CRIB SHEET, Exam 2, Phys 104

oscillation: repetitive motion back and forth about an equilibrium position. To produce an oscillation there must be a **restoring force** that pulls the system back toward the equilibrium position. The inertia of the system determines how quickly it responds to the restoring force. A fast oscillation in a mechanical system is also called a **vibration**.

period: time it takes to complete one oscillation cycle. The unit of period is seconds (s). The period is determined by the restoring force and the inertia.

frequency: the number of oscillations per unit time, which is the same as 1/(period). The unit of frequency is hertz (Hz = 1/s).

amplitude: the maximum displacement of an oscillation cycle.

harmonic oscillator: an oscillator whose restoring force is proportional to its displacement from equilibrium. Such an oscillator has a period that is independent of the amplitude of its motion. Almost all oscillators are harmonic to a good approximation for sufficiently small amplitudes. An **anharmonic oscillator** is one that is not harmonic.

resonance: can refer just to the oscillation of a system, or to the condition when a system is fed energy at a frequency that matches its own oscillation frequency, so that it efficiently absorbs the energy and oscillates more.

pendulum: a mass swinging back and forth (oscillating) under the influence of gravity. Since the restoring force of gravity is proportional to the mass, *the period of a pendulum is independent of its mass* (as in all masses "fall with the same acceleration"). The period of a pendulum is 2π square root of (L/g), where L is the length and g is the acceleration of gravity. A pendulum is a harmonic oscillator to a very good approximation for small and even moderate amplitudes (angles).

sound: patterns of density variation that travel though a medium (like air, water, metal, etc). The speed of sound in air is temperature and pressure dependent. At 20 °C (32 °F) and sea level atmospheric pressure it is 343 m/s, while at 0 °C it is 331 m/s, because being colder the air has a higher density.

wavelength: distance from crest to crest of a wave.

(wave speed) = (wavelength) /(period) = (wavelength) (frequency)

pitch: frequency of an oscillating sound; human range of hearing is 30 Hz to 20,000 Hz. A "tone" is a sound that has a certain pitch.

interval: frequency ratio between two tones. A 2/1 interval is called an "octave", and a 3/2 ratio is called a "fifth".

string vibrations: a string under tension, fixed at both ends, is an oscillator, nearly harmonic for small amplitudes. The restoring force is determined by the tension and the length. A string can vibrate in different **modes**, each with its own frequency. The **nodes** of the vibrational mode are the points on the string that do not move at all. The **antinodes** are the points with maximum amplitude. The lowest frequency mode is called the **fundamental**, and has no nodes. The higher frequency modes are called **harmonics**, and have more nodes. The frequencies of the harmonics are all integer multiples of the fundamental. A string can vibrate in many different modes simultaneously, combining the different modes with different amplitudes and phases. The fact that the displacements in the modes simply add together without disturbing each other is called the **principle of superposition**, which can be traced to the fact that the restoring force is proportional to the displacement. A mode is also called a **standing wave**, and can be constructed as a superposition of two oppositely moving **traveling waves**.

air pipe vibrations: sound in a pipe vibrates much like a string. An open end is a pressure node, since the pressure is fixed to atmospheric pressure. A closed end is a pressure anti-node.

drum head vibrations: an oscillator, but overtones are not "harmonics", since frequencies not integer multiples of the fundamental.

wave interference: enhancing (constructive) or cancelling (destructive) superposition (addition) of waves.

beats: two sound (or other wave) sources with nearby frequencies will combine to produce a sound with a pulsing magnitude with frequency equal to the difference of that of the two sources.

Electric charge: SI unit coulomb (C). All electrons have the same negative charge, all protons an equal amount of positive charge. This is called the **elementary charge** e. 1 C = about 6.25×10^{18} elementary charges. 1 e = about 1.6×10^{-19} C.

Coulomb's law: electric force between charges = $k\, q_1 q_2/r^2$, equal sign charges repel, opposites attract. $k = 8.988 \times 10^9$ Nm^2/C^2 is the **Coulomb constant.**

electric polarization: spatial separation of positive and negative charges.

voltage: electrostatic potential energy per unit charge at a given location (relative to a reference point); SI unit volt = joule/coulomb (V = J/C)

electric field: electric force vector per unit charge at a given location; $\mathbf{F} = q\, \mathbf{E}$; SI unit newton/coulomb = N/C, which is the same as volt/meter = V/m. The electric field is also the **voltage gradient** (voltage drop/distance) in the direction of maximum decrease.

electrical conductor: material like a metal in which electric charges can move freely. Charges always flow to the outside of a conductor, and move so as to make all points on the conductor be at the same voltage. The electric field is thus zero inside a conductor.

The electric field near a sharp (outward) point on a charged conductor is very strong. If strong enough, there is **corona discharge**, wherein charges accelerate fast enough through the air to knock electrons off of atoms and turn the air into a conductor.

piezoelectricity: creation of voltage by mechanical stress, or vice versa.

batteries generate voltage by chemical potential energy difference.

electric current: rate of flow of electric charge; SI unit: ampere = coulomb/second (A = C/s).

electric circuit: path through which electric current can flow. A closed circuit is a complete loop, and open circuit is a broken loop. A short circuit is a short-cut to a smaller loop in a circuit.

electric power delivered by a circuit: $P = VI$ where V is the voltage drop and I is the current.

Ohm's law: $V = IR$, where R is the **electrical resistance**; SI unit of resistance: ohm = volt/ampere (Ω = V/A = Vs/C). Not every material obeys Ohm's law, but it's very common and therefore useful.

Combining the power relation with Ohms law yields $P = I^2R = V^2/R$.

Electrical resistance of a wire is greater for long and skinny wires, less for shorter and fatter ones. The resistance is proportional to length and to the reciprocal of the cross-sectional area of the wire. For conductors, resistance increases with temperature, and for semi-conductors it decreases.

AC: **alternating current**; DC **direct current.**

<u>Magnetism</u>: force created and felt by moving electric charges.

magnetic poles: convenient fiction for thinking about magnetic fields created by currents, where the poles come in opposite pairs ("north" & "south"), spatially separated as a **magnetic dipole**. An isolated magnetic monopole has never been seen, tough theoretically they might conceivably exist.

Coulomb's law for magnetic poles: magnetic force between poles = $\mu_0\, p_1p_2/4\pi r^2$, equal sign poles repel, opposites attract. Here p's are pole strengths, measured in ampere-meters (Am), and $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 is the **magnetic constant (permeability of free space)**.

magnetic field: magnetic force vector per unit pole strength at a given location; SI unit: T= tesla = newton/ampere-meter = N/Am. The magnetic field of the earth is about 0.00005 T. That of a strong button magnet might be 0.1 T.

Magnetic field lines are curves aligned with the magnetic field vector at each point.

Lorentz force: a moving charge q feels a force in a magnetic field: *F_magnetic = q v_perp B*, in direction, perpendicular to both the velocity and the magnetic field, that palm faces when your thumb points along **v** and your fingers point along **B**.

A current carrying wire therefore also feels a force in a magnetic field.

A moving charge or a current creates a magnetic field.

Parallel currents attract magnetically, anti-parallel currents repel.

All matter contains microscopic magnets coming from the spin and rotation of electrons (and even protons are magnets, only weaker than electrons). In most matter they all cancel each other out by opposite orientations. In a **ferromagnetic** material, the spin magnets "freeze" below a certain temperature (the **Curie point**) into alignment with their neighbors, within **magnetic domains**. Normally these domains are randomly oriented with respect to each other, but when they are somewhat aligned the material is **magnetized**, or **magnetically polarized**. A ferromagnetic material that holds its magnetization, even when the magnetic field that initially magnetized is taken away, is a **permanent magnet**.

magnetic induction: a changing magnetic field creates an electric field. Such an electric field is not electrostatic, but nevertheless it produces an effect like a voltage difference, called an induced **emf** ("electromotive force").

Lenz' law: currents created by a changing magnetic field will always produce an effect that opposes the change that caused them.

Electric and magnetic fields carry energy. Their energy densities are proportional to E^2 and B^2 respectively.

A **transformer** uses induction and an iron core to step up or step down an AC voltage. It has primary (p) and secondary (s) coils, wrapped around the core. The ratio of the voltages is equal to the ratio of the number of turns of the coils: $V_s/V_p = N_s/N_p$. Since the power output of the primary is equal to the power input to the secondary, $V_sI_s = V_pI_p$, hence $I_s/I_p = N_p/N_s$

generator: moving a wire in a magnetic field or moving a magnet next to a wire generates an emf in the wire.

motor: running a current in a wire next to a magnet will exert a force on the wire. The **rotor** is the spinning part of the motor, and the **stator** is the stationary part.

AC synchronous motor: stator is electromagnet with AC current, rotor is a permanent magnet. Alternatively the stator might generate a rotating magnetic field, as in the AC 3-phase motor.

DC motor: stator is a permanent magnet, rotor is electromagnet with a commutator and brushes. Alternatively, a brushless DC motor has an electromagnet stator with a switch that changes the current every half-cycle.

universal motor: both rotor and stator are electromagnets fed by the same AC or DC voltage. The rotor has a commutator and brushes (or could have a switch).

induction motor: the stator is an electromagnet producing an alternating or a rotating magnetic field, and the rotor is a loop of wire in which a current is induced, which then feels a force in the magnetic field.

Electromagnetic (em) wave: oscillating pattern of electron and magnetic fields that travels through vacuum at the speed of light $c = 3 \times 10^8$ m/s = 30 cm/ns. Electromagnetic waves are generated by accelerating charges, and they travel perpendicular to the acceleration. They carry energy.

Polarization of em wave: direction of electric field vector. Can be linear or circular, or, generically, ellipsoidal. It points in the direction of the charge's acceleration. Far from the source, the wave front is planar, the electric and magnetic fields are perpendicular to each other and to the direction the wave is traveling, which is the one your *right hand* palm faces when your thumb points along **E** and your fingers point along **B**. In such a wave $E = cB$.

AM: amplitude modulation, 550-1600 kHz (wavelength 300 m @ 1MHz), 10 kHz bandwidth
FM: frequency modulation, 87-106 MHz (wavelength 3 m @ 100MHz), 200 kHz bandwidth
Cell phones: digital frequency modulation, different bands in use, ranging from 700-2700 MHz (wavelength 30 cm @ 1GHz), 30 kHz channel bandwidth
Bluetooth: uses the band 2.4 - 2.480 GHz, which is also used for some cordless phones, baby monitors, wifi, etc. To avoid interference problems bluetooth uses "spread spectrum frequency hopping", switching between 79 frequencies 1600 times per second.

Microwave oven: uses 2.45 GHz, 12 cm waves, generated by a magnetron. Heats by shaking (mainly) water molecules.

Visible light: wavelength 380-760 nm = 0.38 - 0.76 microns. Different frequencies appear to a human eye as different **colors**.

Infrared (IR) light has longer wavelength than visible, and **ultraviolet (UV)** has shorter wavelength.

Rayleigh scattering: scattering of light by molecules or small particles. More effective for shorter wavelengths closer to the size of the particle.

Index of refraction: factor by which light slowed down in a material. If this depends on frequency there is **dispersion**.

Reflection: light (or other waves) partially reflect (reverse direction) and partially transmit at an interface between two media in which the wave speed is different.

Refraction: bending of light (or other waves) at an interface between two media in which the wave speed is different.

Total internal reflection: If the wave speed is faster on the far side of an interface between two media, waves incident from a sufficiently shallow angle will totally reflect.

Rainbows: arise from refraction, reflection, and dispersion of light in spherical water droplets.

Colors from interference: Light reflecting from a double layer, like a soap film or oil on water, combines from the two reflections to a greater or lesser extent in phase depending on the viewing angle and the wavelength of the light. So different colors have different brightness at different viewing angles. Also happens when there are many, equally spaced sources of reflected or transmitted light, as in diffraction grating or surface of a CD or DVD. In the latter case, the path lengths for light from adjacent sources must differ by a whole number of wavelengths, otherwise the interference is completely destructive.

Polarizing filter: blocks or reflects one (usually linear) polarization and transmits the perpendicular one. Polarized sunglasses block horizontally polarized light, which is more pronounced in glare that has reflected off horizontal surfaces. RealD 3D glasses are circular polarizing filters.

LCD: Liquid crystal display. Pixel light travels between crossed polarizers. Liquid crystal orientation controls rotation of polarization, and therefore the brightness of the pixel.

Color perception: Three types of *cone cell* receptors in retina, with different sensitivities to different wavelengths of light. A wide range of color we can perceive can be generated by mixing three *primary colors of light*, or *primary additive colors*, red, blue and green. For example, yellow light can be made from a combination of red and green light. Pigments absorb colors, for example yellow pigment absorbs blue light, leaving the red and green in the incident light to reflect and combine to make yellow. A wide range of color we can perceive can also be made by mixing three *primary colors of pigment*, or *primary subtractive colors*, cyan, magenta, and yellow.

Atomic structure and spectra: each type of atom has particular energy level structure. The **ground state** is the lowest energy state. The electrons don't collapse into the nucleus because of **Heisenberg's uncertainty principle**: the uncertainty in the position times the uncertainty in the velocity must be at least as big as Planck's constant divided by the mass. The electrons don't all pile up in the same lowest energy state because of the **Pauli exclusion principle**: no two electrons can be in the same state. In a **radiative transition** of electrons from a higher to an available lower energy state, a **photon** is emitted, in a process called **luminescence**. Each type of atom has a characteristic set of radiative transition energies, hence a particular **spectrum**. The photon is a "packet" of light whose frequency is related to the energy difference by

energy difference = frequency x Planck's constant, and **Planck's constant** is $h = 6.626 \times 10^{-34}$ J-s. One photon of visible light has a miniscule energy in J. But e.g. a red photon of wavelength 660 nm has an energy equal to 1.9 eV. That means that the electron energy level difference in an atom that produces a red photon would be around 1.9 eV, and the potential difference would be around 1.9 V.

Gas discharge lamps accelerate electrons that collide with and excite atoms, which then emit light in radiative transitions. **Fluorescent lamps** are gas discharge lamps with mercury vapor that emits ultraviolet light. The UV light strikes a **phosphorescent coating** that absorbs UV and re-emits much of the energy as visible light. This process is called **fluorescence**.

Laser light: all the photons have nearly (i) the same wavelength, (ii) the same direction of propagation, (iii) the same phase (oscillating in step with each other). The photons are produced by stimulated emission from a laser medium with electrons "pumped" into excited states, and mirrors on the ends of a cavity so the emitted light will return and stimulate more emission.

LED - light emitting diode: Made from a junction of two materials, works like a waterfall: the ground state of the conduction electrons on one side of the junction has higher energy than that on the other side, so when a current flows across the junction, the downstream electrons can drop to a lower level and emit the energy difference in the form of a photon. A **laser diode** is an LED whose downstream electrons survive long enough in the excited state to play the role of the pumped laser medium. Also mirrors or reflective crystal boundaries confine the radiation into a resonant cavity to allow the laser amplification process.

Photo diode: LED run backward, so when it absorbs a photon it contributes to an electric current. Used in photo detectors.

CCD (charge coupled device): A planar array of "buckets" each of which uses a photo diode to collect an amount of charge proportional to the amount of light that it absorbed. The charge is read out by shifting the charges from one row to the next by manipulating the voltages on the buckets, and shifting sideways to read out the last row. Used in digital cameras.

Optical fiber: Total internal reflection in a glass fiber with graded index of refraction makes a "light pipe". Minimal absorption and dispersion occur at the infrared wavelength around 1550 nm. Pulses can travel 50 km without loss of the signal. Amplification is done by passing the light through an EDFA, an optically pumped medium with excited atoms that are stimulated by the incoming pulse of light to emit more light in a laser fashion.

X-rays: produced e.g by accelerating electrons, and colliding them with heavy atoms. Used medically for imaging and for "therapy", i.e. to kill cancer cells. Imaging with 87 keV X-rays exploits the **photoelectric effect**: a tightly bound core electron absorbs an X-ray photon and gets ejected from the atom. Higher energy photons are needed for therapy, in order not to be absorbed too much, e.g. around 1 MeV. These can be obtained by accelerating electrons to higher energies, or from nuclear decays. In the latter case they are called **gamma rays**. They deposit energy in cells mostly by **Compton scattering**: colliding with an atomic electron and knocking out the electron, while continuing on as a lower energy photon. The electron has a lot of energy and this can damage molecular bonds in DNA. The Compton scattering is a relatively rare event, and most of the photons pass through. To target the cancer beams are directed from many angles, with the beams intersecting at the cancer.

1 eV = 1 electron-volt: the energy acquired by an electron accelerated across a potential difference of one volt. Visible light photon energies are in the neighborhood of 2 eV, depending on frequency. 1 keV = 1000 eV, 1 MeV = 1,000,000 eV.

Proton therapy: radiation therapy with proton beam, whose initial energy can be adjusted so the protons slow and deliver the punch at a pre-selected location.

MRI - magnetic resonance imaging: With body in a strong magnetic field, radio frequency radiation flips proton spins in hydrogen atoms. The spins flip back into alignment with the magnetic field at a rate that depends on the chemical/tissue environment. This relaxation is monitored with the radio frequency radiation that the flipping spins emit. Plane to be imaged is selected by tuning magnetic field with gradient coils.

Nuclei - made of protons and neutrons (**nucleons**), held together by the **nuclear force** (a.k.a. **strong interaction**), while the protons repel electrically. Nuclei with the same number of protons but different numbers of neutrons are **isotopes**. A nucleus is around 100,000 times smaller than the atom built by electrons around it, and its mass is around 4000 times greater than the mass of the electrons.

Radioactive decay: With too few or too many neutrons a nucleus with a given number of protons is unstable to spontaneous decay, a random event that has a certain probability of happening in any given time interval. The **half-life** is the time it takes half of the nuclei in a sample to decay, on average. **Radioactive nuclei** can emit either **alpha particles** (helium-4 nuclei), **beta rays** (electrons or their anti-particle, **positrons**), or gamma rays, or a combination thereof. A lone neutron decays, with a half-life of 10 minutes, to a proton, an electron and a neutrino. This is called **beta decay**. Neutrons in nuclei can be stable, if there are not too many, since creating the proton near the other protons costs too much energy. But otherwise neutrons in nuclei can decay, which is also called **beta decay**. Example: Cobalt-60 beta decays with a half-life of 5.3 years to nickel-60 in an excited state, which then decays emitting two gamma rays, of energies 1.33 MeV and 1.17 MeV, which are used (for example) in medical radiation therapy. Another example is americium-241, which decays, with a half-life of 432 years, to neptunium-237, emitting an alpha particle and a 60 keV gamma ray. Americium is used (for example) in smoke detectors.

SI (Systeme International) units

length	m	meter
time	s	second
mass	kg	kilogram
velocity	m/s	
acceleration	m/s^2	
force	$N = kg\ m/s^2$	newton
energy	$J = Nm = kg\ m^2/s^2$	joule
power	W = J/s	watt
pressure	$Pa = N/m^2$	pascal
temperature	K	kelvin
entropy	J/K	
volume	m^3	
particle density	$1/m^3$	
mass density	kg/m^3	
frequency	Hz = 1/s	hertz
electric charge	C	coulomb
voltage	V = J/C	volt
electric field	N/C = V/m	
electric current	A = C/s	ampere
electrical resistance	Ω = V/A	ohm
magnetic pole	A-m	
magnetic field	T = N/A-m	tesla