

THE AMAZING STORY OF QUANTUM MECHANICS:
A MATH-FREE EXPLORATION OF THE SCIENCE THAT MADE OUR WORLD

BY JAMES KAKALIOS

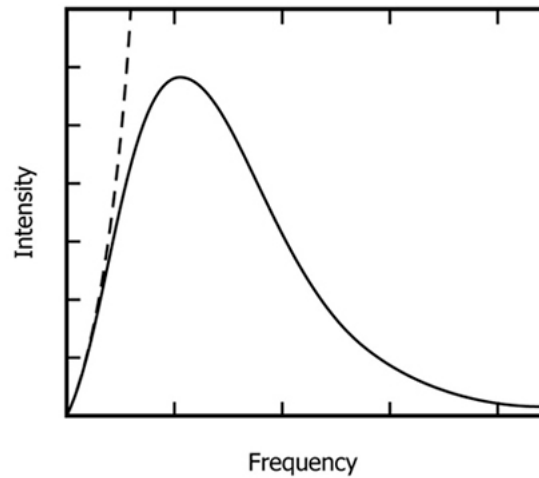


Figure 2

A plot of the light intensity given off from a “blackbody” object as a function of the frequency of light. The measured curve (solid line) shows that the total amount of light emitted is finite, while the pre-quantum mechanics calculated curve (dashed line) continues to rise as the frequency of light increases. That is, before quantum mechanics, physics predicted that even objects at room temperature would give off an infinite amount of light energy in the ultraviolet portion of the spectrum—a clearly ridiculous result.

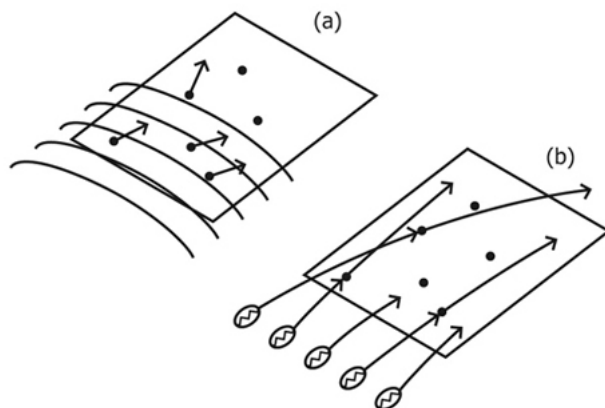


Figure 3

Cartoon sketch of pebbles on a beach, pushed up toward the top of the beach by either ocean waves (a) or by photon bullets (b).

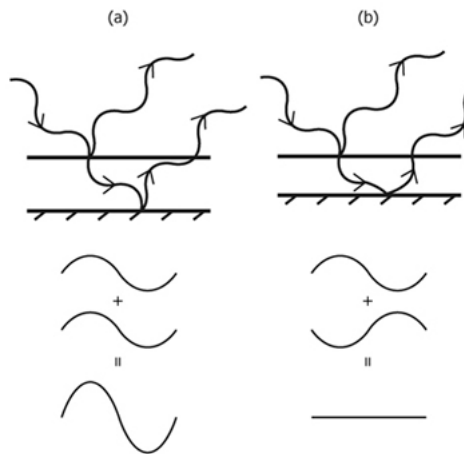


Figure 4

Sketch of a light wave reflecting from the top and bottom surfaces of an oil slick. In (a) the wavelength and thickness of the slick result in constructive interference of the wave reflected from the top surface, and the wave that travels through the slick reflects from the bottom surface and then exits the slick. For constructive interference the light would be very bright when viewed from the top. In (b) the wavelength and thickness result in destructive interference, in which case no light would be observed from the top surface.

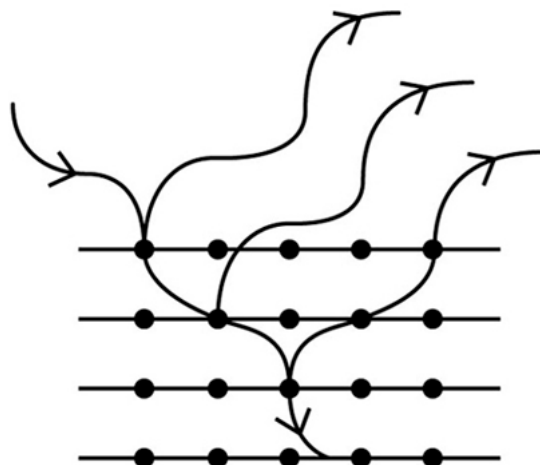


Figure 6

Cartoon sketch of de Broglie matter waves for electrons scattering from the planes of atoms in a crystal. If the separation between atomic planes in the solid is commensurate with the de Broglie wavelength of the electrons, then interference of the scattered electrons will be observed. The intensity of electrons will be high in directions where the matter waves constructively interfere and there will be no observed electrons in directions for which destructive interference occurs.

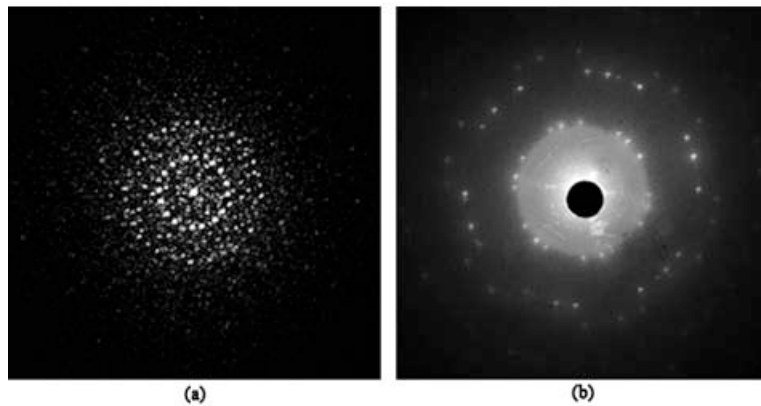


Figure 7

Examples of light diffraction (a) and electron diffraction (b). The image on the left is obtained by passing a green laser light through a fine-mesh metal screen (not unlike a screen door) and shining the light on a wall several feet from the screen. The light scattering from the metal wires, arranged in a periodic array, leads to a symmetric constructive (bright-green spots) and destructive (dark regions) interference pattern. On the right an electron beam in a cathode ray tube passes through a graphite crystal. The momentum of the electrons is chosen so that their de Broglie wavelength is on the order of the spacing between atoms in the crystal. The atoms in the crystal scatter the electrons in a similar manner as the wire mesh does to the laser beam.



Figure 8

In the 1960s, Dick Tracy comic strips predicted a future in which we traveled via personal flying garbage cans levitated by the power of magnetism.



Figure 9

Angular momentum was a frequently invoked physics principle for futuristic weapons of war, as shown in the cover of the April 1930 Air Wonder Stories.

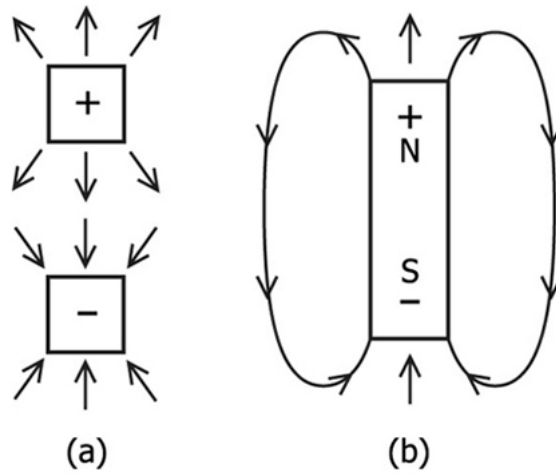


Figure 10

Sketch of the electric field from an isolated positive and negative charge (a) and from the two charges forming a dipole pair (b). The same field lines are found for a magnetic dipole, where the North pole plays the role of the positive charge, and the South pole acts like a negative charge.

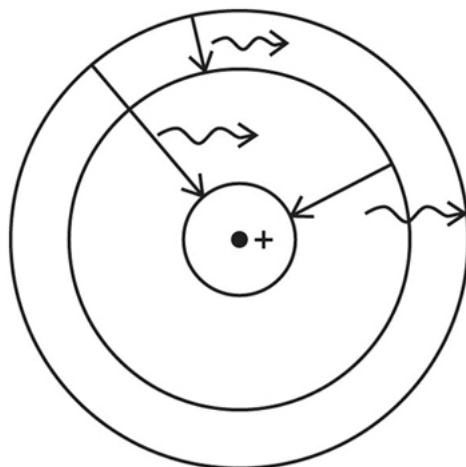


Figure 12

Sketch of Bohr's proposed discrete electron orbits about a positively charged nucleus. Only certain trajectories are allowed, and an electron has a different energy depending on which orbital path it is on. The electron emits or absorbs light only when moving from one orbit to another.

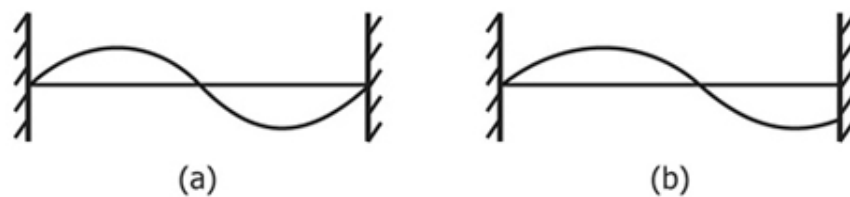


Figure 14

Sketch of an allowed standing wave for a vibrating string clamped at both ends (a) and a wave that is not possible (b).

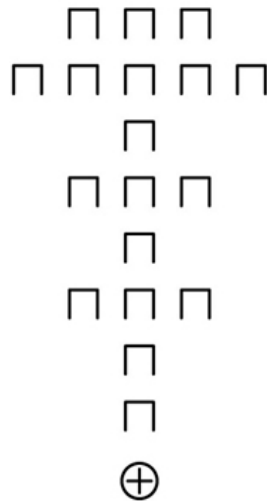


Figure 15

Cartoon sketch of the possible quantum states, represented as seats in a lecture hall that an electron can occupy, as determined by the Schrödinger equation for a single electron atom. In this analogy the front of the lecture hall, at the bottom of the figure, is where the positively charged nucleus resides. Upon absorbing or releasing energy, the electron can move from one row to another.

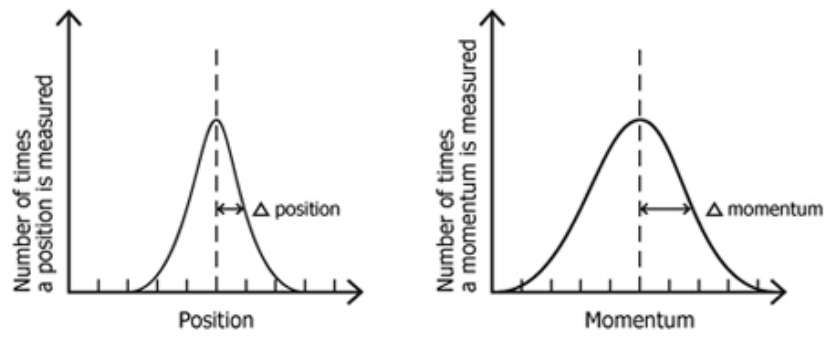


Figure 16

Plot of the histogram of measured positions (a) and momenta (b). The vertical dashed lines represent the average values of position and momentum, and the small arrows indicate the standard deviation for each measurement.



Figure 17

Sketch of two possible de Broglie matter waves for an electron. In the top curve, the electron is associated with a single wave. As one needs only one wavelength to describe the wave, the momentum is perfectly known, but at the cost of an infinite uncertainty in the location of the electron. In the bottom curve many different waves, each with different wavelengths, have been added to yield a “wavepacket.” The uncertainty in the spatial location of the electron is reduced, but there is a corresponding increase in uncertainty in the electron’s momentum.

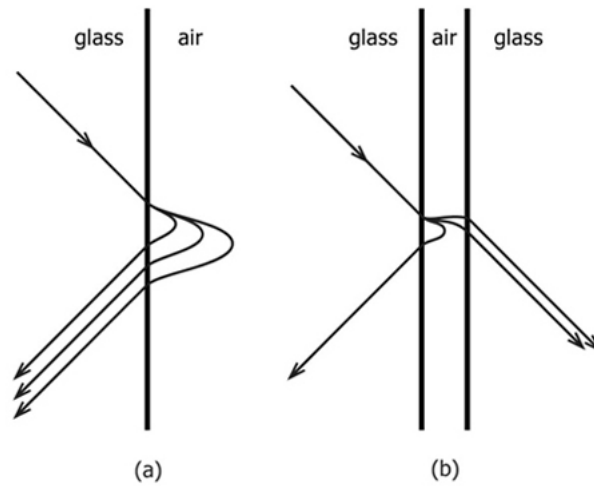


Figure 18

Cartoon sketch illustrating a light wave, which is normally reflected at a glass/air interface and may have a small amplitude leaking into the air. If another piece of glass is placed near the first (the separation should be no more than a few wavelengths of the light), then the wave may be able to propagate into the second material. A similar phenomenon occurs with matter waves during quantum mechanical tunneling.



Figure 20

Image of a pencil (belonging to a certain fictional physicist) that appears broken at the air/water interface due to the different speeds of light in the two media.



Figure 23

Buck Rogers, in his daily syndicated newspaper strip in 1929, employs an “atomic torpedo” to devastating effect.

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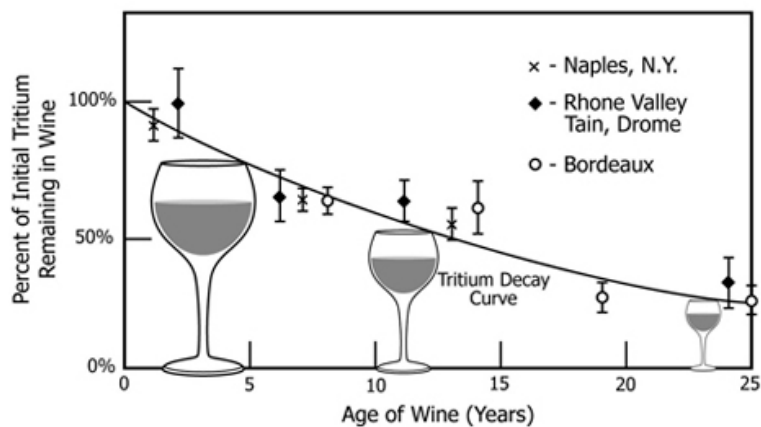


Figure 25

Plot of the time dependence of tritium concentration in “heavy water” contained in wine bottles. The age of the water sample is determined by the vintage printed on the bottle’s label. The longer one waits, the less tritium is present, due to radioactive decay. The solid line is a fit to the data of an exponential time dependence, with a half-life of 12.5 years.

Reprinted figure with permission from S. Kaufman and W.F. Libby, *Physical Review* 93, 1337 (1954).

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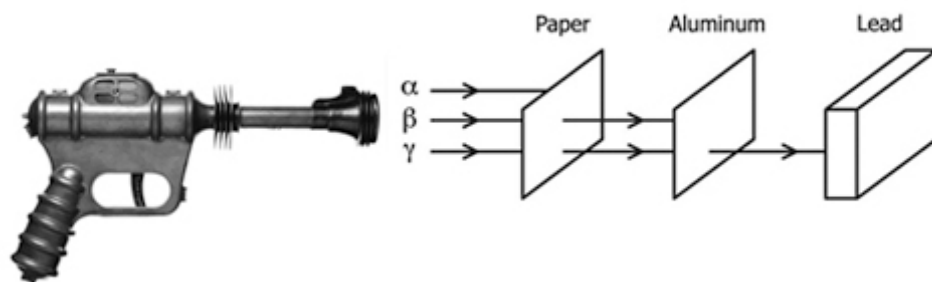


Figure 26

A sketch of a 1936 Buck Rogers toy ray gun and nuclear radioactivity consisting of alpha particles, beta rays, and gamma ray photons. (The toy shown is a Buck Rogers Disintegrator Pistol, model XZ-38, and did not actually emit high-energy sub-atomic particles). All three types of radiation have roughly the same energy of a few million electron-Volts, but they are stopped by different levels of shielding. The alphas are blocked by a sheet of paper, which the betas can penetrate, but are themselves stopped by a thin aluminum sheet. High-energy light in the form of gamma rays passes through both, and a thick block of lead is needed to stop them.

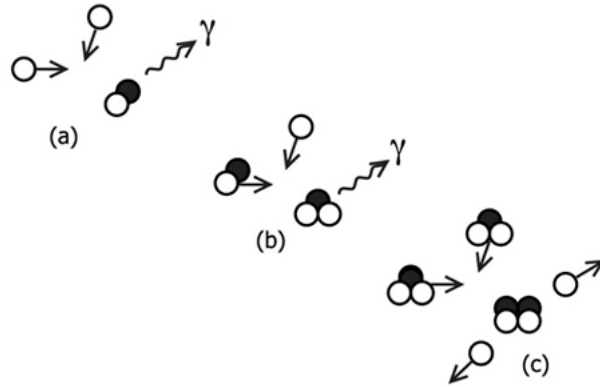


Figure 28

Sketch of the nuclear reactions in the center of the sun by which protons (hydrogen nuclei) combine to form alpha particles (helium nuclei). In step (a), two protons (represented by open circles) tunnel together, where the Weak force converts one proton (open circle) into a neutron (dark circle). The proton and neutron then form a bound deuterium nucleus, with the release of a gamma ray photon (the positron and neutrino released are not shown for simplicity). The deuterium can then collide with another proton in step (b) and form a bound proton-proton-neutron nucleus, termed Helium-3. In step (c) we indicate a possible reaction where two Helium-3 nuclei collide and form a stable Helium-4 nucleus (two protons and two neutrons), with the release of two protons and another gamma ray. Similar mechanisms result in the fusion of helium nuclei to synthesize heavier elements, such as carbon and oxygen, and up.



Figure 29

Cartoon of the wave patterns observed on the surface of a pond when one rock is tossed into the water (a), and when two rocks are simultaneously tossed, near but not touching each other (b).

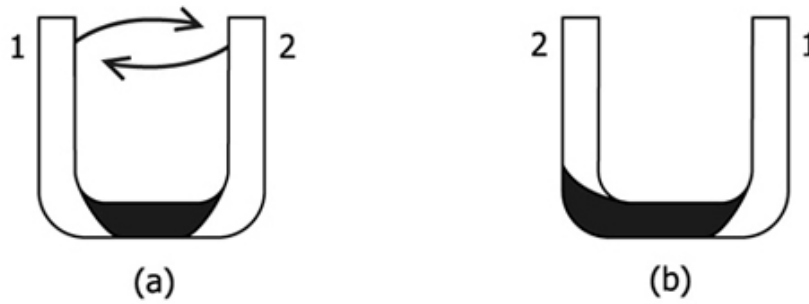


Figure 30

Cartoon sketch of a ribbon with different colors on each side, where the ribbon is presented so that each end displays the same side (the white side in this case). Switching the two ends results in a half-twist in the ribbon. Only another rotation creates a full twist in the ribbon that can now be removed by flipping one side of the ribbon twice.

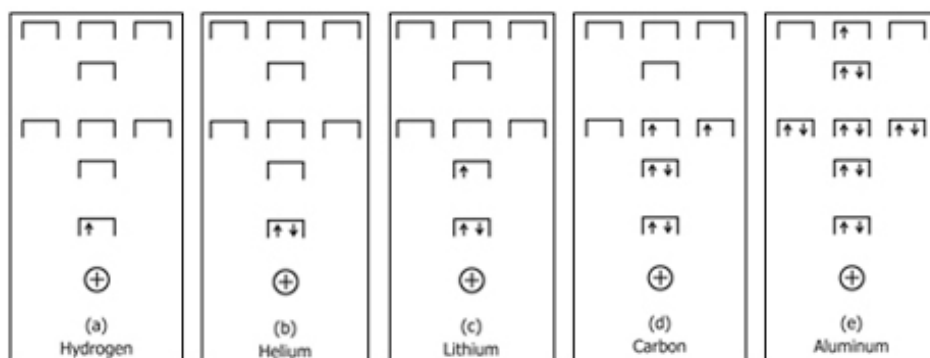


Figure 31

Representation of the allowed quantum state solutions to the Schrödinger equation for an electron in an atom as a set of seats in a classroom. The Pauli principle indicates that each seat can accommodate two electrons provided they have opposite spins. Shown from left to right are the occupied quantum states for atoms containing one, two, three, six, and thirteen electrons, corresponding to hydrogen, helium, lithium, carbon, and aluminum, respectively.

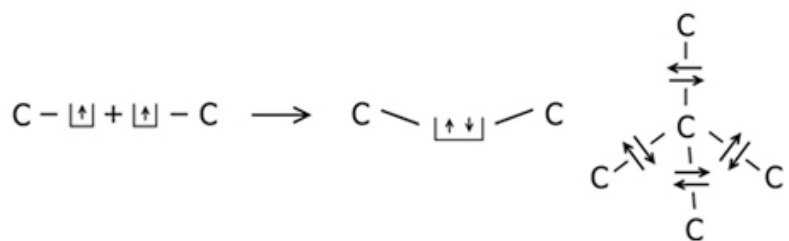


Figure 32

Sketch of the lowering in energy when two unpaired electrons from adjacent carbon atoms overlap and form a carbon-carbon bond (a). Also shown is a sketch of the configuration of carbon when in the diamond configuration, allowing four chemical binds with its neighbors, in a tetrahedral orientation (b).

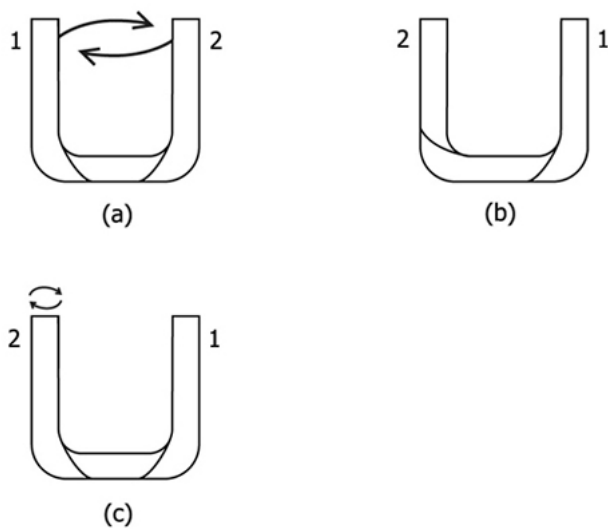


Figure 33

Cartoon sketch of a ribbon with the same color on each side (a). Switching the two ends results in a half-twist in the ribbon (b) that can be undone by rotating one side of the ribbon (c), restoring the original configuration.

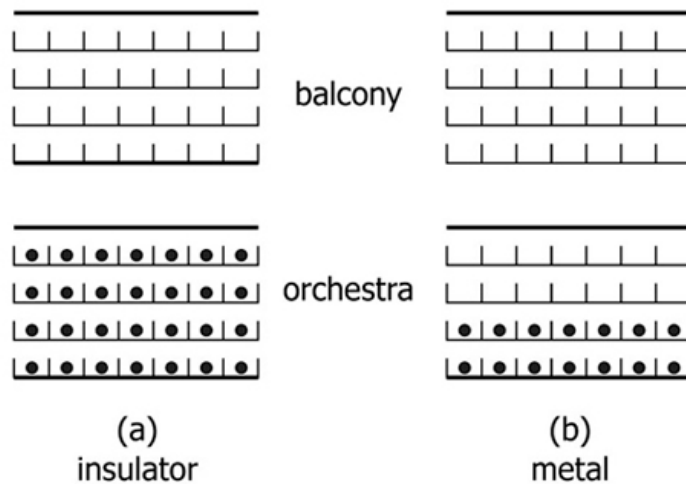


Figure 34

Sketch of the band of quantum states from the highest energy occupied levels in a solid and the band formed from the next highest energy available quantum states. In an insulator (a) the lower band is analogous to a completely filled orchestra in an auditorium, where there is an energy gap separating the electrons in the lower band from the band of empty states (the balcony). The second figure (b) shows a situation where the lower orchestra is only half-filled and the electrons have ready access to empty seats—which describes a metal.

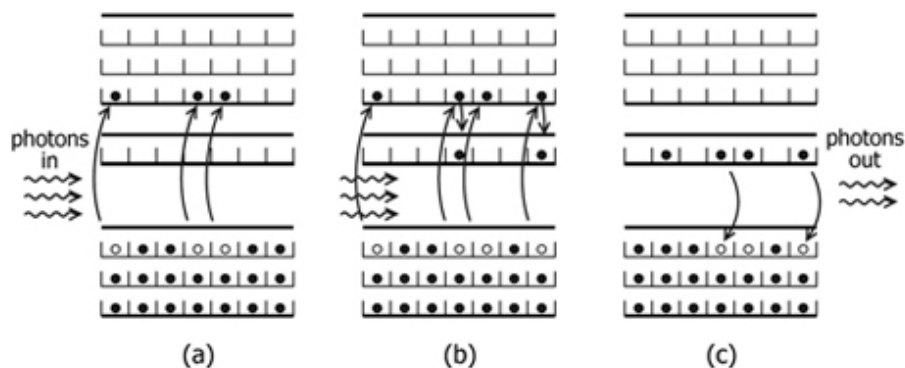


Figure 35

Sketch of the band structure of a fluorescing solid, represented by a filled orchestra, an empty balcony at a high energy, and an unoccupied mezzanine level at a slightly lower energy than the bottom of the balcony. When the solid is illuminated with white light, electrons are easily promoted from the orchestra to the balcony, and photons are emitted when the electrons fall back into the lower level. Occasionally an electron will wind up in the mezzanine level, from which the transition rate to the orchestra is low. When the light exposure is stopped, these charges trapped in the mezzanine will eventually drop back into empty spots in the orchestra, emitting slightly lower energy photons in the process. In this way the material will give off light after being illuminated—that is, it will glow in the dark.

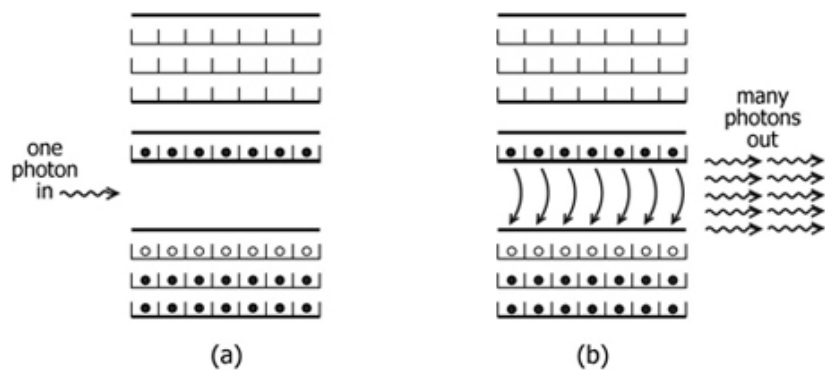


Figure 36

The auditorium model from the last chapter, only now the occupation of the mezzanine level is quite high. A single photon can stimulate an electron in the mezzanine to drop down to an empty seat in the orchestra, emitting a photon in the process. This photon can in turn induce another electron to make this transition, with the net effect that a very large number of electrons may be stimulated into dropping down to the lower energy band, all emitting identical energy photons. This procedure is the basic physical mechanism underlying the laser.

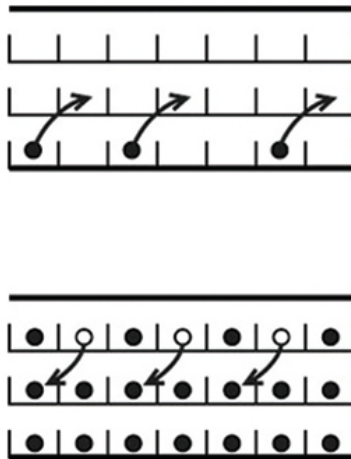


Figure 40

Sketch of nearly filled lower energy and nearly empty higher energy bands in a semiconductor. There will be some electrons promoted up to the “balcony” that can carry current (as they have easy access to higher energy quantum states, so they are able to gain kinetic energy and carry an electrical current). At the same time the vacant seats in the orchestra are also able to act as positive charge carriers, as other electrons slide over to fill the vacancy.

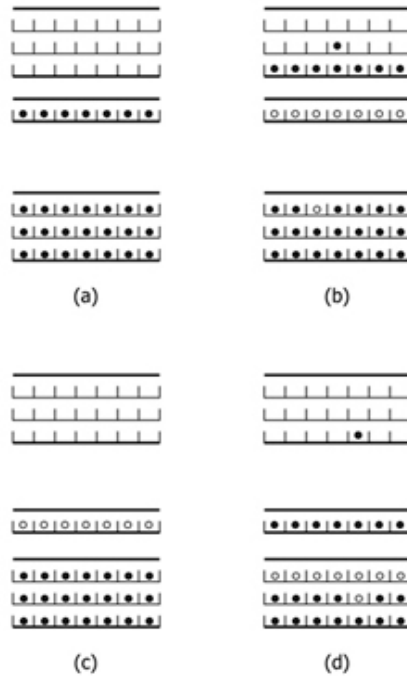


Figure 41

Sketch of a semiconductor where impurity atoms are added, resulting in a mezzanine level beneath the balcony, which at low temperatures is normally filled with electrons (a) that are easily promoted at room temperature into the previously empty balcony (b). Alternatively, different chemicals can produce states right above the filled orchestra (c) that at low temperatures are normally empty of electrons. At room temperature electrons can be easily promoted from the orchestra to these lower “lounge” seats, leaving empty seats (holes) in the orchestra that are able to carry electrical current (d).

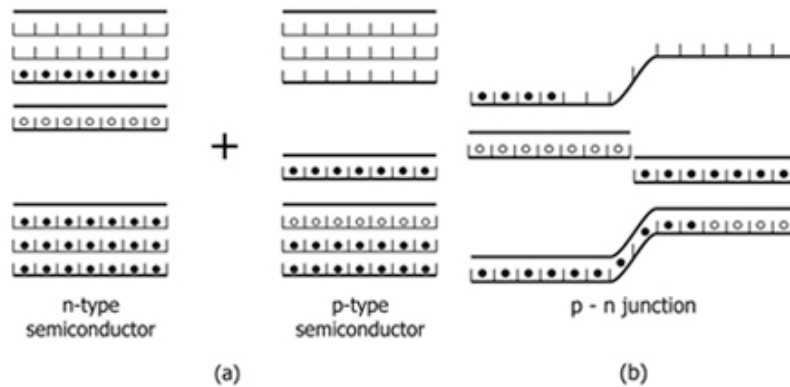


Figure 42

Sketch of an n-type doped semiconductor and a p-type semiconductor (a) brought into electrical contact, enabling electrons from the n-type side to fall into holes from the p-type side, leaving behind positively charged mezzanine seats and negatively charged lounge seats in the n-type and p-type semiconductors, respectively. These charged mezzanine and lounge seats create a built-in electric field that affects the flow of electrical current through the semiconductor. The influence of this electric field is to tilt the two auditoriums, relative to each other (b). For simplicity only the first rows of the balcony and orchestra are shown on the figure to the right (b). If an external voltage is applied across this junction, it can cancel out this built-in field, making it easy for a current to pass from one side to the other.

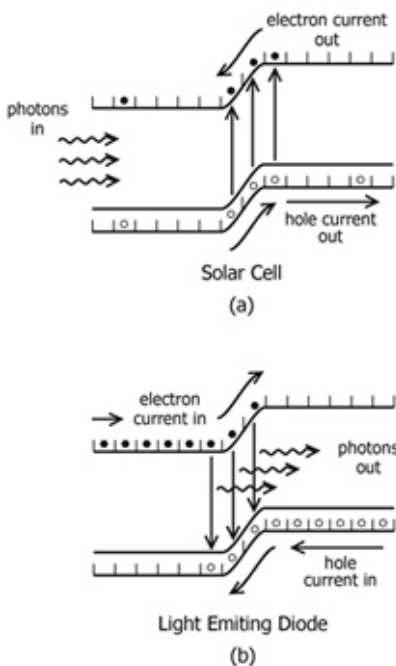


Figure 43

Sketch of a p-n-junction that absorbs light, promotes electrons up into the balcony and leaving holes in the orchestra. The electrons on the p-type (right-hand) side in the balcony are at a higher energy and can easily move down to the balcony states on the left-hand side of the material. An electrical current thus results from the absorption of light (a), and a diode in this situation is called a solar cell. Alternatively, if I force an electrical current through the diode, pushing electrons from the n-type side to the p-type side (and holes in the opposite direction), then at the interface region where the density of electrons and holes is roughly equal, there will be many opportunities for the electrons to fall from the balcony to the orchestra, emitting light as they do so (b). The device run in this way is called a light-emitting diode.

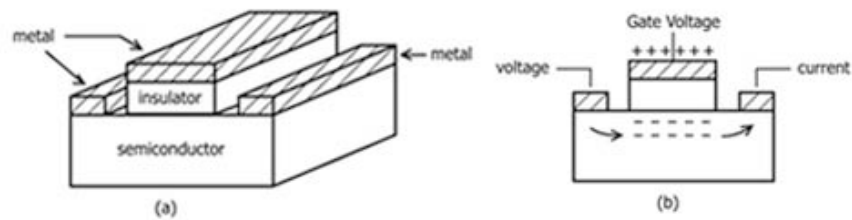


Figure 44

Sketch of a simple transistor device structure (a). Two metal electrodes on the top of the semiconductor are used to pass a current through the device. A thin insulator (such as glass), on which is a metal electrode, lies on top of the semiconductor between the two metal electrodes used to pass the current. When a positive voltage is applied to the “gate electrode,” positive charges accumulate on the top of the insulator, which attract electrons in the semiconductor to the region underneath the insulator (b). These electrons improve the ability of the semiconductor to pass a current between the two metal electrodes, and the current is made much larger by the application of the “gate voltage.”

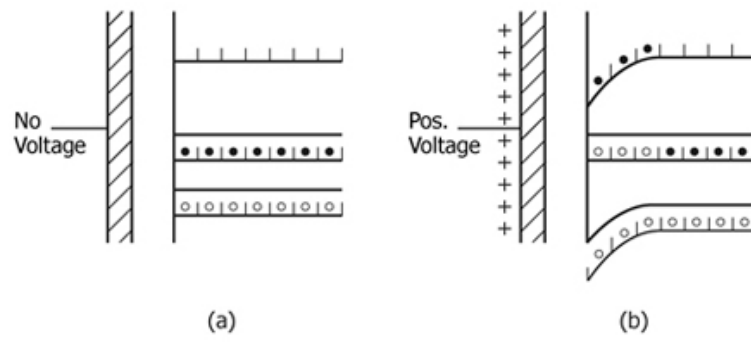


Figure 45

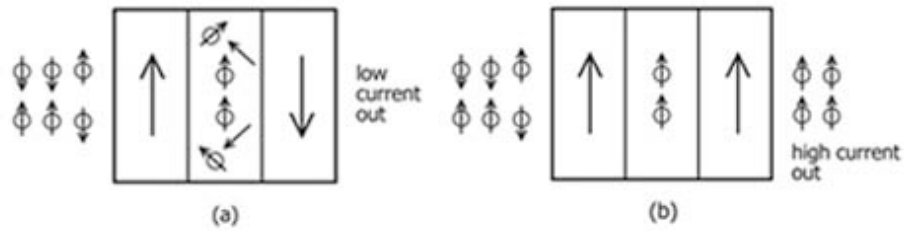


Figure 47

Sketch of the device structure used to measure magnetic fields with an electrical current in a computer hard drive. An electrical current has both a negative charge and a built-in magnetic field resulting from its quantum mechanical intrinsic angular momentum (“spin”). Electrons flowing into the device are magnetically polarized by the first layer. In (a), the second layer is aligned opposite to the first, so the electrons polarized by the first layer are repelled by the second, and a very small current results. In the second case (b), the second magnetic layer is aligned in the same direction as the first, and the polarized electrons easily pass through the second layer. This configuration would present a low resistance to the flow of current, while the first case (a) would represent a high resistance state.

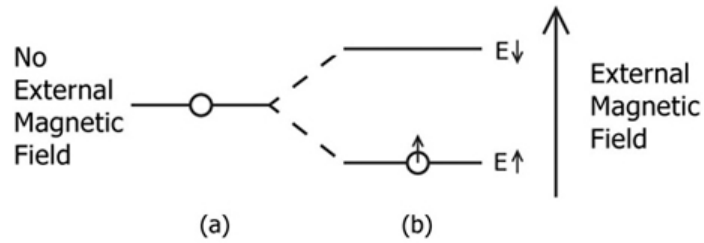


Figure 48

Sketch of the energy level of a single proton in the nucleus of a hydrogen atom (a) when no outside magnetic field is applied and (b) when a field is present. In the second case the proton's energy is lowered if its own intrinsic magnetic field points in the same direction as the outside magnet, and the energy is higher if it points in an opposite direction. In this figure the proton is indicated with its spin aligned with the external magnetic field and thus in the lower energy state. If the spin were opposite to the external field, the proton would reside in the higher energy state.

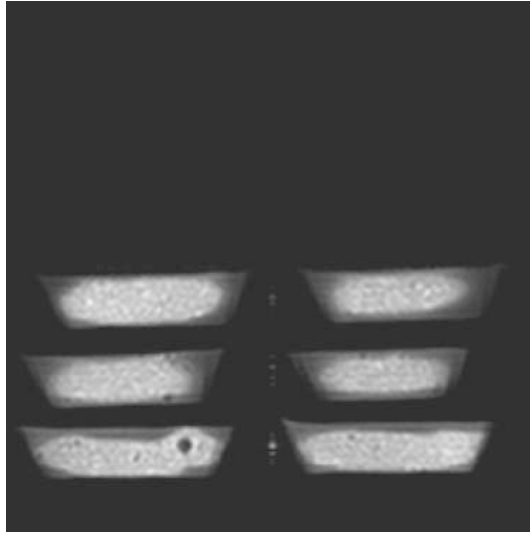


Figure 49

Magnetic Resonance Image of three packets of peanut butter cup candy. The difference in spin relaxation times provides a basis for contrast between the chocolate coating and the interior filling, confirming the presence of the peanut butter inside the candy without having to bite into the candy (not that we wouldn't be willing to make such sacrifices for science!).

Courtesy of Professor Bruce Hammer at the University of Minnesota.