Roland Haitz:
Twenty Years of Mentorship, Collaboration and Inspiration[1]

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Roland Haitz had by any measure a rich life. Others can speak better to his formative pre-professional years, and to the two early phases of his professional career: his "semiconductor device electronics" phase while at the Shockley Semiconductor Lab and Texas Instruments, and his "low-power optoelectronics" phase while at Hewlett-Packard. I had the privilege of working with Roland during the third phase of his career, in what might be called his "power optoelectronics" phase while at Hewlett-Packard, Agilent and QuarkStar. These were the two decades spanning roughly 1995 through 2015 – major chunks of both his and my careers. Throughout this period, I benefited enormously from his mentorship, collaboration and inspiration, and it is a pleasure to reminisce about these.

Our papers together

Let me start with the papers we co-authored together. There were only four, so not many, but I like to think we made each one "count" -- and behind each paper are stories that shed light both on Roland's character as well as on some of the history.

1999: "The Case for a National Research Program on Semiconductor Lighting"[2] I sometimes think of this as the "solid-state lighting goes from impossible to possible" paper. It was "just" a white paper: at the time it was too forward-looking and too much of a call to action to be published in a scholarly journal. Instead, it was sponsored and distributed by the Optoelectronics Industry Development Association, whose then-President, Arpad Bergh, knew both Roland and me and encouraged us to put our heads together to write it. We enlisted help from two collaborators, Fred Kish (then at Hewlett-Packard) and Jeff Nelson (then at Sandia), and got to work. The theme of the paper, that solid-state lighting for general illumination was someday possible and could lead to massive energy savings, was not totally new: in 1998, Japan had initiated their "Light for the 21st Century" national project with just such a theme.[3] But our paper provided the first *quantitative* data and projections in support of the theme. The data were from Roland's diligent and prescient collecting of quantitative cost and performance benchmarks from many years of light-emitting-diode (LED) technology:[4] when plotted logarithmically versus year, it showed a Moore's-Law-like exponential progress that has since come to be known as Haitz' Law; and when extrapolated out a couple of decades into the future, it suggested that LED technology would someday out-compete traditional technologies for general illumination. The projections were from Roland's quantitative analysis of the co-evolution of industry revenue, research and development (R&D) investment, technology evolution, market penetration, and global energy savings. Of course, even buttressed by quantitative data and projections, it took courage[5] to extrapolate out so far into the

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[1] Sandia National Labs Review & Approval # for this article: SAND2015-7782 S (2015).
[2] R. Haitz, F. Kish, J.Y. Tsao, J.S. Nelson, "The Case for a National Research Program on Semiconductor Lighting," presented at the Annual Forum of the Optoelectronics Industry Development Association (1999).
[3] See, e.g., the "Light for the 21st Century: The Development of Compound Semiconductors for High Efficiency Optoelectronic Conversion" Year 2000 Report of Results (Japan Research and Development Center of Metals' National Project, 2000), English translation by K.V. Sereda and J.Y. Tsao in 2002. The target of this program was "an energy efficiency twice that of traditional fluorescent lamps, through the use of long-life, thin, lightweight, GaN-based high-efficiency blue and ultraviolet LEDs."
[4] The data were from the famous optoelectronics division of Hewlett-Packard that Roland headed for many years. This division was to LED technology in the 1990's-2010's what Fairchild was to silicon integrated circuit technology in the 1950's-1970's: the organization from which a diaspora of alumni went on to distinguish themselves at LED companies throughout the world.
[5] That courage didn't come from thin air, but as is often the case with Roland came from a combination of theory and data: first was our understanding from theory that the extrapolation was not forbidden by fundamental physics; second

future – LEDs circa 1999 were so wimpy – so it is a testament to Roland's courage and vision that he was willing to call so boldly for a national research program to help turn that extrapolation into reality.

2010: "Solid-State Lighting: 'The Case' 10 Years After and Future Prospects"[6] I sometimes think of this as the "solid-state lighting goes from possible to certain" paper. The ten years from 1999 to 2010 were full of surprises, and this "ten years later" paper gave us the opportunity to discuss where we went right and where we went wrong with our original predictions. Perhaps where we were most right was that Haitz' Law did indeed continue, not just for the red LEDs that the original Haitz' Law data had been collected for, but for the white LEDs that were necessary for the holy grail of general illumination. That continuation of Haitz' Law triggered a virtuous spiral of industry and government R&D investment, technology improvement, penetration of existing (and development of new) markets, and industry revenue available for further R&D investment. Nonetheless, we were surprised by some of the details of the virtuous spiral. For example, we were surprised that the "green-yellow gap" hadn't been closed, and that phosphor approaches to white light ended up prevailing. We were also surprised at some of the stepping-stone markets that the industry was using to drive progress enroute to general illumination – in particular the increasing importance of the market for LED-backlit liquid-crystal displays. Indeed, because of the magnitude of these stepping stone markets, industry R&D investment was both larger than we had anticipated and larger than the government R&D investment that was important but ended up smaller in scale than we had originally called for. Nonetheless, through both the non-surprises and surprises, incredible progress *was* made, and by 2010-2011 one could for the first time say that the displacement of traditional by solid-state lighting had become a future certainty.

2011: "Solid-State Lighting: Why It Will Succeed, and Why It Won't be Overtaken"[7] I sometimes think of this as the "solid-state lighting goes from now to forever" paper. It was one thing to be convinced that solid-state lighting had become a certainty. But, in trademark bold Roland fashion, this paper went further, and made the prediction that, in the end game, the characteristics of solid-state lighting would make it difficult if not impossible for it to be overtaken by *any* subsequent technology. Those characteristics are: continued headroom for efficiencies to 75% and beyond; easy compatibility with digital control for increased functionality and especially increased efficiency of light *use* (not just light creation);[8] and a lighting element whose purchase cost was negligibly small compared to its operating cost.[9] Even with these powerful characteristics the prediction is bold, but, again, with his trademark courage Roland was willing to make it.

2015: "The Blue LED Nobel Prize: Historical Context, Current Scientific Understanding, Human Benefit"[10] This was our last paper together, and the last paper of Roland's life. With the awarding of the

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was Sandia's recent experimental demonstration of a semiconductor light emitter with an efficiency, 50%, of the order of what we were extrapolating to [K.L. Lear, K.D. Choquette, R.P. Schneider, S.P. Kilcoyne, K.M. Geib, "Selectively oxidised vertical cavity surface emitting lasers with 50% power conversion efficiency," Electronics Letters **31**, 208 (1995)]. Note that Sandia's demonstration was a powerful existence proof, but was in the infrared rather than the visible, and at power levels much lower than what would eventually be needed for general illumination.

[6] R.H. Haitz, J.Y. Tsao "Solid-state lighting: 'The case' 10 years after and future prospects," Physica Status Solidi (a) **208**, 17-29 (2011).

[7] R. Haitz and J.Y. Tsao, "Solid-state lighting: why it will succeed, and why it won't be overtaken," Optik & Photonik **6.2**, 26-30 (2011).

[8] Roland was fond of saying that photons from near-point-source semiconductors, unlike those from traditional incandescent and gas-discharge lamps, are "trained early" and thus would be more easily directed in space ("photon herding," he would often call it). Combined with easy control of the intensity of semiconductor light emitters, Roland was a big fan of the digital control of solid-state lighting in time and space for enhanced efficiency of use. He was also a big fan of other kinds of digital control, e.g., of the chromaticity of solid-state lighting for human health.

[9] This last characteristic was one that Roland often came back to in his thinking. Because lighting-device purchase cost would ultimately be small compared to lighting-device operating cost, Roland argued in 1999 that the return on industry investment in solid-state lighting R&D would be both insufficient as well as incommensurate with benefit to society, hence industry R&D investment needed to be augmented by national R&D investment. Using exactly the same argument, Roland argued in 2011 that the return on industry R&D investment in any newer technology would likely also be insufficient to enable that newer technology to develop to the point of being competitive with solid-state lighting.

[10] J.Y. Tsao, J. Han, R.H. Haitz, and P.M. Pattison, "The Blue LED Nobel Prize: Historical context, current scientific understanding, human benefit," Annalen der Physik **527**, A53-A61 (2015).

2015 Nobel Prizes in physics to the inventors (Isamu Akasaki, Hiroshi Amano and Shuji Nakamura) of the blue LED, it was clear to the world how important solid-state lighting was going to be to humanity. This paper was an opportunity to put solid-state lighting into a much larger historical perspective. We enlisted help from two collaborators, Jung Han (Yale University) and Morgan Pattison (advisor to the Department of Energy), and got to work. The paper ended up having three major parts: an overarching historical context consisting of the many other semiconductor science and technology breakthroughs that preceded the blue LED breakthrough; our current scientific understanding of the blue LED breakthrough itself; and the massive human benefit the blue LED breakthrough was just beginning to unleash. Having been a student of William Shockley, and having either participated in or watched unfold in close proximity virtually every semiconductor science and technology breakthrough, Roland was uniquely positioned to write the overarching historical context.[11] He chose to divide the breakthroughs into five periods: Ge diodes and transistors, Si bipolar, Si MOS (metal-oxide-semiconductor), "conventional" III-V's, and "unconventional" III-N's. Having myself only lived through the latter two of these periods, I would not have had the confidence to place either the "conventional" III-V's or the "unconventional" III-N's at the same level as Si. But Roland did have that confidence, and his accounting of why, and his recounting of the key breakthroughs of each period, were done with his characteristic attention to truth, detail, and sense of historical context.

My lessons learned

Throughout these twenty years, I had the privilege of many conversations with Roland. Some conversations were during the co-authoring of our papers – we debated pretty intensely both the validity and presentation of the various arguments. But many conversations were in between the co-authoring of our papers – particularly during the last few years of his life when we tried to have chats, whenever his health permitted, every few weeks. These were our "catch up" conversations: Roland was intensely interested in the latest breakthroughs in research; I was intensely interested in Roland's unfailingly interesting insights into the importance (or unimportance!) of those breakthroughs. Space and my memory are too short to enumerate all that I learned from Roland. But if I were to try to capture a few of the "big" lessons I learned – lessons I wish I had learned at a younger age and indeed lessons that I would most wish to pass on to a younger generation of researcher – it would be these.

Truth. I think, first and foremost, Roland was after truth. He wasn't fussy about how it came: if through data, he was happy; if through deep analytical thinking, he was happy; if through unimpeachably credible sources, he was happy. But his bar for what he would take to be truth was set very high. As those who have interacted directly with him can attest, Roland was not shy to interrogate, to criticize, and to counter-argue – until his very high bar was met.[12] Conversations with Roland were rarely "feel-good" conversations filled with social niceties; they were intended to reveal truth. Never would an emperor with no clothes have gotten past Roland. And never would Roland have made a technical decision driven by artificial social consensus; he insisted always on deep intellectual debate. His confrontational style was not for everyone, but to me it was refreshing and inspiring.

Courage. I think, second, Roland was courageous. Maybe this is connected to his desire for truth. Sometimes the truth leads you to conclusions that are difficult to believe on the face of it, and then it takes courage to follow those truths. Sometimes people call that kind of follow-through "vision," and certainly the outcome can be visionary. But, more than anything else, I think it represents courage. Roland had critics. Certainly it was easy for those who hadn't thought through the arguments to view his call for a national research program in solid-state lighting as simply a ploy to get government funding for a research area of parochial self-interest. But Roland's call for such a national research program was by no means parochial self-

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[11] During the first, semiconductor device electronics, and second, low-power optoelectronics, phases of his career, Roland served as editor of the well-known IEEE Transactions on Electron Devices. In 1976, he invited Gerald Pearson to co-edit with him a special issue that he was quite proud of. It contained historical accounts of the most important semiconductor science and technology breakthroughs up until that time: G.L. Pearson, R.H. Haitz, Eds., "Special Issue: Historical Notes on Important Tubes and Semiconductor Devices," IEEE Transactions on Electron Devices **ED-23**(7) (July, 1976).

[12] Or woe to the person he was interacting with if it were not met!

interest – he would not have tolerated that for even a nanosecond. His respect for truth and his courage to follow truth to its logical conclusion was what led him to his call for a national research program in solid-state lighting.

Work. I think, third, Roland placed enormous value on work, and on the contributions to society that followed from work. Even after he retired formally from Agilent, and even as he struggled with the cancer that he ultimately passed away from, his passion for work was enormous. During the four months before he passed away, he spent much effort, despite severe pain, co-authoring the Blue LED Nobel Prize paper discussed above. During the four years before he passed away he had also been hard at work at QuarkStar on "asymmetric light valves," an ingenious new concept that may form the basis for a future generation of very-high-extraction-efficiency blue and white LED light engines. For many, work is the means someday to *not* work. For Roland, my sense is that work was not that at all; it was something to embrace because it is an integral part of life and gives it purpose.

Engineering. I think, fourth, and perhaps it should be higher up in this list, Roland had a genius for engineering, and by that I mean a genius for understanding the interfaces between engineered products and, on the one side, their scientific working principles and, on the other side, the economics of their markets. Roland was a master of those interfaces. An example of his exercising of the former interface was the asymmetric light valve mentioned above, in which he elegantly brought together geometric ways of looking at light propagation and scattering in the presence of curved interfaces. An example of his exercising of the latter interface was his projections in 1999 of the likelihood of future energy savings due to solid-state lighting. He carefully modeled industry return on R&D investment before counterintuitively concluding that, for an energy service such as lighting, the long-term return to the manufacturer of the device would be insufficient to justify the investment to improve the efficiency of the device – an "externality" that required government investment.[9] I didn't always appreciate it at the time, but in hindsight I realize that what he was doing in these and other examples is really the essence of engineering.

Behind every great person…

I close by mentioning that, through the years I worked with Roland, I also had a few times the privilege of interacting with his wife, Bente. Their devotion to each other was inspiring to me. Roland would often joke, when he was retiring from HP, about the "honey do" projects that Bente had lined up for him, always with a sense of pride and affection.[13] I am reminded that a community of support is essential to all great people; Bente certainly provided that for Roland.

[13] Of course, the changing of light bulbs in high places was on his list to someday eliminate, by replacing light bulbs with long-lived solid-state lighting!