Perspectives on the future of photonics: the best is yet to come

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One of the surprises in the run up to, and during, the United Nations' International Year of Light and Light-based Technologies (IYL) in 2015 was the nearly universal lack of awareness of how life depends completely on light, and of the widening role of photonics-based technologies in our lives today. I recognize how little credit or attention we also give to oxygen or water. Like the light from the sun that brings and sustains life, and that eons ago brought most of the energy we now consume, these crucial contributors to life are rarely thought of, not only by the general public but even within the technical community. On being reminded of what photonics enables today, practitioners of photonics were however quick to acknowledge the increasing role of photonics in modern life. That was one of one of the successes of the IYL.

I have to remind myself when talking to student groups that these young people do not recall times before digital imaging, before photons connected people all over the planet. Does it require having lived through times when x-rays of some body part required wet chemical processing, and the large film sheet being delivered or carried to the physician for interpretation, to appreciate x-ray images being sent electronically to my doctor within seconds? The great disruption that we know as digital imaging started in Bell Labs in 1969. Smith and Boyle got Nobel recognition in 2009, and still the convergence of imaging and computing is in its infancy. Imaging without optics could change an industry. "Artificial intelligence" applied to imaging promises or threatens—depending on where you are standing—to change the practice of professions dependent on image interpretation.

The scope and influence of photonics is staggering. Much of life today depends on semiconductor chips and memory. Who knows of and marvels at the 10-billion-transistor silicon processor at the heart of the smart phone? (It is a "phone" only by legacy, for screens, cameras, and photonics, not sounds, dominate the information i/o of these devices.) That the fabrication of the entire device, and the small processor and memory chips in particular, required the development of powerful, efficient, and reliable lasers is little known. The average device user is oblivious to the marvel of printing circuits at the 7-nm (soon to be 5-nm, then 3-nm) dimension.

The extraordinary photonics-driven progress and influence of what is called Moore's law has brought us new challenges. Advances in semiconductor technology will require leaps of creativity. Only about 25 silicon atoms fit across 5 nm, and quantum effects come into play. Increasing the speed of getting information into and out of chips, and the heat generated by such dense processing in silicon, are already requiring new thinking. The future lies in photons replacing electrons across the information world, in our mobile devices and in the proliferating data centers. As someone whose very smart boss in 1980 was one of the many recalling Abbe's laws who proclaimed optical lithography dead, I have come to expect and receive miracles from the science and engineering community that pushed not just the technology but the global economy to today's heights. My faith persists!

In some ways the production of chips is a pioneering subset of the advances to come to industry, sometimes dubbed Industry 4.0. Precision with laser tools, sophisticated metrology, laser (and other) additive manufacturing, and smart machine vision are some of the photonics-based components of this next industrial revolution. The rate of adoption will depend in part on increasing the interest and involvement of people with photonics skills in the challenges of manufacturing. Unfortunately, in the "Western world" in particular there are strong scientific cultural forces working against this.

The highly competitive automotive manufacturing sector has been adopting aspects of Industry 4.0. And while there is a lot of excitement in this important consumer market segment around autonomous vehicles, photonic sensors are already making driving safer. I am reminded when I get an older rental car of the benefits of rearview cameras and blind-spot detectors. The camera-enabled autopilot features of one electric car have given me a glimpse of the possible future, and what I have seen of the lidar sensing system in another suggests safer roads ahead. Photonic gyros in every large passenger plane make these behemoths already almost autonomous. Quantum photonic compasses lie ahead. Laser measurements of speed and wind will likely replace the pitot tubes implicated in some recent tragedies. Photonics will continue to improve transportation systems of all kinds in ways proposed before the photonics technology was ready and affordable, and in ways we have not yet thought of.

VR (virtual reality), AR (augmented reality), and MR (mixed reality) are applications of photonics undergoing intense development. While the concepts are not new, market realization seems imminent with the advances in the photonics headgear and the affordable processing power. Entertainment and games may be what drive the large consumer interest, but the technology has great promise for medical applications, for training, and in Industry 4.0 factories.

One of the successes of photonics has been the adoption of solar power. Around 100 GW of solar generation was added across the world in 2017. What long seemed inevitable to those aware of the potential of this environmentally friendly resource has been excruciatingly slow to

A star-formation site, nebula NGC 6357, showing the scope of photonics on a macro scale. Image reproduced with permission. X-ray: NASA/CXC/PSU/L.Townsley et al.; Optical: UKIRT; Infrared: NASA/JPL-Caltech.

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come. The transition to solar and other renewables remains far from complete of course, with all renewables producing still only around 20% of U.S. electricity. Solar energy is economically competitive today, and can be made more so with further photonic engineering. Storage, the inertia of already capitalized polluting power generation and its associated grid, and politics are slowing adoption, but solar is becoming a preferred energy source for new power generation plants. Whether the fossil fuel era ends due to dwindling supplies, or better, due to moves to protect our fragile planet, photons will play a major role in providing part of a feasible alternative.

More efficient lighting, especially LEDs, again a product of photonic engineering, seems to be already reducing the electricity needs in the affluent parts of the world. These light sources will greatly reduce the global energy burden as billions increase their use of lighting, and as the world deals with the scandal of the light poverty that afflicts almost a billion humans.

As one looks across science, one sees photonics enabling progress everywhere. Particle detection at CERN, Super-Kamiokande, Gran Sasso, and so on rely on optical detectors. Optical techniques pervade chemistry. Lasers are used for analysis of plasmas, solid state materials, and every form of matter from rocks on Mars to human eyes or skin. The exquisitely precise LIGO laser systems verified century-old hypotheses, and exawatt lasers will shortly test our understanding of the physics of the vacuum. Attosecond probes are bringing more understanding of fundamental dynamic behaviors at the atomic and molecular level, while the increasing accuracy of optical clocks now requires a redefinition of time. Astronomy has always been dependent on optics. It has been my good fortune to be able to marvel at the images of our small blue planet, the heavens as seen by Hubble, and the astounding close-ups of the planets and Pluto. And these inspiring images were produced by technology now considered old, if not obsolete.

Healthcare may be the field of greatest photonics activity. It embraces the routine use of medical imaging in clinics of all kinds, traditional and new devices in vision care, and ever more sensitive optical instruments to analyze bodily fluids.

Ophthalmologists were early adopters of photonics technology for both diagnostic and therapeutic applications. Lasers have long provided the "gold standard treatment" for slowing retinal deterioration, and now femtosecond lasers are preferred for cataract surgery. Those who elect can have laser vision correction. With now ubiquitous OCT (optical coherence tomography) and advances in retinal imaging, eye examinations may provide early warning of neurodegenerative disease, allowing better understanding and, ultimately, mitigation.

Genomics, which brings the hope of better understanding and is already used to personalize treatments, is mostly based on optics and powerful (photonics-printed) processors. The cost of getting the genomic data has dropped at a rate that outstrips Moore's law. We have only begun to glimpse the complexity and sense the possibilities of using similar technology to unravel the other omics.

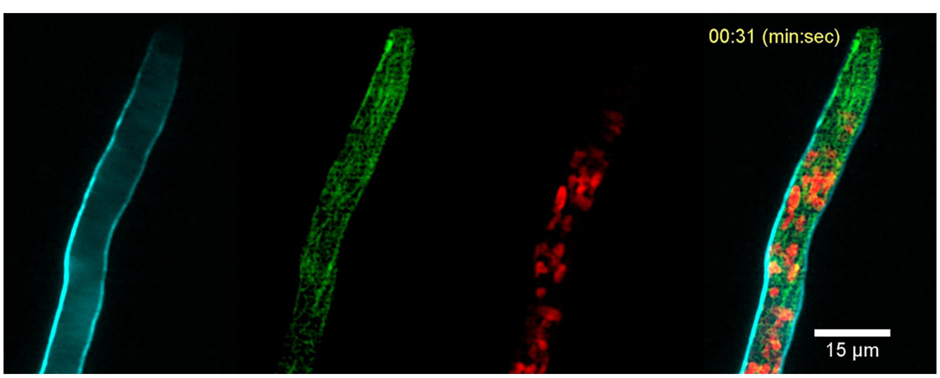
Beyond the clinics, the number of laboratories engaged in biomedical research that use photonics, and those developing photonics techniques, continues to grow. Diagnostics techniques continue to dominate. It is difficult to keep up with the acronym-rich field of sub-Abbe microscopy. The potential for real-time disease detection using light scattering and polarization techniques needs focus.

At the same time as more sophisticated photonics-based techniques and equipment are realized, the adaptation of smart mobile devices for field work shows tantalizing promise to bring medical tests into homes. It will be important to find economic support to deploy these through the developing areas of the world that lack local physicians and medical equipment.

Advances in photonics can offer further wonderful changes to our world. I have concerns about how quickly and efficiently we will unleash the potential. It is financing from taxpayers that supported the research that has taken us this far. As competition for tax revenues grows in our world of changing demographics, it will be challenging to continue to claim tax monies for something that the taxpayer does not see as beneficial. That is still a reality for photonics today where photons brings a quizzical look and optics means eyeglasses. We have made some inroads in some centers of government in gaining recognition, but much more needs to be done.

I already alluded to my second concern. I have had the pleasure of interacting with many of today's photonics students, impressively bright and well-motivated young people. I do not see enough encouragement or pathways for them to bring the power of photonics to the world of manufacturing, to agriculture and the food chain, or to energy. There certainly is scope for a fulfilling career within photonics, and photonics will diffuse out into wider use. My hope is that more of the talented people who are acquiring photonics expertise will find motivation and support to build the bridges to the many sectors that can benefit substantially from our technology.

My experiences of the optics and photonics community, the creativity and resilience, leave me happily confident that I will see my life blessed with more benefits of photonics. Others will be able to look back to say, yes it was indeed the century of the photon. The best is yet to come.



Multicolor imaging of a living hypha of *Neurospora crassa*, showing the range of optical technology on a micro scale. Image reproduced with permission. J. Licea-Rodriguez et al., *J. Biomed. Opt.* **24**(1), 016501 (2019).

Eugene G. Arthurs was CEO of SPIE, the international society for optics and photonics, from 1999 to 2018. He received his BSc (1st class honors) in 1972 in physics and his PhD in 1975 in applied physics from Queens University Belfast, Northern Ireland. His PhD research was in generation and measurement of tunable ultrashort pulses. In 1973, he taught the MSc class in optoelectronics at Queens while continuing his research. He then moved to Imperial College in London where he conducted research on lasers sponsored by the U.S. Air Force. He joined Barr and Stroud PLC in Scotland as head of the Laser Department in 1975. In 1980 he joined Quantronix Corporation in New York, leading laser applications development and then managing its business for the semiconductor equipment market. From 1983 to 1997, he was with Oriel Corporation in Connecticut, initially as vice president of technology and marketing and from 1991 as president. He was president and CEO of Cleveland Crystals Inc. from 1997 to 1998. He is a fellow of SPIE and OSA and serves on corporate and advisory boards.