fundamental, not only at this instant in time to humans, but over evolutionary time to all species. To illustrate its importance, here let me take a relatively large digression, and say a few words about the interplay between light and evolution.
- 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 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 this 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, 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 light is fundamental to humans as a species.
- EXAMPLES OF LIGHT AND HUMAN PRODUCTIVITY. Now, back to the original story. Solid-state lighting will enable us to consume the light we already consume more efficiently, and in those situations we will save energy and that is a good thing. But solid-state lighting will be so much lower in cost and higher in functionality that it will open up new opportunities to consume light, and that is also a good thing because of the importance even on an evolutionary scale of light to our human species and our human productivity. So I'd like to spend most of the remainder of this talk running through four examples of new opportunities to consume light and enhance human productivity.



- EXAMPLE 1. Example one is plain old illumination, the original incentive for solid-state lighting. But plain old illumination, we now know, affects not just our human productivity directly, it also affects our human productivity indirectly, through our health. Indeed, people now talk about 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 system that enables our human productivity, whether at work or at play.
- CIRCADIAN REGULATION. Then there is the retino-hypothalamic tract in blue. This, amazingly, is one that we are only just now beginning to figure out, as the photoreceptors that it starts with were only discovered a few years ago. 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 – all of which feed into human health.
- GOOD AND BAD. Of course, with good comes bad, and some of you may have seen the recent warning from the American Medical Association, which discusses the potential detrimental effects of cool-white-LED street lights, because by being exposed to them at night, they anti-synchronize your Circadian rhythm. Certainly one of the advantages of solid-state lighting is that one can tune the color temperature so that they are warm-white and have reduced blue. But an interesting alternative solution could be exposure to much higher light fluxes during the day to overwhelm such anti-synchronizations. The human eye is so nonlinear sometimes we don't notice, but the typical office environment illumination level is a miserly 500 lux, while the typical outdoor illumination level, even on a cloudy, overcast day, is a generous and very comfortable 5,000 lux. In other words, there is room for 10x higher indoor daytime illumination levels if we were to find that these bring health benefits.



- EXAMPLE 2. Example two is indoor farming, potentially on an industrial scale. Some of you have probably heard 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 very interesting long-term story in which plants and their environment might be artificially co-evolved in complex and beneficial ways.
- MANIPULATING PLANT ENVIRONMENTS. The reason? Plants have evolved over hundreds of millions of years to respond in all sorts of ways to their environment – whether it's temperature, the chemical environment of its roots and leaves, gravity, or the quality and quantity of sunlight. What we can now do better than we could do before is artificially engineer this environment, including with artificial lighting. With artificial lighting we can potentially optimize the match between the wavelengths of the photons and the wavelengths that various photoreceptors are sensitive to – and you can see here that there are a lot of photoreceptors all with different functions and different wavelengths they are sensitive to. This will push solid-state lighting to develop wavelengths different from those that the human eye cares about – e.g., in the deep red, almost infrared.
- MANIPULATING LIGHT DELIVERY. This will also push solid-state lighting to develop novel delivery schemes. The reason? Because photons fill two separate functions for plants. First, they are of course 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 the possibility of plants in which the directional components of the environment (photons and gravity) are tailored 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 not just of indoor farming, but of farming itself.
- MANIPULATING PLANTS. And of course it's not just their environments, plants *themselves* can be engineered – either through direct genetic engineering or through breeding and artificial selection – for morphologies or other properties that enhance how they interact with their environment. There will be an interesting co-evolution of plant biology and plant environment, just as there has been for outdoor farming, but now with indoor farming and with much more human control.

Example 3: Displays

10^{-4} m²

1 m²

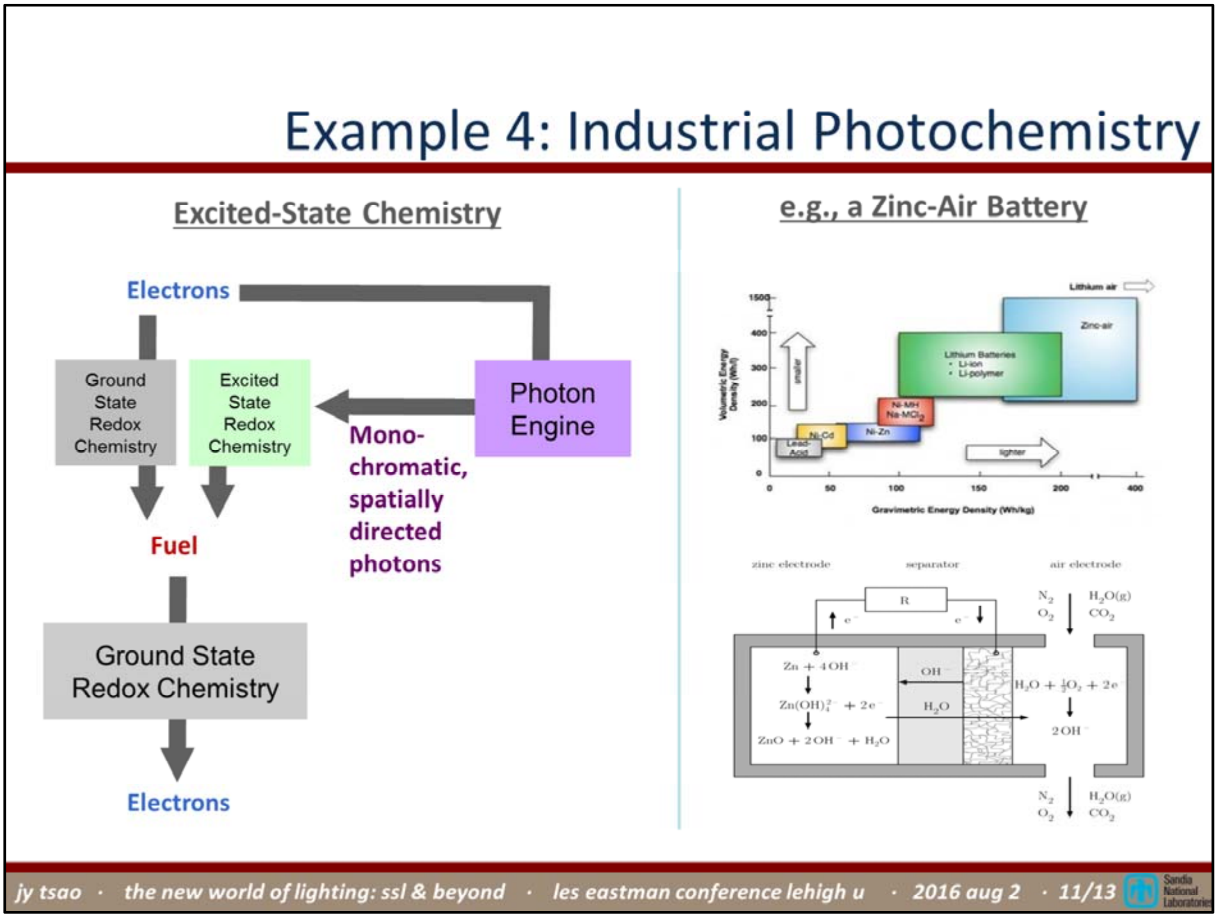
From Corning's "A Day in the Life"

10^{4} m²

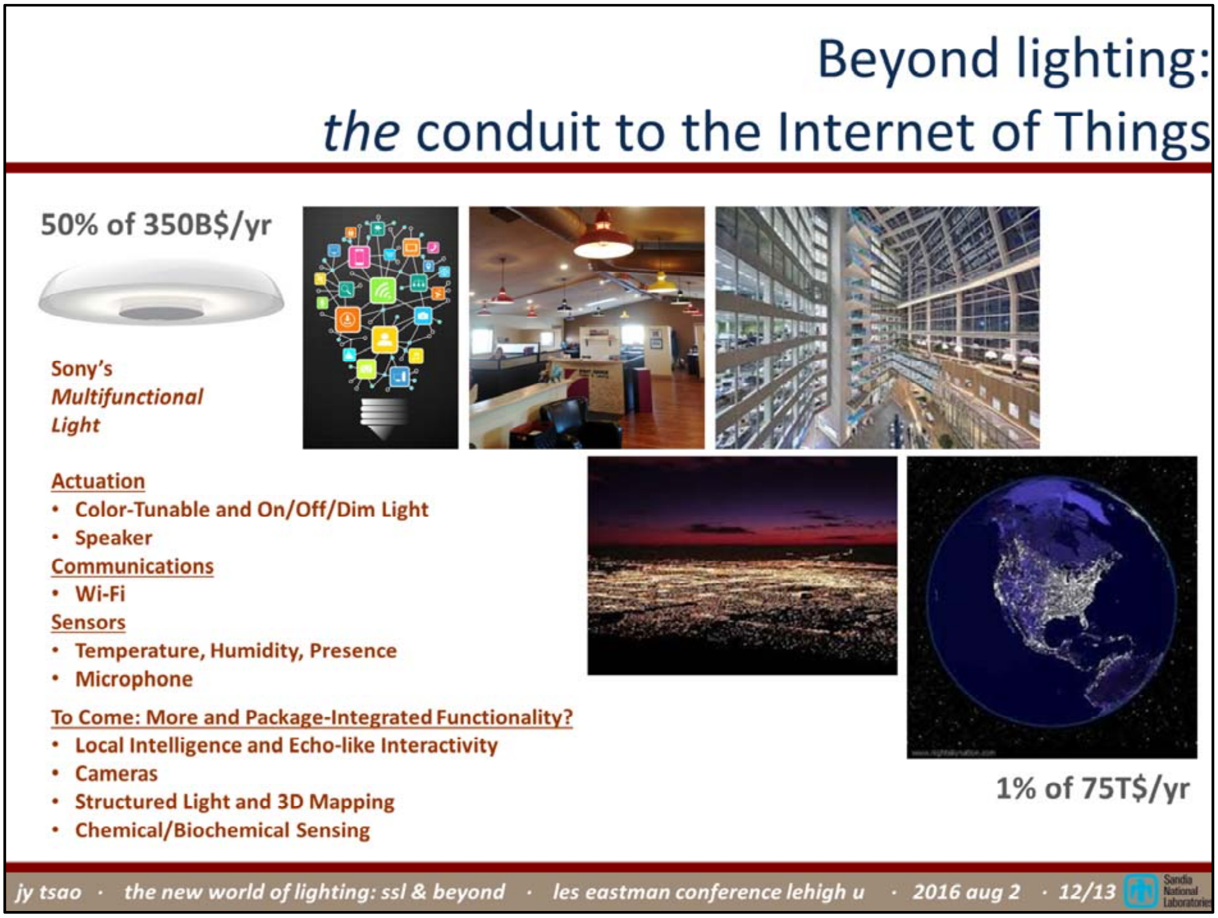
The chips are free, but they're just too bright, and need to be tiled:

$$\text{Tiling Factor} = \frac{E_{display}}{E_{chip}} \approx \frac{(50\ A/cm^2)\cdot 3V \cdot (300\ lm/W)}{5,000\ lux} \approx \frac{500\ Mlux}{5\ klux} \approx 100,000$$

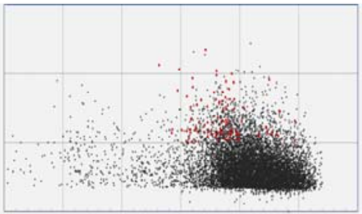
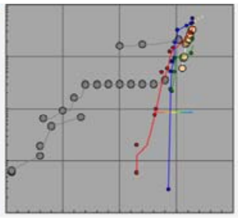
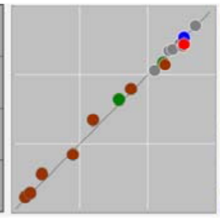
- EXAMPLE 3. Example three is displays. Displays of course are sort-of everywhere. But considering how useful they already are to us, and how much more useful they could be if there were more of them, it is actually surprising to me that they aren't really everywhere. Why aren't they? Because, in the end, they are still very expensive. You can afford them if they are really small, like in a mobile device. Or you can afford them if they are massively shared, like in a stadium display. But if they are both large and not shared, they're just too expensive.
- WHY? Why is this? I just said that LEDs are almost free, why can't LED displays also be free? It's because LEDs are too bright. In fact, it is *because* they are so bright – you get so much light out per unit chip area – that the photons from LEDs are almost free. So you can't reduce their brightness and still have them be free, you have to use them at full brightness. But a display that bright would be blinding. So you have to *tile* the LEDs – you have to dice them into tiny chips and tile them onto areas that are about 5 orders of magnitude larger than the areas of the LEDs themselves. This is a tough nut to crack, though a lot of people are trying to crack it. And if someone does, that immediately revolutionizes the economics of displays, and displays might literally be everywhere.



- EXAMPLE 4. Example four is industrial photochemistry. Up until now, photons have been considered expensive. You would only use a photon to drive a chemical process if there was a lot of unique value added by that photon. You would never use it on an industrial scale, the way you might use electrons in industrial electrochemistry. But in the coming world where photons and electrons have almost the same cost, you *might* consider using photons. The benefit would be if there are chemical routes that are not accessible through ground electronic states, but are accessible through excited electronic states that can be occupied through photo-excitation.
- FUEL CELL. In a fuel cell, for example, instead of using electrons to recharge the fuel cell through ground-state redox chemistry, could one use photons to recharge the fuel cell through excited-state redox chemistry.
- ZN-AIR BATTERY. To make this even more concrete, consider the Zn-Air battery, which has many advantages, including the highest volumetric and gravimetric energy densities of just about any battery currently being considered. You start with Zn metal and air. Then you discharge the battery by oxidizing the Zn to ZnO. But then you're stuck with ZnO, which is extremely difficult to reduce back to Zn. But ZnO is photo-decomposable through an unstable excited electronic state, so one could imagine using photons in a very clever geometry to decompose the ZnO back into Zn metal and air.
- NOT A CHEMIST. I'm not a chemist, so that's about all I dare say. But I think the time is ripe for chemists, especially photochemists, to begin thinking about possibilities for industrial photochemistry using photons that are almost as inexpensive as electrons.



- BEYOND SSL. OK, I've just given four examples of how solid-state lighting -- in particular the advent of really inexpensive photons – might open up new uses for light and new opportunities for increased human productivity.
- BEYOND LIGHTING. But solid-state lighting is also leading to a powerful side benefit that has nothing to do with how inexpensive its photons are, indeed has nothing to do with the consumption of photons. It has only to do with 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, at every scale: at the scale of a single room in a building, at the scale of a building, at the scale of a city, and at the scale of a nation indeed 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, and it already has grid power, why not turn it into a hub for all sorts of other Internet-of-Things functionalities?
- SONY. Indeed, Sony just took a baby step, announcing in January of this year its so-called "Multifunctional Light" fixture. 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. It has a microphone. Ultimately, with the addition of more local intelligence, this light fixture will listen and talk to you just like Amazon's Echo does, and on top of all that will light your room and sense the room's state. 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 chemicals and biochemicals that one either wants or doesn't want.
- INTEGRATION. All this functionality, separately manufactured then integrated into this fixture would of course be super-expensive. So the key in the future I think will be functional integration at the package level, and then perhaps even at the chip level – to the point where the LED chip or package contains all of these other functionalities almost for free.
- IMPACT. The impact? Well, to put that in some perspective, all along solid-state lighting has been thought to have the potential to double the efficiency of lighting, and therefore to halve the amount of money we spend on energy for lighting. Globally that's 50% of about $350B/yr, or $175B/yr. If through its enabling of the Internet of Things global productivity increases by even as little as 1%, the impact would be 1% of about $75T/yr, or $750B/yr. So it's very possible that this side benefit of solid-state lighting will be its largest benefit yet. Certainly something no one could have predicted in the early years.

- THANK-YOU. With that, thank-you very much. I would love to have questions and open-ended discussion.