Modern Physics Laboratory (Physics 6180/7180)

Instructor: Randy Ellingson

Experiments addressing such topics as: atomic, condensed matter and nuclear physics, such as Zeeman, Raman, and Hall Effects, Doppler shifts, X-ray diffraction, Scanning tunnleing microscopy, and alpha, beta and gamma ray spectroscopies. Prerequisite: PHYS 6140/7140

Undergraduate version: Molecular and Condensed Matter Laboratory (PHYS 4580): Experiments in molecular and condensed matter physics such as Raman scattering and photoluminescence, X-ray diffraction, Mossbauer effect, Hall effect, NMR and scanning tunneling microscopy.

Laboratory Scheduling for 6180/7180

- Need to choose lab "teams" of 2 or 3 students, and schedule laboratory session days/times which fit your schedules.

- Each lab is 4 hours; suggested times are Monday* 2:00 – 6:00 pm; Tuesday 8:00 am – noon and/or 1:00 – 5:00 pm; Wednesday 8:00 am – noon, Thursday 8:00 am – noon.

*Note that Monday Jan. 18 (MLK Holiday) will need to be rescheduled to later that week.

Overview Information

- Teaching Assistant: Ryan Zeller, ryan.zeller@rockets.utoledo.edu
- Laboratory locations: MH 2026 and MH 3010.
- LabView – used for *instrument control* (e.g., stepper motor in x-ray system, and wavelength control in Spex monochrometer) *data acquisition* (pulse counting from the Geiger-Müller tube and the photomultiplier (PMT), and input/output -- e.g., setting the current in the electrical conductivity and Hall experiments).
- Safety information: (a) radiation safety (intense x-ray, γ-ray, and α-particle sources), (b) argon-ion (Ar^+) laser (non-ionizing radiation)
- Experimental overviews – x-ray diffraction in crystals, Geiger-Müller tube, origins of x-rays, γ-rays, and α-particles, electromagnet and magnetic field measurement with hall probe (Bell Gaussmeter), and measurement of Hall voltage in hall-effect experiment

Overview Information (continued)

- Introduction to principles of vacuum systems and cryogenics in preparation for low-temperature experiments on semiconductors.

- Introduction to some detectors used to detect ionizing radiation (e.g., alpha and gamma radiation) as well as non-ionizing radiation (e.g., light in the UV-Vis-NIR range).

- Principles of lasers, including diode lasers; current-voltage relations of semiconductor junctions.

- Units – importance of proper handling of units, and use of SI units wherever possible (provide conversion information).

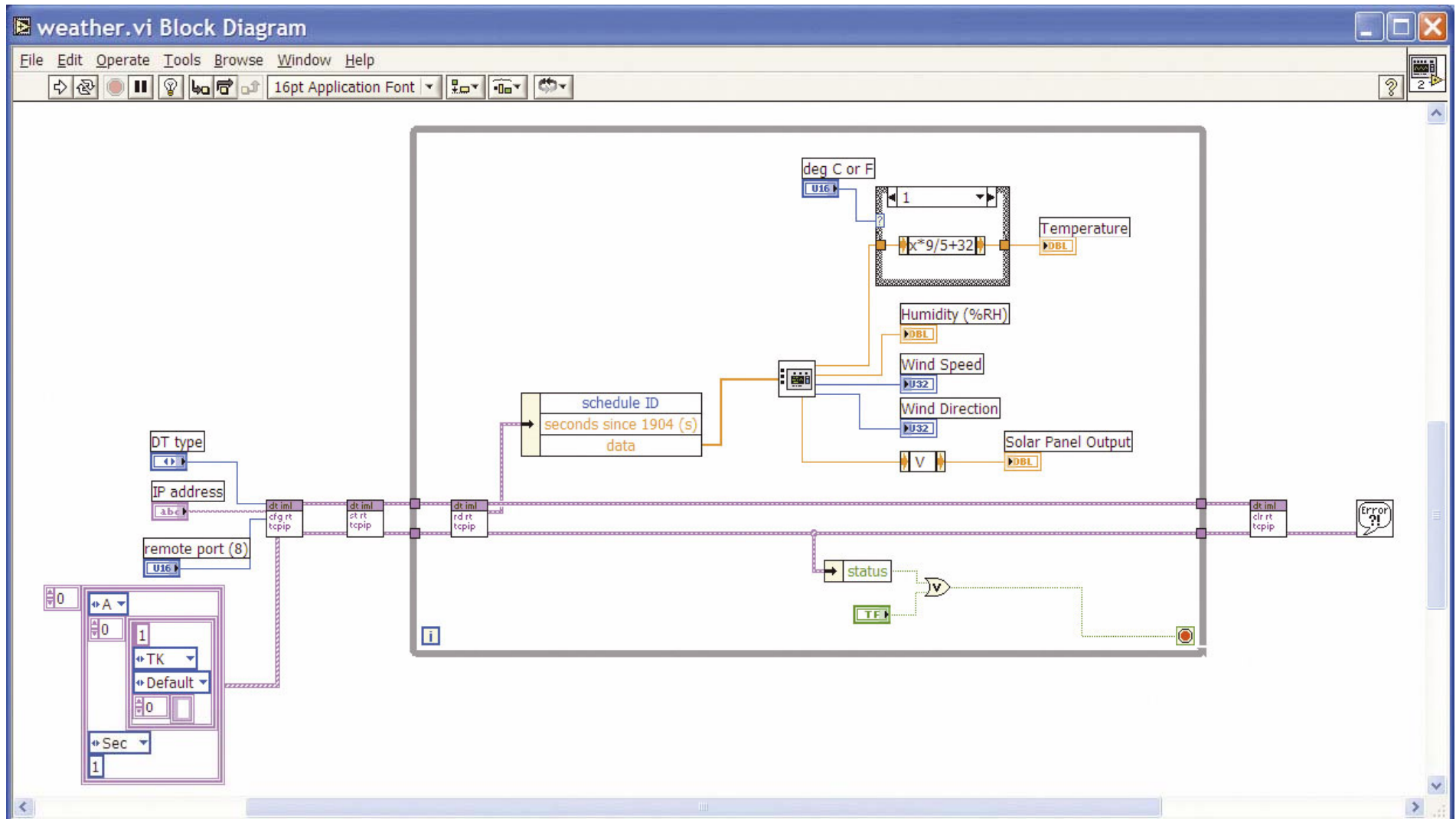- Introduction to error analysis and error propagation.

Instrument Control (LabView Virtual Instruments)

LabView .vi Front Panel
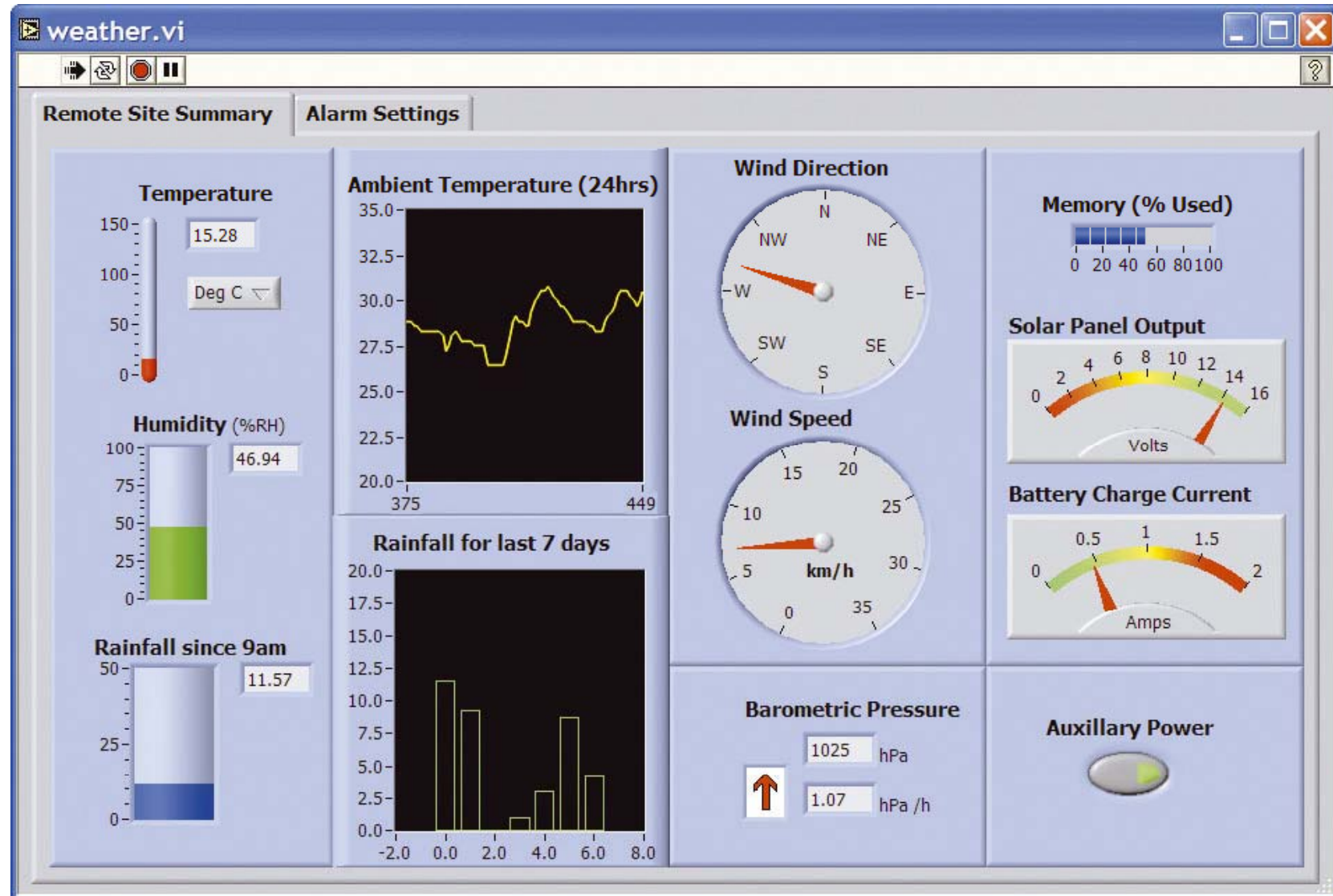
Instrument Control (LabView Virtual Instruments)

LabView .vi Block Diagram

Data Acquisitionwith LabView Virtual Instruments

DAQ = "Data Acquisition"

Select Hardware Features →

- ADC resolution (analog-to-digital), e.g., 12 bits, or 16 bits: determines the ultimate resolution of converting an analog (continuous) voltage to a digital value. For example, on a 0-10 V scale, a 16-bit resolution gives you a least-significant bit voltage value (resolution) of 10 V/2^{16} = 153 μV (0.153 mV, or 1.53 x 10^{-4} V).

- Sampling Rate (of ADC): maximum rate at which sequential A-to-D conversions can proceed. E.g., 250 kS/sec indicates that 250,000 samples per second is possible.

Multi-Function DAQ Hardware

- Typical multi-function DAQ hardware (e.g., from National Instruments) includes capabilities of Analog In (AI), Analog Out (AO), Digital Input-Output (DIO), and Pulse Counter hardware.

- AI refers simply to analog to digital conversion.

- AO refers to essentially using the multi-function DAQ as a voltage source (e.g., to drive an LED, or provide a logical (digital) value to a circuit or instrument input).

- DIO refers to single digital lines. Digital in general means that the line (wire, or terminal) will have either 0 V or 5 V applied to it ("high" or "low"); more specifically, TTL is often used as the gauge for high/low settings.

- TTL = "Transistor-Transistor Logic", for which "low" is 0 V to 0.8 V and "high" is 2.0 V to 5.0 V.

- Pulse counting refers to electronics which can count digital pulses which conform to "digital" specifications.

Laboratory Safety

- Utmost importance -- avoid injury to yourself or others, and maintain health and well-being.

- Specific safety issues:

  - **Electrical dangers**: electrocution dangers exist, especially with potentially high-current electronics. Typical circuit breakers switch at ~100x the lethal current; only a GFCI-protected circuit is designed to protect against electrocution. Do not mess with (attempt to repair, or otherwise test or modify) power supplies or other electronics not part of the standard laboratory procedure. And most importantly, think about the connections you make to reduce the likelihood of unintended results.

  - X-rays and γ-rays are both types of ionizing radiation which can seriously damage living tissue as well as introduce cellular damage including DNA damage.

Laboratory Safety (continued)

- α-particles interact strongly with any material since they're +2 charge results in strong interaction. Therefore, there is little danger from α-particles external to the body (heavily absorbed by air, so few reach the skin). However, ingesting α-particle source material could result in significant health impact.

- Read and review "*Radiation Safety Fundamentals Workbook*": http://ehs.ucsc.edu/lab_research_safety/pubs/ram/Rsfw58.pdf

   This workbook contains useful fundamentals on the origins of various forms of radioactivity, as well as on safety practices associated with radioactivity in the workplace.

- Laser safety amounts to avoiding exposure to the very intense (highly directed, collimated, and often concentrated through focusing) laser light source. While damage can occur from laser-induced burn, the primary risk is that of exposure to the eye.

Radiation: Atomic Emission of x-rays, γ-rays, and α-particles

- Ionizing and non-ionizing radiation: radiation which contains sufficient energy to eject electrons from atoms is referred to as *ionizing* radiation; in contrast, *non-ionizing* radiation has insufficient energy to eject an electron from an atom.

- Ionizing radiation presents a larger health concern since a single quanta can produce many ionized atoms which subsequently damage cells, DNA, and tissue.

Brief Review of Atomic Structure

- Each atom consists of a positively charged core (the *nucleus*, contaning protons and neutrons, held together by nuclear forces) surrounded by negatively-charge shells (electrons).

- Electrons exist in specific energy levels (orbits) around the nucleus.

- Element is determined by # of protons. I.e., atoms of the same element have the same # of protons, but can differ in the number of neutrons. Atoms of the same element (same # or protons) with different # of neutrons are *isotopes*. Since # of protons identifies the element, remember that # of protons is referred to as the *atomic number* (Z).
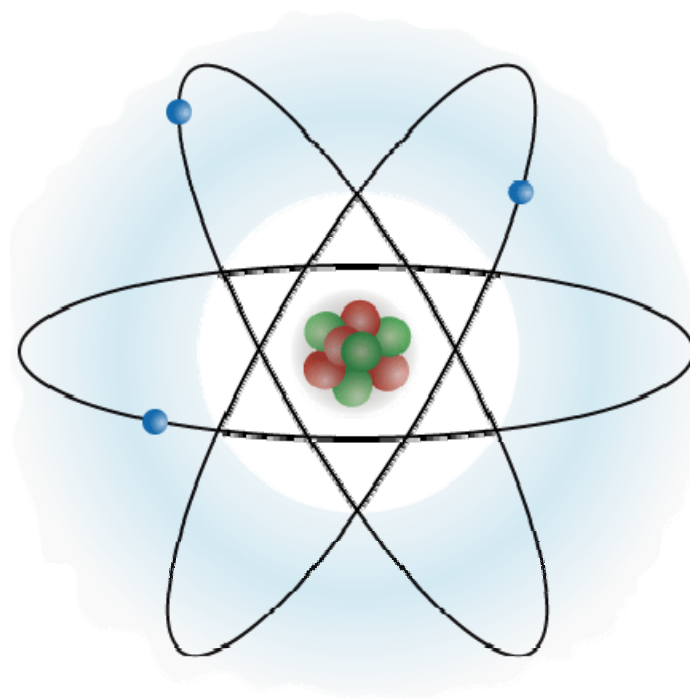
Masses:
$m_e = 9.11 \times 10^{-31}$ **kg**
$m_n = 1.67 \times 10^{-27}$ **kg**
$m_p = 1.67 \times 10^{-27}$ **kg**

Brief Review of Atomic Structure (continued)

- Charges: electrons (-1e), protons (+1e), and neutrons (0).

- Magnitude of the charge on an electron = 1.602 x 10^{-19} Coulombs.

- Electrons are bound to the atom's nucleus through the Coulomb force, in which opposite charges attract ("electrostatic force").

- Ions: basically, an atom is uncharged if the # of electrons = # of protons, and if not, you've got an *ion* (a charged atom).

- Terminology for atoms, generalized to isotopes: (what is a nuclide?) A specific nuclide can be annotated as follows:

$$_{P}^{A}X$$
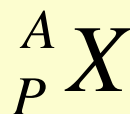
where *A* is the atomic mass number (# of protons + # of neutrons), *P* is the # of protons, and *X* is symbol for the element. Examples:

$$_{1}^{1}H \quad \text{("hydrogen-1")} \qquad _{2}^{4}He \quad \text{("helium-4")}$$
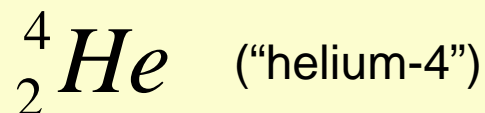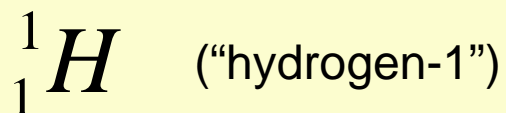
Radiation (continued)

- Ionizing radiation sources -- what are they?

  – X-rays and γ-rays are both high energy photons. Their distinction as x- or γ-rays depends on their source: x-rays are emitted by electrons outside the nucleus, while gamma rays are emitted by the nucleus.

  – X-rays are generated by a vacuum tube by accelerating electrons released by a hot cathode to a high velocity. These electrons then impinge upon a metal target (tube's anode), creating the X-rays. γ-rays result from what is essentially a nucleus relaxation event which typically follows a nuclear decay event such as alpha- or beta-decay.

  – α-particles are doubly-charged helium nuclei, written as He^{++} or He^{2+}. An alpha particle consist of two protons and two neutrons, and is emitted from the nucleus of an atom in a radioactive decay event. Typically, only heavy radioactive nuclides decay by alpha emission, e.g. in the decay of Radium-226 as follows:

  $$^{226}_{88}Ra \rightarrow\, ^{222}_{86}Rn +\, ^{4}_{2}\alpha$$

  – β-particles result from β -decay, in which a neutron converts to a proton plus and an electron, and the electron (β-particle) ejects from the nucleus.

Vacuum systems

- A vacuum is a volume of space essentially empty of matter, such that the pressure of the volume is considerably less than that of the surrounding atmosphere.

- A **vacuum pump** is a device that removes gas molecules from a sealed volume in order to leave behind a partial vacuum. The vacuum pump was invented in 1650 by Otto von Guericke. (Wikipedia)

- Pumps can be categorized according to three techniques (Wikipedia):
  - **Positive displacement** pumps use a mechanism to repeatedly expand a cavity, allow gases to flow in from the chamber, seal off the cavity, and exhaust it to the atmosphere (e.g., roughing pump).
  - **Momentum transfer** pumps, also called **molecular pumps**, use high speed jets of dense fluid or high speed rotating blades to knock gas molecules out of the chamber (e.g., a turbo pump or diffusion pump).
  - **Entrapment** pumps capture gases in a solid or adsorbed state. This includes **cryopumps**, **getters**, and **ion pumps** (e.g., a cryo pump).

Vacuum systems (cont.)

Mechanical pump

Cryo pump

Turbo pump

	pressure (Torr)*
Atmospheric pressure	760
Low vacuum	760 to 25
Medium vacuum	25 to 1×10^{-3}
High vacuum	1×10^{-3} to 1×10^{-9}
Ultra high vacuum	1×10^{-9} to 1×10^{-12}
Extremely high vacuum	$<1\times10^{-12}$
Outer Space	1×10^{-6} to $<3\times10^{-17}$
Perfect vacuum	0

* 1 Torr = 1/760 atm, which is approximately equal to 1 mm Hg.

Detectors

- **Surface barrier detector**: A type of junction detector, used for detections of ionizing radiation, made from a wafer of n-type Si which is subjected to etching and surface treatments to create a thin layer of p-type material; finally, a thin layer of gold is evaporated onto the detector's surface.

- **Geiger-Müller detector**: these detectors are used to detect ionizing radiation, and operate on the principle that when an ionizing particle passes through the hollow gas-filled tube, the ions produced enable conduction of electricity and generate an amplified current pulse as output. Typical output is in the form of counts per minute, and an audible click is often generated to indicate a detection event.


Geiger counter (based on Geiger-Müller tube)

Detectors (cont.)

- **Photomultiplier tube (PMT):** a PMT works on the principle of the *photoelectric effect*, in which an incident photon with sufficient energy frees an electron from a photocathode. PMTs multiply the current from incident light by as much as ~100 x 10^6 (gain), and can be used as single-photon detectors for very sensitive photon counting applications.

  Gain in a PMT follows from *secondary emission*, in which an energetic electron impacts an electrode, thereby freeing another electron to contribute to the current. The electrons are accelerated from electrode to electrode (called dynodes), and it is from this multi-state process that amplification (gain) occurs. PMTs are sensitive in the ultraviolet (UV), visible (Vis), and near-infrared (NIR) spectral regions.
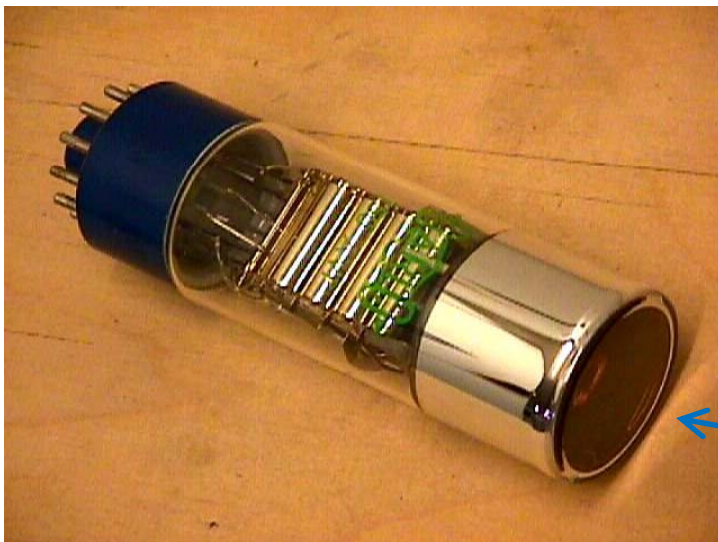
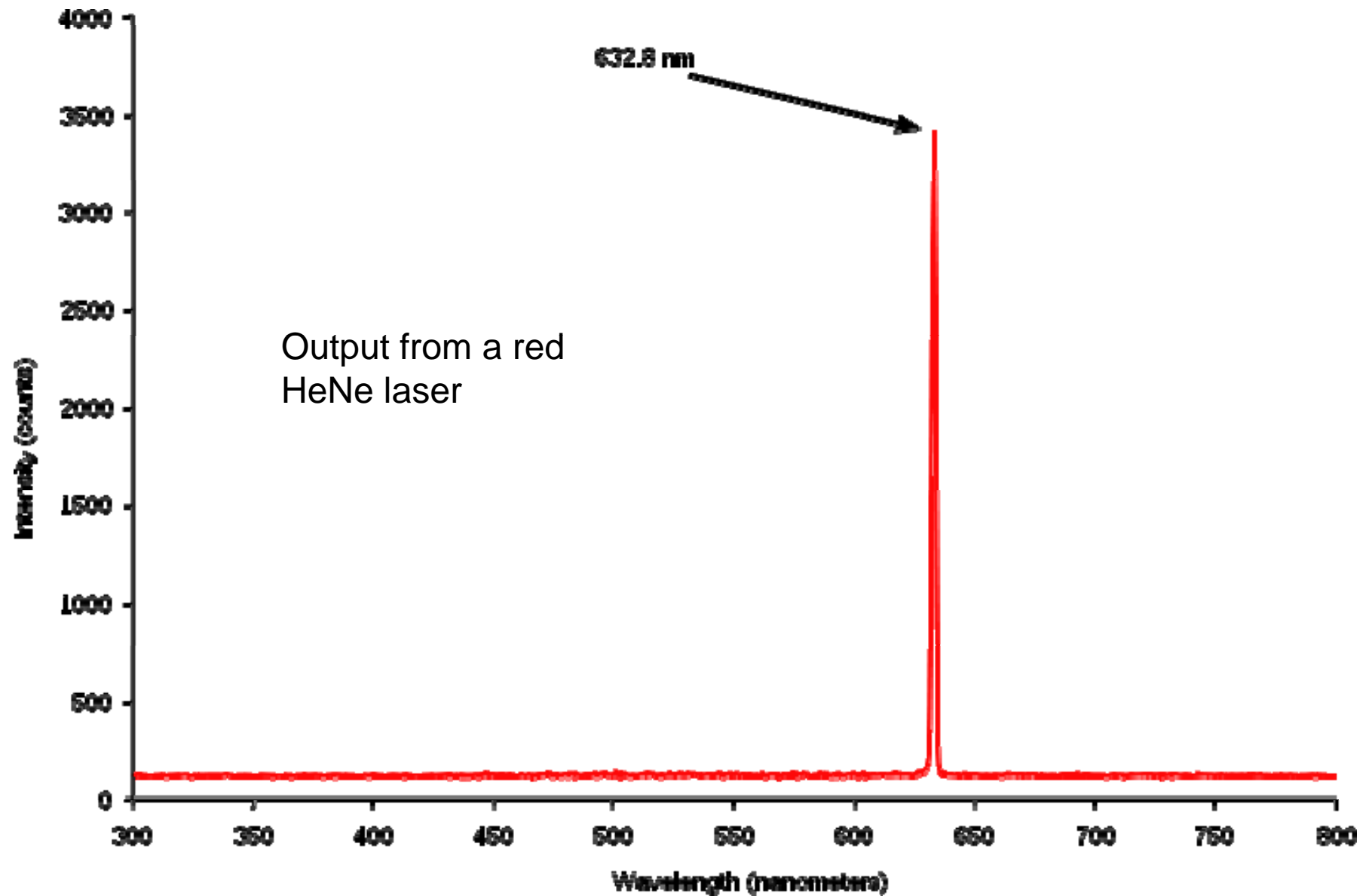Typical PMT (end-on) detector.

Detector end

Lasers

- LASER stands for <u>L</u>ight <u>A</u>mplification by <u>S</u>timulated <u>E</u>mitted <u>R</u>adiation.

- Continuous wave (cw) laser sources have very high spectral purity. Main forms of pulsed operation rely on either Q-switching or modelocking.

- Argon-ion (Ar^+) lasers emit at several wavelengths: 351 nm, 454.6 nm, 457.9 nm, 465.8 nm, 476.5 nm, 488.0 nm, 496.5 nm, 501.7 nm, 514.5 nm, 528.7 nm. Dispersion (e.g., using a prism or a diffraction grating) allows us to select one spectral line from many.

off the mark.com by Mark Parisi

IT'S THE BIRTH OF MY SON: SPECIAL EDITION! I ADDED EXPLOSIONS, MORE SCREAMING AND NOW HE SHOOTS LASERS ON THE WAY OUT!

HOME MOVIES WITH GEORGE LUCAS

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Lasers – high spectral purity


Output from a red HeNe laser

Lasers – general principle of operation

- All lasers must have a *gain medium*, and a means by which the gain medium places atoms into an electronic excited state.

- Excited atoms relax by emission of a photon. For any given emission, the photon's energy will correlate to the specific electron transition, but the photon will exit traveling in a random direction.

- Such a photon, in resonance with other excited atoms in the same (original) state as the atom which was the source of this photon, can induce an identical transition from these identically-excited atoms.

- Feedback of photons using an optical cavity is essential to build up sufficient gain to achieve *oscillation* of the laser (i.e., to exceed the gain threshold for lasing).
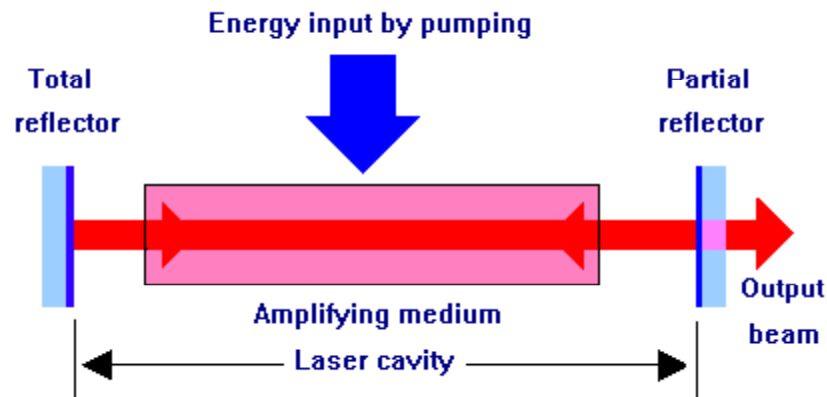
Units

- Please use Standard International units (SI units) wherever possible to: improve accessibility and value of your data, establish good practices (data make sense to the widest audience), and (often) simplify the science.

- If you feel it is appropriate to use a non-SI unit, please note this in your synopsis/report, and if at all possible, provide the information necessary to convert to SI units. Example of non-SI units: eV commonly used for photon energy.

- Please double-check your work using units analysis to confirm that your answer makes physical sense!
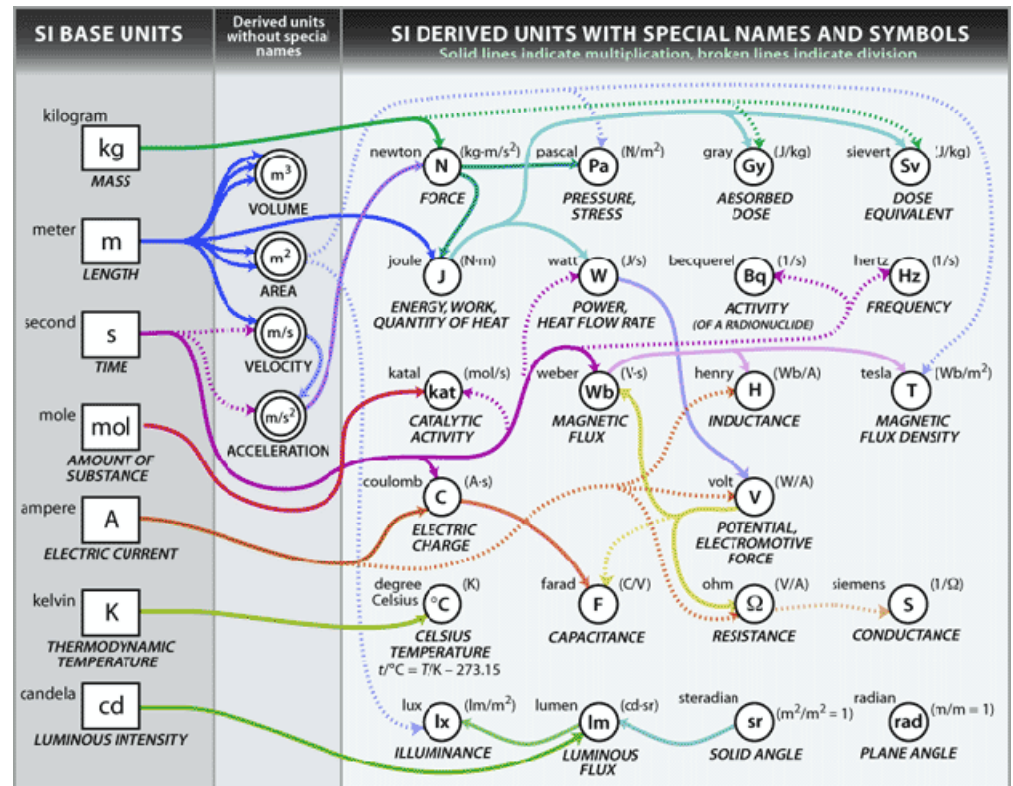
Error analysis, uncertainty, precision, accuracy

- Errors in experimental data arise from unavoidable uncertainty in measurements.

- Errors should be characterized and analyzed systematically.

- *Systematic* errors result from repeatable problems that tend to shift all measured values in the same direction away from the true value.

- *Random* errors vary from one measurement to the next, due to (e.g.) response of instrument to input, noise (electronic, etc.), or statistical processes.

- *Poisson statistical processes* occur at random times with an average rate. When counting such events for a given time interval, these processes result in an error $\Delta n = (n)^{1/2},$ where n is the average number of events during the given time interval.

- *Precision* refers to the degree to which repeated measurements fall reliably at or very near the same value (which may or may not be the correct value).

- *Accuracy* refers to the degree to which the measured value(s) fall at or very close to the true value.

Error handling and propagation

- See handout (to be emailed)

- See also:
  http://teacher.pas.rochester.edu/PHY_LABS/AppendixB/AppendixB.html