PHYS 207 begins with cheap (terribly inefficient) SPADs

We have been leaders, in partnership with our professional societies, in providing good-quality Single-Photon Avalanche Detectors (**SPADs**) and in providing faculty/staff training in hands-on methods for more than 40% of all U.S. Physics departments (so far) instructional labs about, *e.g.*, single photons, and quantum physics. This is a very big deal. Our goal at Illinois Wesleyan is to develop a *model* (scaffolded) program for the rest of the world to emulate. — The SPADs that we have distributed have high "Quantum Efficiency," but do cost ~ $2000 each and can be accidentally destroyed through exposure to common levels of room lighting. So, in addition to implementing methods aimed at *protecting* these devices, we instead *start out* our PHYS 207 students with some terribly inefficient (but wonderfully cheap) detectors, so that they can learn important device principles without concern. — We have identified a (very) few makes and models of common (*i.e.*, cheap) light-emitting diodes (LEDs) that, when reverse-biased to very near "breakdown," act as a *Geiger-mode avalanche detector*. (Mostly, photons ***go right through*** these cheaper devices, without effect, but very rarely they will detect one.)

1) Students can use these reverse-biased LEDs to directly observe the current pulses generated by avalanche detectors, without having to deal with the high voltages associated with a Geiger tube.
2) As a precursor to creating a "counting circuit" (*i.e.*, a scalar) students first build a simple *comparator* circuit, which will **digitize** the pulse produced by the avalanche detector.
3) An inexpensive ("Teensy") microprocessor will then be used to complete a measurement system.

Along the way, students will:

- Learn more about the pulses associated with avalanche detectors, including the quenching of pulses, the kinds of time constants associated with such devices, and "dead time" (and how to measure dead time using time-between-events distributions), and "after-pulsing" in avalanche photodiodes.
- Learn something about semiconductor device physics, including the temperature dependence and spectral response of the LED/SPAD.
- Learn to use electrical "breadboards," power supplies, and oscilloscopes
- Learn something about operational amplifiers
- Learn about comparators (which helps with understanding the triggering of oscilloscopes)
- Learn common methods of *signal conditioning*, as a precursor to further electronic processing
- Learn common "rules of thumb" used for histogram plots
- Use a single-photon detector to illustrate properties of random counting experiments
- Use limiting probability distributions to perform statistical analysis on a physical system
- Discuss "*photon bunching*" and the need for "*anti-bunching*" for *true* single quanta experiments.

Required reading from Taylor, *An Introduction to Error Analysis*

- Histograms and the *Normal* Distribution (Taylor 5.1-5.3: pp. 121 - 135)
- A **homework problem** on the *Exponential* Distribution (Taylor Problem # 5.6, p. 155)
- The *Poisson* distribution (Taylor Ch. 11: pp. 245 - 254)
- Summary of the Square-Root Rule for a Counting Experiment (Taylor 3.2: pp. 48 - 49)

Your **lab notebook** should *describe* p-n junctions, LEDs, photodiodes, and avalanche photodiodes, explaining the *physics* behind their behavior. Available references include:

[1] Semiconductor Devices, by Bart Van Zeghbroeck

[2] E. Rutherford, *Radioactive Substances and Their Radiations* (Cambridge University Press, 1913).

[3] D. Renker, "Geiger-mode avalanche photodiodes, history, properties and problems," *Nuclear Instruments and Methods in Physics Research A*, **567**, 48-56 (2006).

[4] S.M. Sze, *Physics of Semiconductor Devices*, 2nd Ed. (Wiley, 1981).

[5] M. Levinshtein, J. Kostamovaara, S. Vainshtein, *Breakdown phenomena in semiconductors and semiconductor devices* (World Scientific, 2005).

[6] E. Hergert, S. Pitek, "Understanding key parameters of silicon photomultipliers," *Laser Focus World*, November 2014, pp. 45-49

[7] P. Horowitz & W. Hill, *The Art of Electronics* (Cambridge University Press, 1989).

Single-Photon Detectors (a *long series* of labs)

If I were a geeky young student, rather than a geeky old professor, phrases that would excite me *might* include “Quantum Information,” or “Spy Technology” or “Next-generation Internet” or “Programmable Optics for Virtual Reality, Augmented Reality, and Mixed Reality” or “Autonomous Vehicles” or “Machine Vision.” It turns out that the opportunities in Optics & Photonics extend well beyond those areas, but generating student excitement has been a key point of discussion recently. Accordingly, IWU's Physics department has voted to implement new CONCENTRATIONS in Optics & Photonics and in Quantum Science & Technology. In part, these reflect common interests among the faculty members of the department, but also reflect areas of significant opportunity for our students. Internship opportunities in Quantum have seen explosive growth and those who go on to get a Masters in Optics & Photonics will command significantly higher starting salaries than nearly any other kind of Engineering (see *Optics & Photonics Global Salary Report*). Of course, going on for a Masters degree is just one out of five distinct paths our students take to become Engineers. We also offer, for example, the dual-degree (Physics + Engineering) option, where it turns out that our “*Mathematical Methods in the Physical Sciences*” course (**PHYS 304**) is a structural “backbone,” giving our students what typically turns out to be a stronger *applied* math background than the average student who went directly to an Engineering school as an incoming first-year student, and is now entering their third year of university. This stronger *applied* math background is one of several reasons our 3:2 students typically have higher-than-average GPAs at our partner institutions, and we have been looking at ways to *increase* the advantage our students gain, informed by ***co-valuing*** **the formalisms of physics with the hands-on experimental “grapplings,” and with the (computer-based) programmatic approaches**. — By highlighting Concentrations in ways that reinforce this “three-legged stool” of student development, we add significant marketability to their portfolios. Our goal is to create a very high-quality **series of scaffolded courses**, which feed into a strong system of support and engagement, encouraging student participation in projects that are of interest to them. — Whereas PHYS 106 only asks students to map out optical systems by considering a few "sample" rays of light, PHYS 307 (“Optical Physics”) and “Scientific Imaging” (PHYS 308) show that more powerful treatments consider the superposition of “*many* paths,” and provides computational tools to promote that kind of power. PHYS 207 complements these, and stands alongside Quantum Optics: The Momentum of the Photon (PHYS 317), which provides further introduction to single-photon quantum mechanics, offered in parallel to our traditional upper-level E&M (PHYS 406) and additional Quantum courses (PHYS 321, PHYS 322, PHYS 407). Our approach is unique in that it presents Quantum Optics (a formalism of wave-particle duality applied to light, in PHYS 207 and 317 and 407) alongside *parallel* discussion of Classical Electrodynamics (a formalism appropriate in the limit of astronomical numbers of photons, in PHYS 106, 307, 308, and 406), presented as a story of energy and momentum. Our aim is to leverage clear physical understanding provided by analysis of laser beams (containing astronomical numbers of photons), so as to provide context for discussions of some of the “weirdness” of modern physics, which emerges quite strikingly at the ***single***-photon level.