PHYS 207 begins with cheap (terribly inefficient) SPADs

We have provided, in partnership with our professional societies, good-quality Single-Photon Avalanche Detectors (**SPADs**) along with hands-on methods for (so far) one-third of all U.S. Physics departments to teach about single photons, and quantum physics. This is a very big deal. Our goal is to develop a model program for the rest of the world to emulate. — The SPADs that we have distributed have high "Quantum Efficiency," but do cost about $ 1700 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 some of the device principles without concern. — Some makes and models (but certainly not all) of common (*i.e.*, cheap) light-emitting diodes (LEDs) will, 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 can:

- 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.

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

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

Your **lab notebook** should contain descriptions (including references) of: p-n junctions, LEDs, photodiodes, and avalanche photodiodes: explain the physics behind the behavior you expect to observe. Some references to consider might be:

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

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

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

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

[5] E. Hergert, S. Pitek, "Understanding key parameters of silicon photomultipliers," *Laser Focus World*, November 2014, pp. 45-49 (www.laserfocusworld.com)

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

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

If I were, personally, a geeky young student, rather than just a geeky old professor, some of the 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, the Physics department has voted to implement a new **CONCENTRATION** in Optics & Photonics (which could, alternatively, be a **MINOR** for those not majoring in Physics). In part, this reflects a common interest among the faculty members of the department, but also reflects an area of significant opportunity for our students. Those who go on to get, say, 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 four distinct paths our students take to become Engineers. We also offer, for example, the 3:2 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 Optics & Photonics 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, up through student participation in a "Signature Work Seminar," which our students will take in their final semester at IWU, extending projects that 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 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 Quantum (PHYS 407) courses. 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.