FIGURES

for

Waves in an Impossible Sea

by Matt Strassler

On the following pages are the figures and figure captions from *Waves in an Impossible Sea*, for diverse uses (such as with an audio book.)

Please note:

- Figure 13: Atomic resolution STEM imaging of perovskite oxide La0.7Sr0.3MnO3. By Magnunor (Own work) CC BY-SA 4.0 via Wikimedia Commons. (https://creativecommons.org/licenses/by-sa/4.0)
- Figure 31: "Wind Map" by Martin Wattenberg and Fernanda Viégas (hint.fm/wind); may not be reproduced without their permission.
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- All figures, excepting Figures 13, 16, 28, 29. 31 and 42, were created by illustrator (and physicist) Dr. Cari Cesarotti.

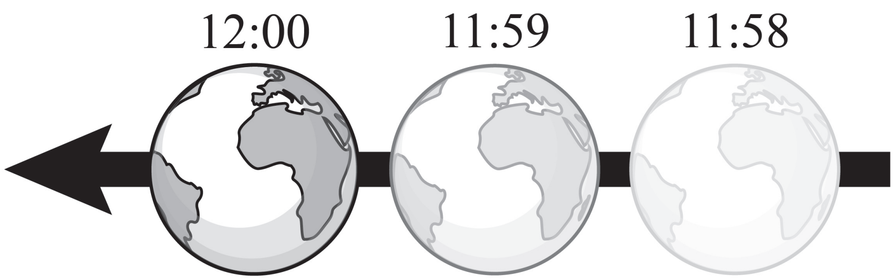

Figure 1: As seen from our galaxy's center, the Earth (shown at three locations one minute apart) travels at tremendous speed.

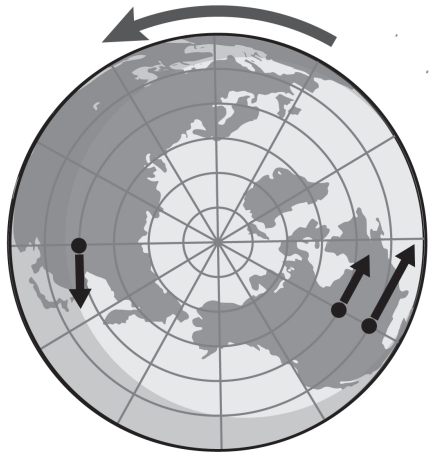

Figure 2: Sleeping babies are all in motion relative to one another. As seen from our planet's north pole, their speeds and directions (black arrows) vary with their latitude and longitude. Any one location on the planet will be seen, from another location, as traveling in a daily circle.

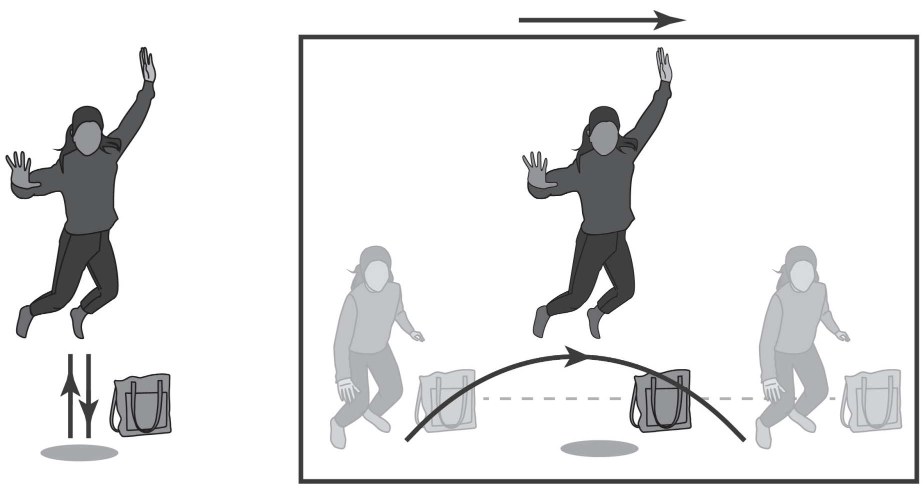

Figure 3: If you're at home and jump straight up (left), you will land where you started; the bag sitting a foot away won't move. If you jump in an airplane overhead, your own experience of the jump will be the same as at home (left). Someone on the ground will see your jump as an arc (right), but your motion is synchronized with the plane's motion, so that you jump and land at the same spot on the plane's floor.

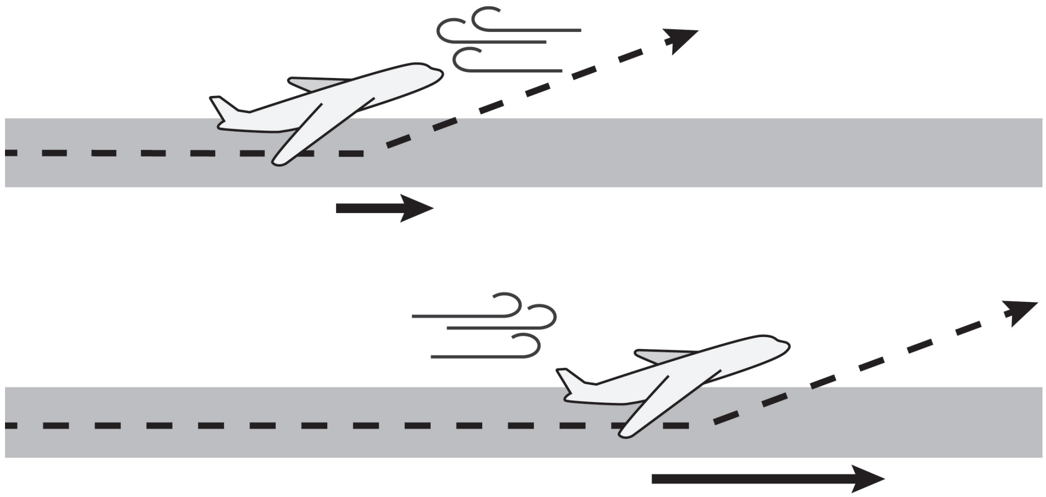

Figure 4: (Top) A plane flying into a headwind can take off with a ground speed lower than its airspeed. (Bottom) A plane with a tailwind requires a ground speed higher than its airspeed and thus more runway for its takeoff.

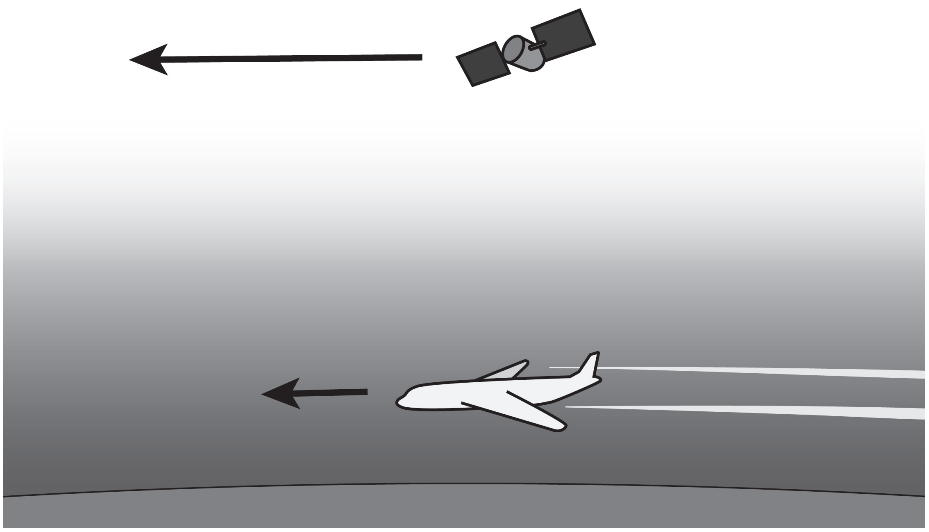

Figure 5: An airplane, flying through the atmosphere, must run its engines continuously to fight air resistance. But a satellite above the atmosphere can coast at much higher speeds than a plane without using an engine.

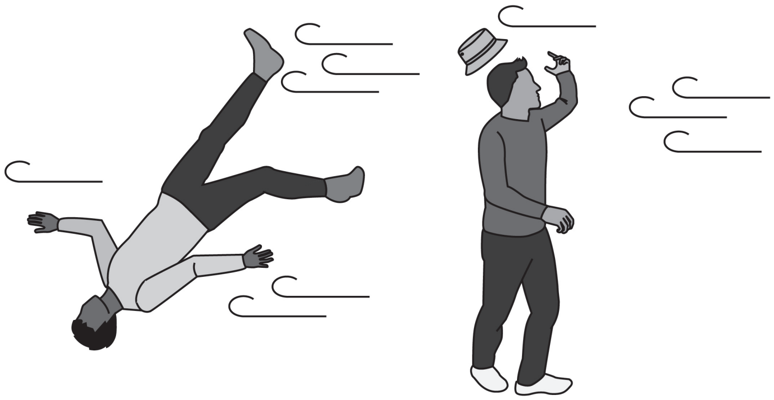

Figure 6: A member of our species might lose a hat on a windy day, but a Styrenian, with the same size but far less mass, might lose contact with the ground.

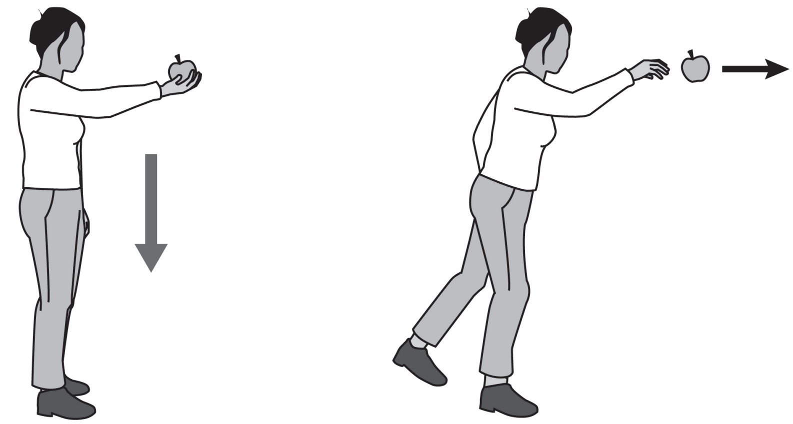

Figure 7: The difficulty of holding an object against gravity's pull (gray arrow) grows with its weight, while the difficulty of throwing an object horizontally (black arrow) grows with its mass. Out in deep space, the object would have no weight, but its mass would be the same; it would be as difficult to throw as ever.

Figure 8: Your weight varies with your location; your mass does not. Near geostationary satellites (G), your weight (from Earth's pull) would be one-fortieth of what it is on Earth (E). On the Moon (M), where Earth's pull is tiny, the Moon's pull would give you a weight one-sixth of what it is on Earth. Out in deep space, well away from all other objects, your weight would be nearly zero.

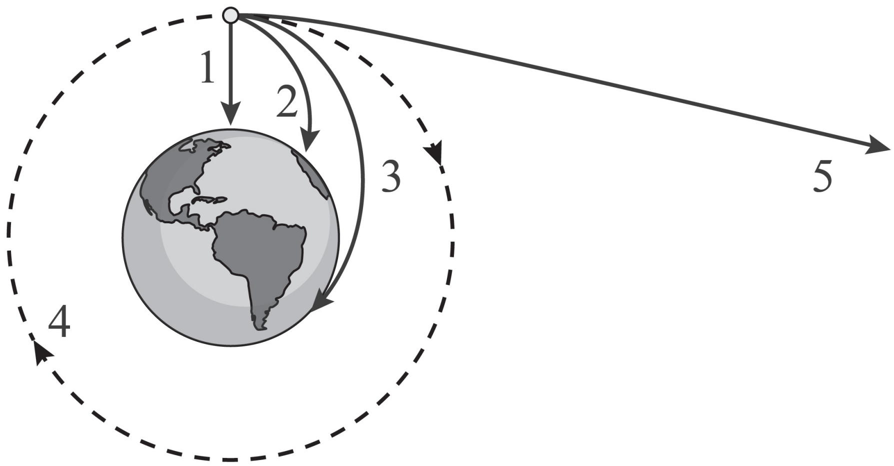

Figure 9: A stationary object, released far beyond the Earth's atmosphere, would fall toward the Earth's center (1). If moving too slowly to the right, it would descend and impact the Earth (2), (3). At too high a speed, it would escape the Earth entirely (5). But at an intermediate speed, its motion would balance gravity's pull, allowing it to orbit the Earth (4).

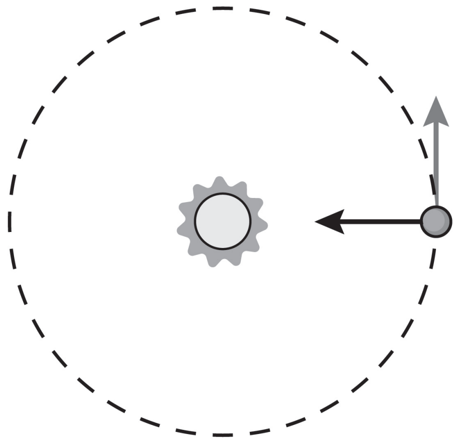

Figure 10: Kepler imagined that planets had to be pushed along in their orbits (gray arrow). Newton, assuming the coasting law, guessed that they had to be pulled toward the Sun (black arrow).

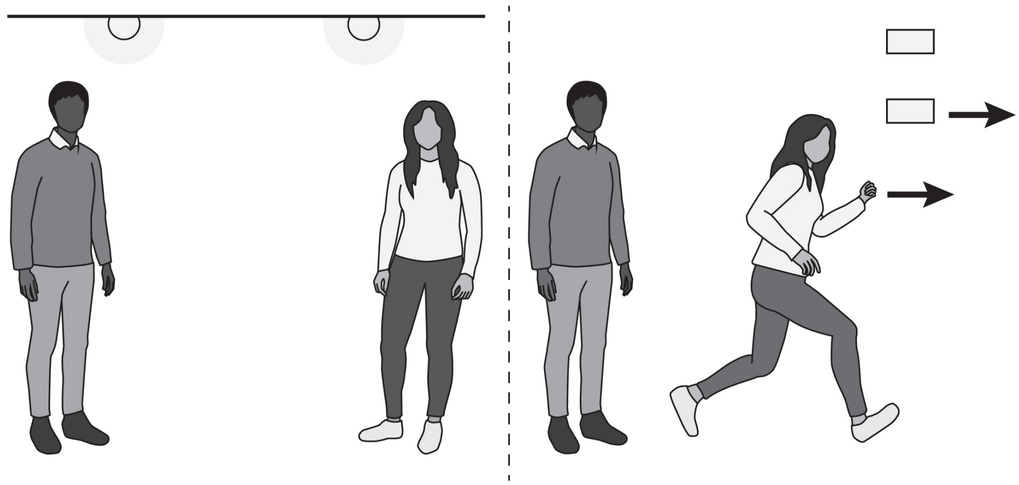

Figure 11: (Left) Two identical lightbulbs; the bulb at left, closer to Andrew, seems brighter to him. The reverse is true for Zelda. (Right) Two identical bricks with the same rest mass. From Andrew's perspective (and ours), the lower one moves to the right and has larger intransigence. From Zelda's perspective, the upper one moves to the left and has larger intransigence.

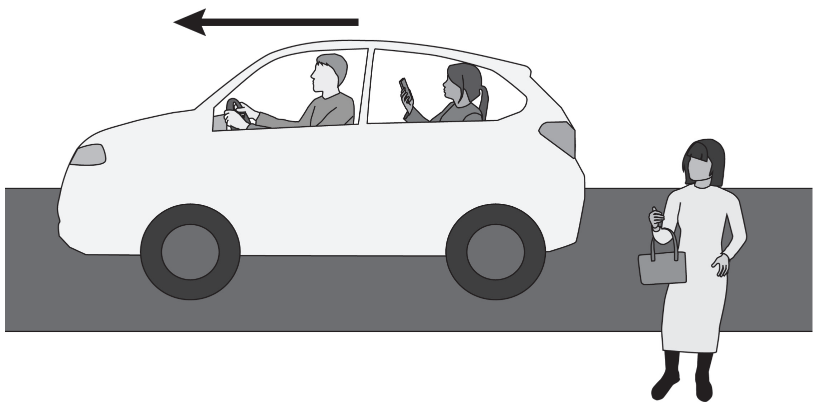

Figure 12: The rest mass of a cell phone in the car is its intransigence as measured by people in the car, relative to whom it is at rest. For a person standing on the sidewalk, the phone's intransigence is larger than its rest mass. All observers agree on these statements.

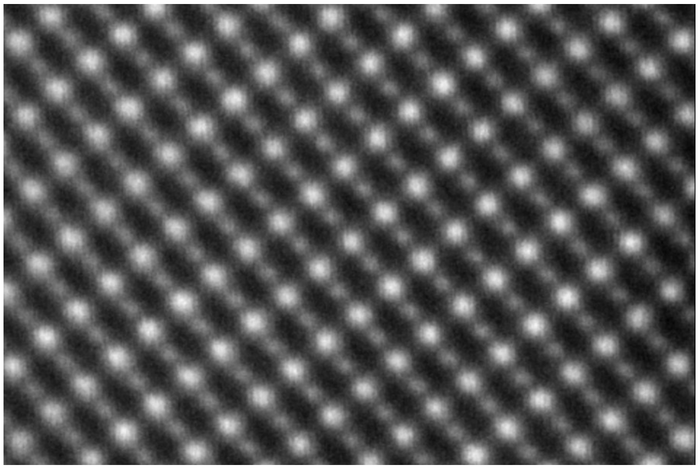

Figure 13: An image of atoms of different elements in a crystal, made by a transmission electron microscope. Rather than detecting the reflection of visible light, this microscope detects how the material blocks a narrow electron beam. Image cropped and rotated.

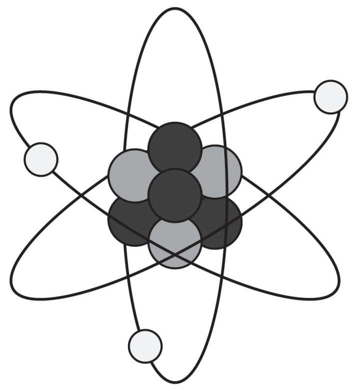

Figure 14: The universal atomic cartoon, whose electrons orbit a nucleus made of protons and neutrons, drawn in different shading to distinguish them. A real atom is very different; the nucleus is tiny, the electrons even smaller.

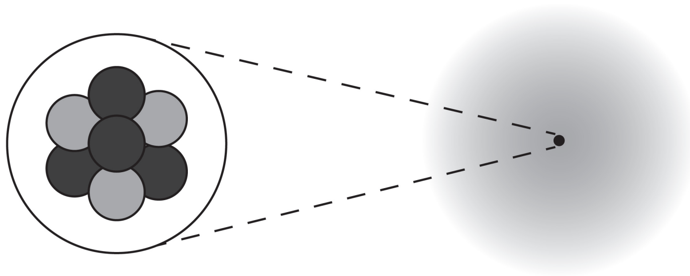

Figure 15: A better cartoon of an atom, with a tiny nucleus of protons and neutrons surrounded by a cloud of even tinier electrons. It is still not to scale.

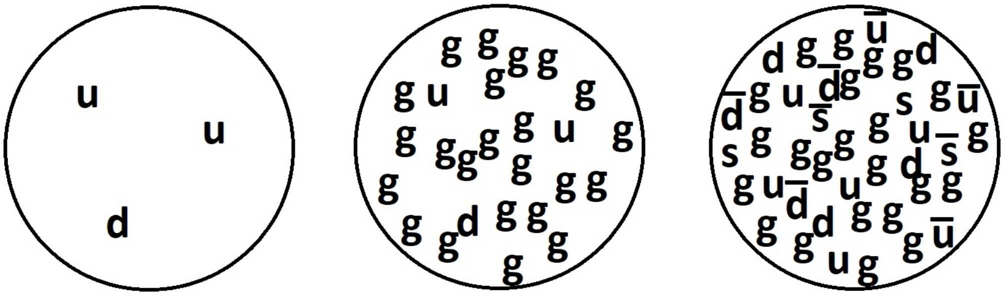

Figure 16: The proton, shown in an imaginary snapshot, is made (left) of two up quarks (u) and a down quark (d), plus (center) an ever-changing number of gluons (g) and (right) pairs of quarks and anti-quarks ($u, \bar{u}; d, \bar{d}; s, \bar{s}$), all moving at speeds at or near c.

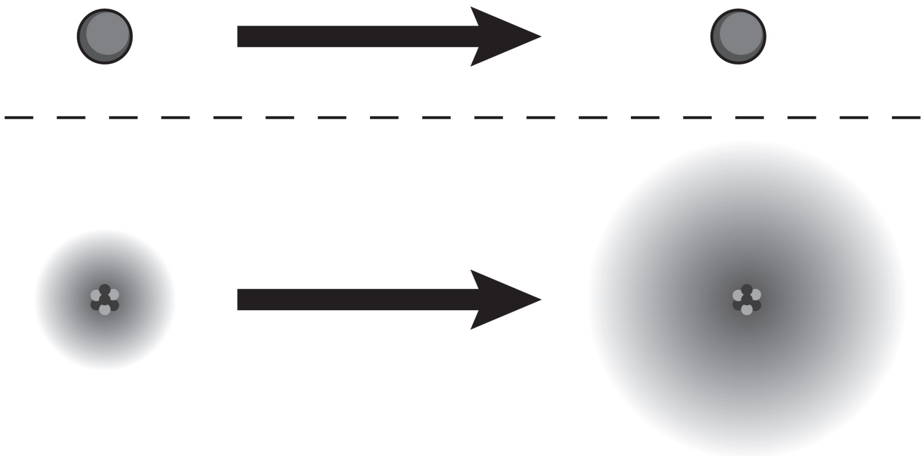

Figure 17: (Top) If quark rest masses were smaller, protons would hardly change. (Bottom) If the electron's rest mass were smaller, atoms would grow and become more fragile.

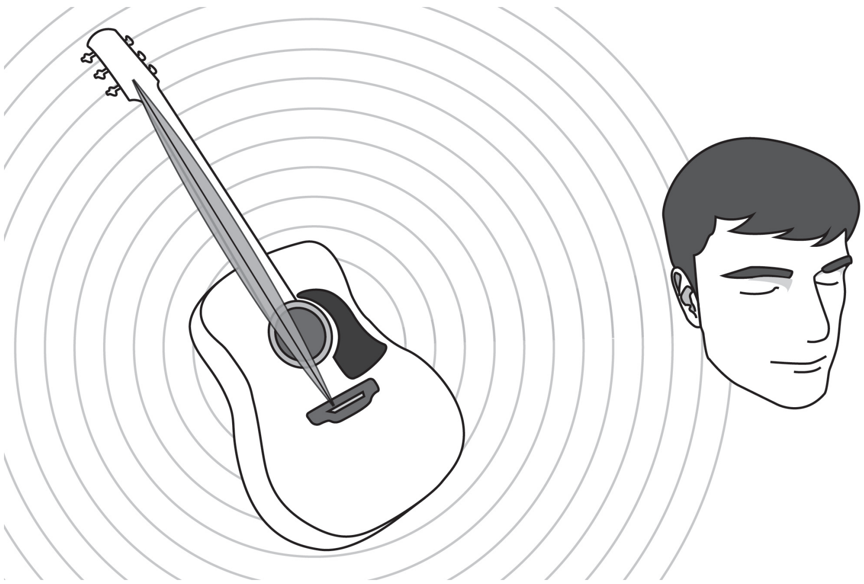

Figure 18: The player plucks a string, adding energy so that it vibrates. Sound waves carry off some of this energy and transfer it to listeners' eardrums, making them vibrate, too.

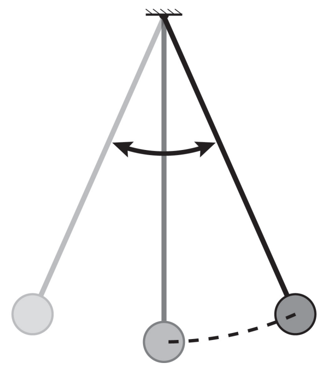

Figure 19: The frequency of a pendulum is how often it swings; its amplitude is how widely it swings (dashed line). The two are independent (as long as the amplitude is not too large).

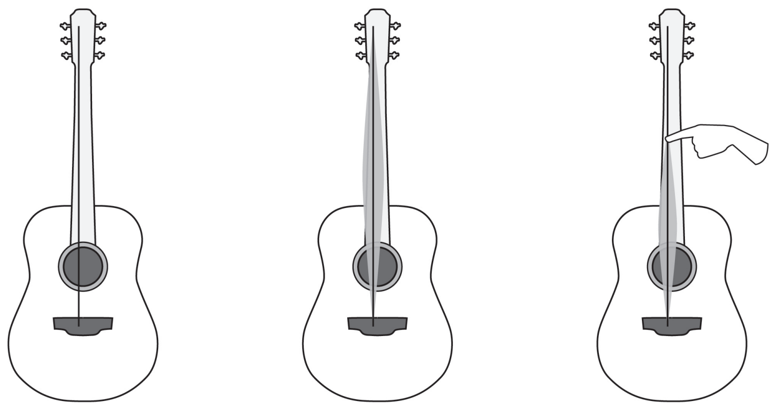

Figure 20: (Left) A guitar, showing one string. (Center) If plucked, the full-length string will vibrate at the string's resonant frequency. (Right) If the guitar player shortens the string by placing a finger on it, the resonant frequency increases, and the string produces a higher note.

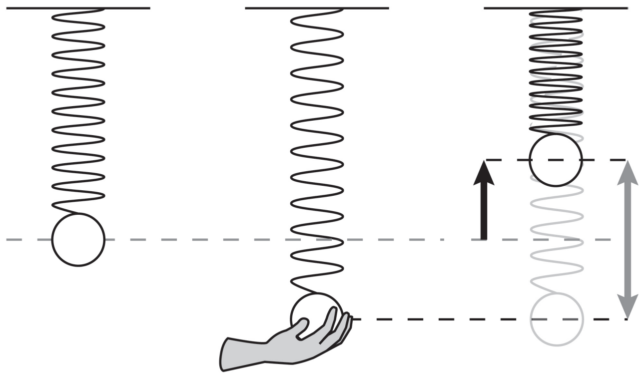

Figure 21: (Left) A ball hanging from a spring. (Center) The ball is pulled and then released. (Right) The ball bounces with the spring's resonant frequency, even while its amplitude (black arrow) gradually decreases due to dissipation. The frequency of the bounce will increase if the spring is tightened.

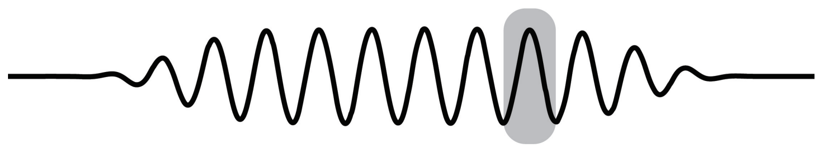

Figure 22: A simple wave in physics-dialect is a chain of crests and troughs of comparable size, while in English, a wave is just one crest (shaded.)

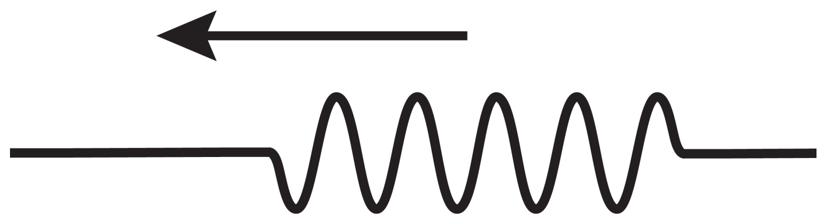

Figure 23: A traveling wave with five crests, such as can be made by wiggling a long string's end five times. It has an amplitude (its crests' height and its troughs' depth) and a frequency (how often a spot on the rope rises and falls as the wave passes).

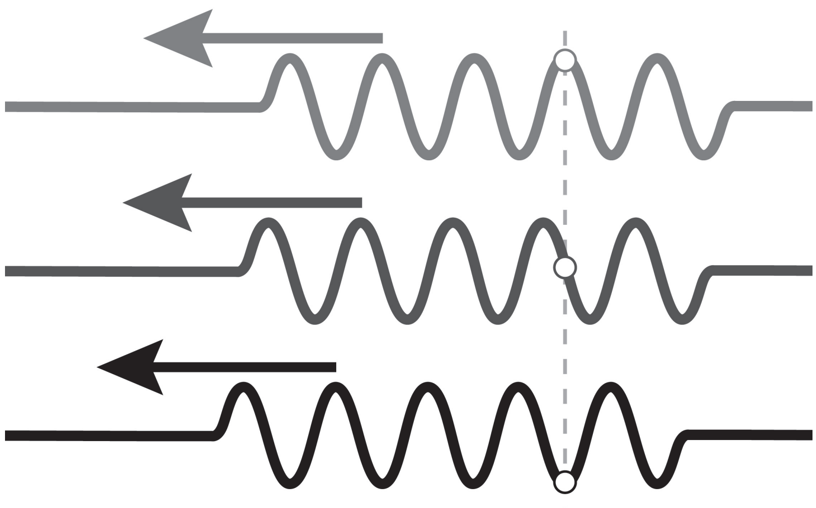

Figure 24: wave traveling to the left, depicted at three successive moments. Though the wave travels horizontally, the rope does not; each part of the rope, such as the white dot, moves purely vertically. The dashed line shows that the dot's horizontal position does not change over time.

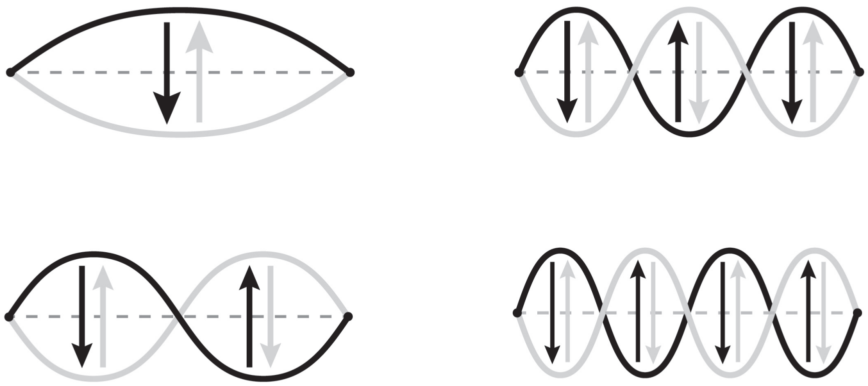

Figure 25: (Top left) The basic standing wave commonly seen on a guitar string, shown initially (black) and after a half cycle (gray). The other panels display its first three harmonics.

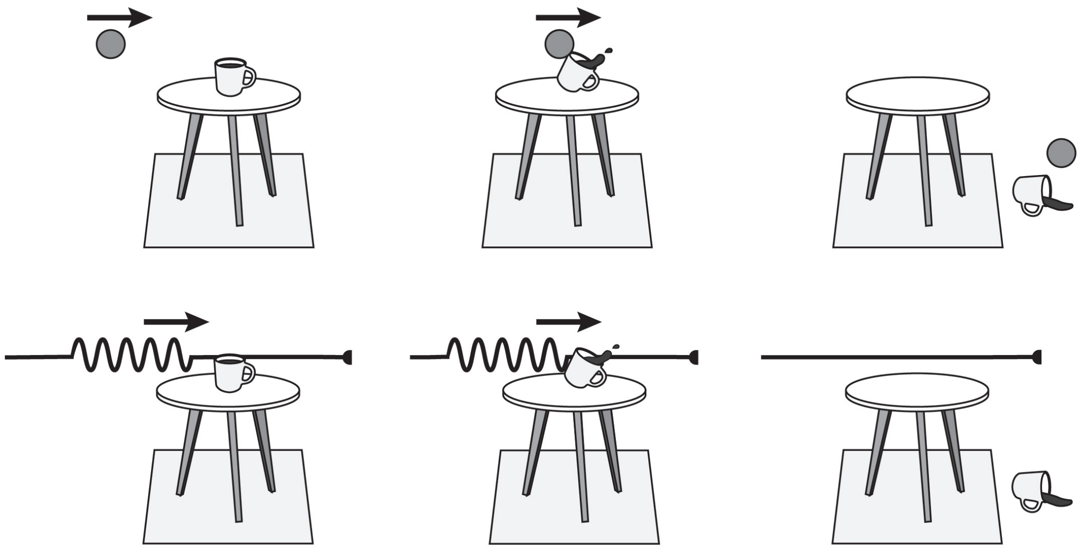

Figure 26: (Top) A ball can be thrown to knock a cup off a table. (Bottom) A wave on a rope that passes near the cup can do the job, too.

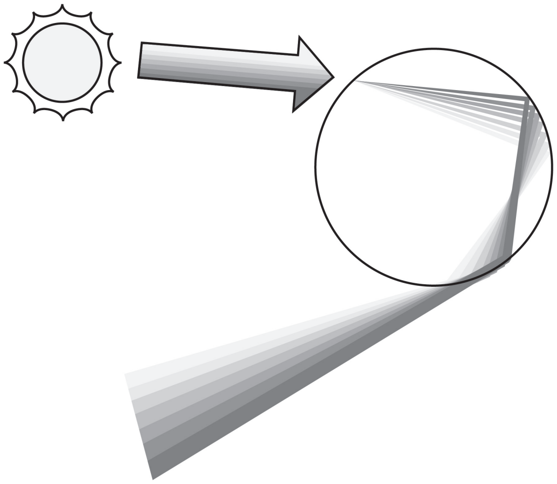

Figure 27: A refraction, a reflection, and a second refraction inside a raindrop breaks up sunlight into its various frequencies, some of which we can see as different colors, and sends them out of the raindrop at slightly different angles.

Figure 28: A rainbow appears narrow only because we are blind to both infrared (IR) and ultraviolet (UV) light.

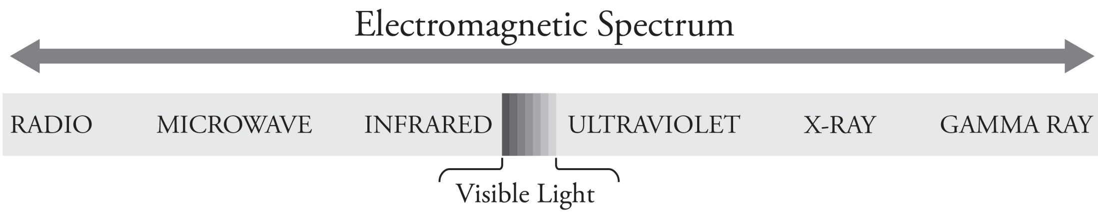

Figure 29: The spectrum of electromagnetic waves, illustrating schematically the continuous range of frequencies from lowest at left to highest at right. Also shown are the arbitrary divisions by scientists of the invisible frequencies into regions, and the very narrow range (not drawn to scale) that is visible to the human eye.

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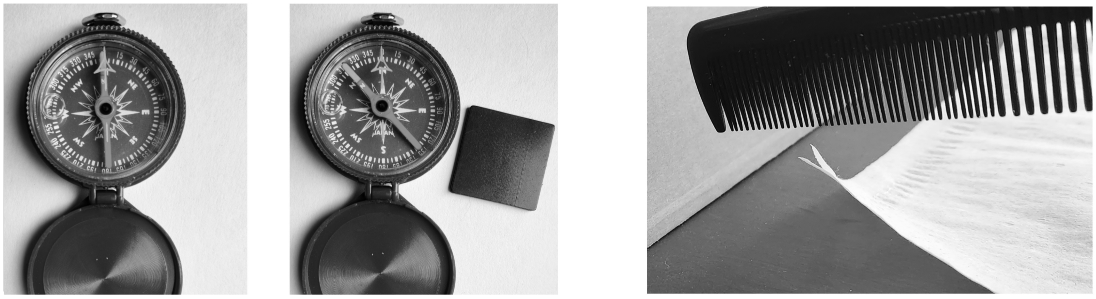

Figure 30: (Left) The magnetic field around a magnet (black square) can rotate a compass that would normally align with the Earth's steady magnetic field. (Right) The electric field around a recently used comb can pull on tissue paper without contact between comb and paper; this is an example of "static electricity."

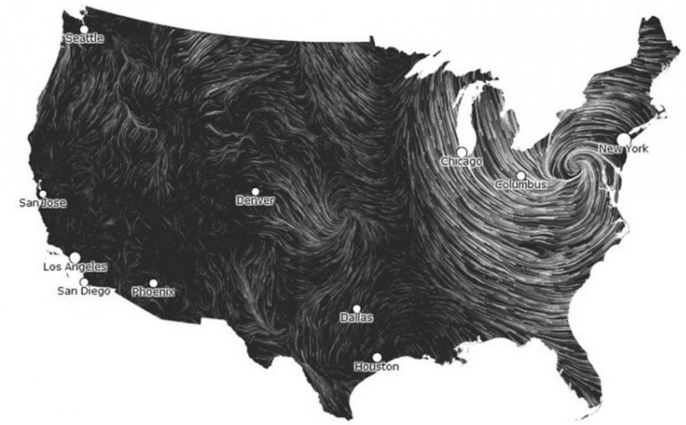

Figure 31: The wind field (with lines' orientation and brightness corresponding to wind direction and speed) just above the surface of the United States on October 30, 2012, soon after tropical storm Sandy came ashore from the Atlantic Ocean. "Wind Map" by Martin Wattenberg and Fernanda Viégas (hint.fm/wind).

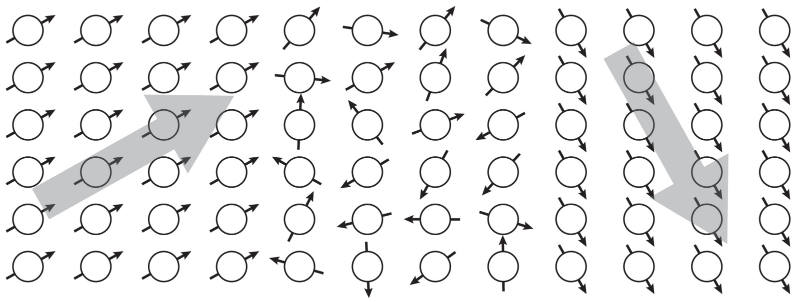

Figure 32: Atoms in an iron block; each acts as a tiny magnet (black arrows). Where they are randomly oriented, as at center, there is no net magnetization, but where they are aligned, there is a measurable magnetization field (gray arrows). Not to scale; the number of atoms is far greater than shown.

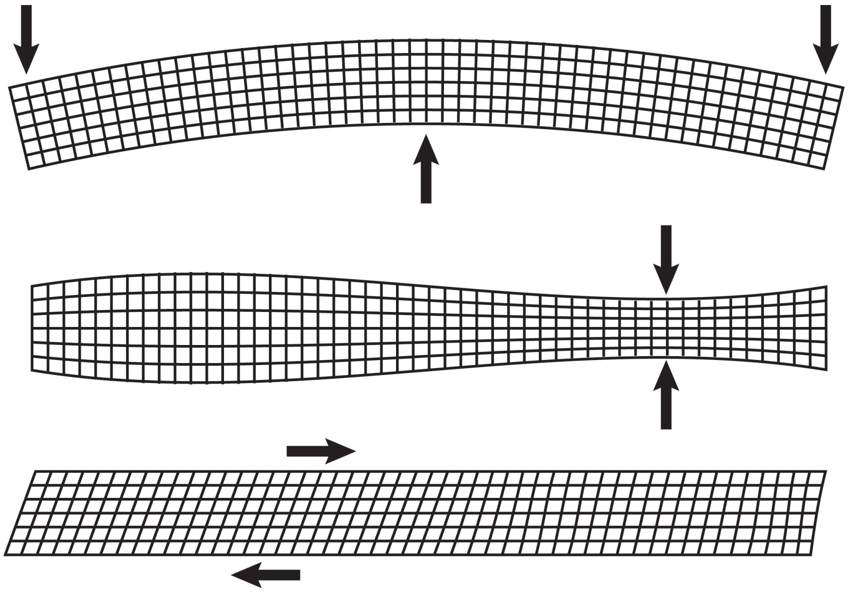

Figure 33: A thin aluminum sheet's bending field (top) is easy to see, but the compression and leaning fields (middle and bottom), much more obscure to a casual observer, reveal hidden details of the sheet.

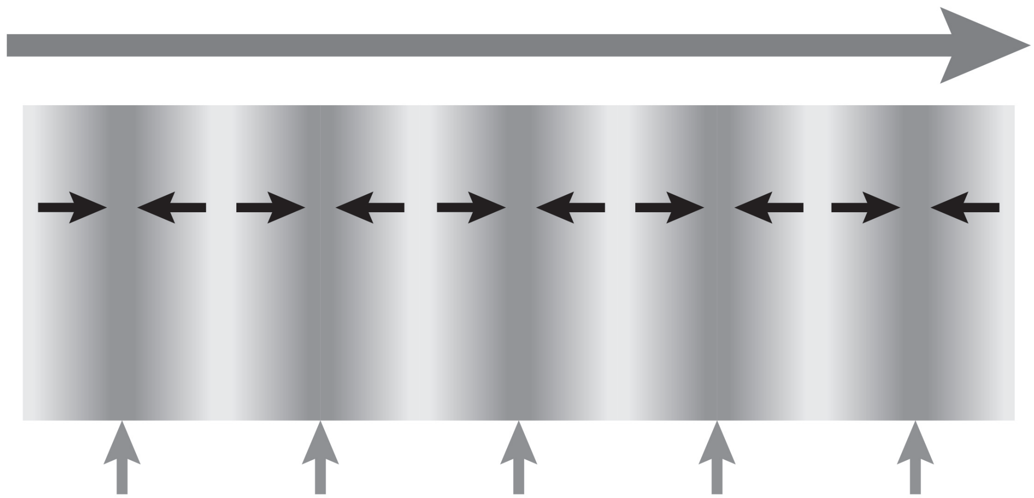

Figure 34: A simple sound wave traveling to the right (long gray arrow). It has crests (more concentrated air, in darker shading and indicated with vertical arrows) and troughs (less concentrated air, in lighter shading). The wind field is rippling, too (black arrows).

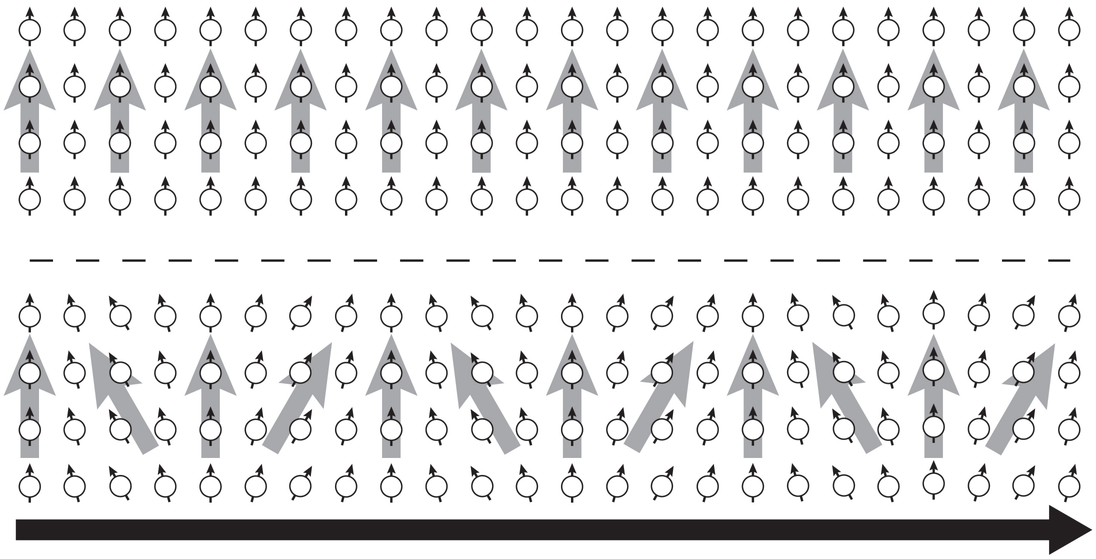

Figure 35: (Top) Magnetized iron; the atoms are aligned, as is the magnetization field (gray arrows). (Bottom) As a spin wave moves to the right through magnetized iron, the atoms' orientations and the magnetization field rock back and forth.

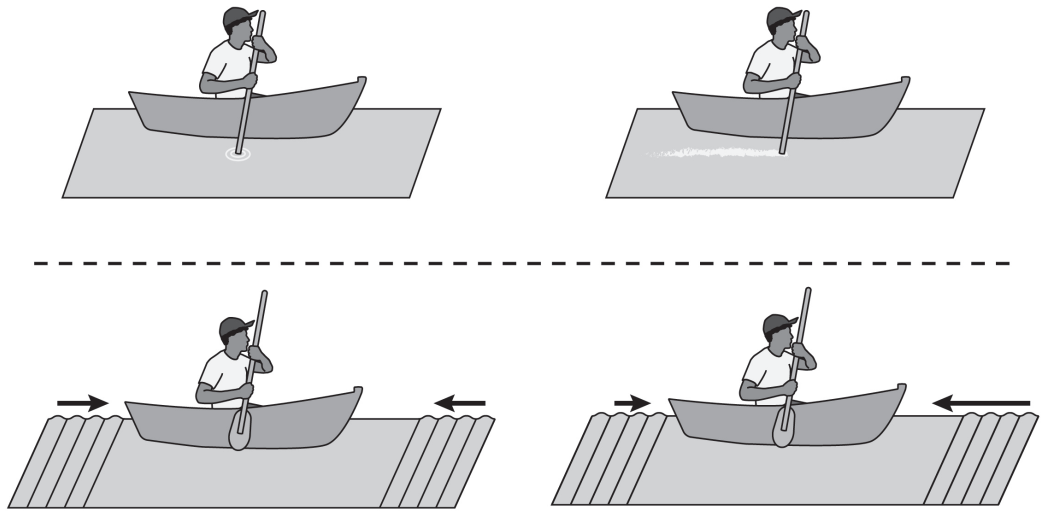

Figure 36: How to determine motion relative to an ordinary medium, as seen by someone stationary (left) or right-moving (right). (Top) The drag method, showing (right) the wake created by an oar moving through the water. (Bottom) The wave speed method, with wave speeds indicated by black arrows.

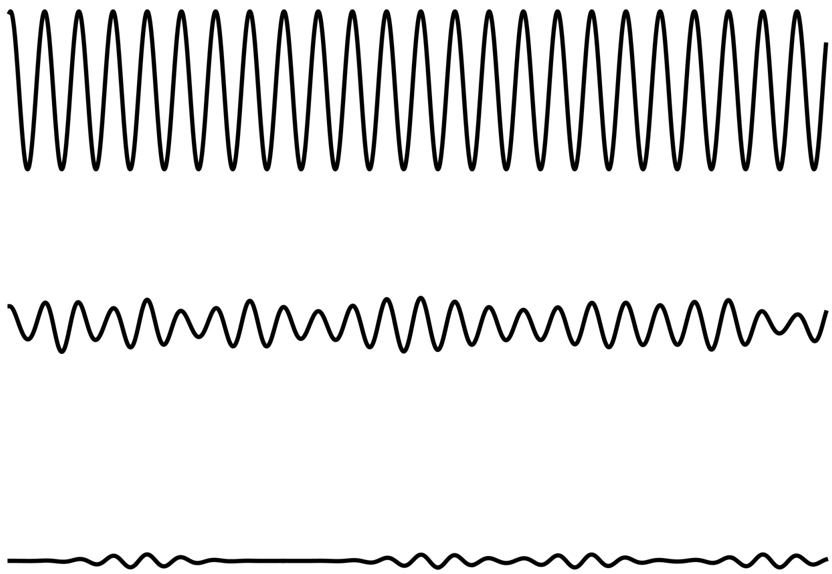

Figure 37: Light waves from a laser at high, medium, and low intensity, traveling to the right; schematic, and not drawn to scale. (Top) A steady, simple wave. (Middle) The light becomes unsteady. (Bottom) The light occasionally flashes at random times; each flash, a brief ripple, is a photon.

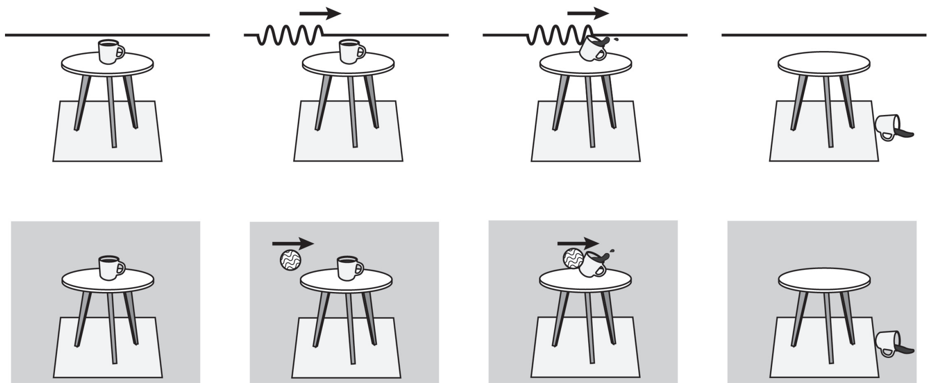

Figure 38: (Top) A rope stretched near a table; a wave approaches, strikes a cup, and travels on, leaving the rope behind. (Bottom) The universe's fields (shaded gray); wavicles in a ball approach, strike a cup, and travel on, leaving the fields behind.

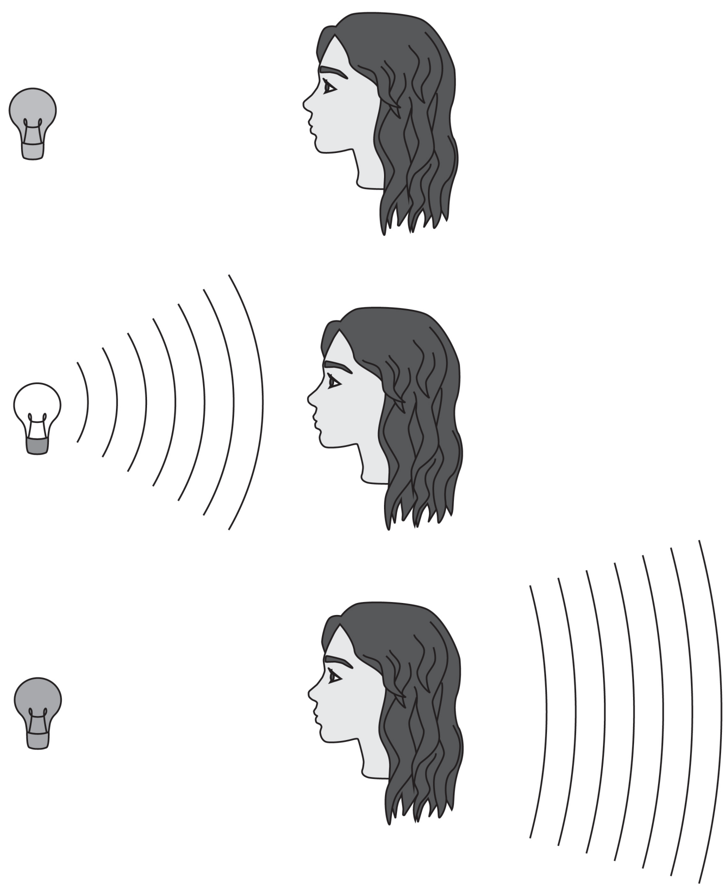

Figure 39: (Top) Before a lightbulb flashes, the electromagnetic field's value is zero. (Middle) Once it flashes, waves of light move through the electromagnetic field. (Bottom) After they pass, the electromagnetic field is again zero.

Figure 40: (Left to right) A particle of zero size has a sharp trajectory. But a wavicle's path, measured gently, is fuzzy. A collision with another particle may shrink an elementary "particle" to an extremely tiny size, but immediately thereafter, it will spread out. If a particle with a finite size, such as a proton, undergoes a similar collision that shrinks it too far, it will slosh internally and will be converted into multiple particles.

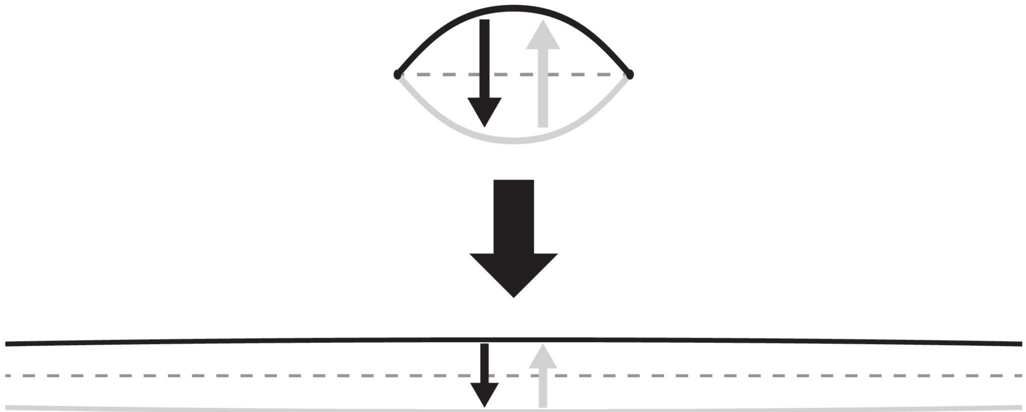

Figure 41: Toward visualizing a stationary electron: start with the standing wave shown at the top, and then stretch the wave horizontally, shrink it vertically, and increase its frequency to obtain the broad standing wave shown at the bottom.

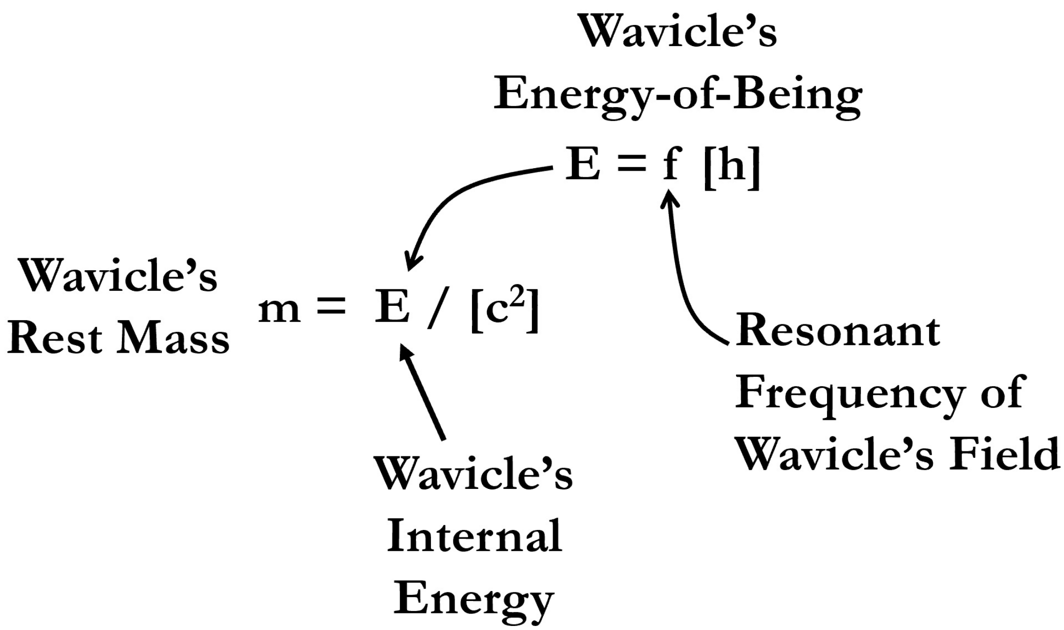

Figure 42: The origin of the relation between m and f via the combination of the relativity and quantum formulas.

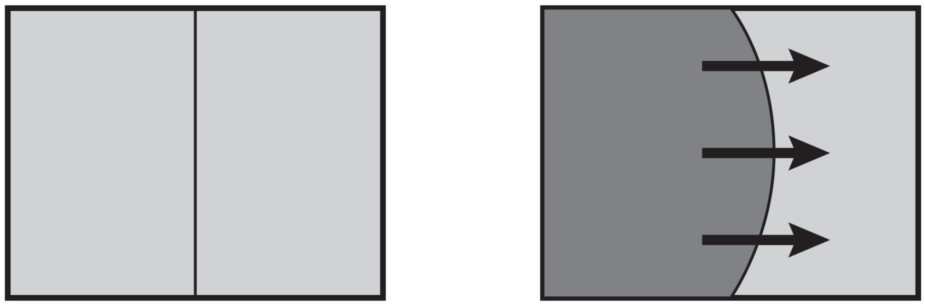

Figure 43: (Left) With the same pressure on both sides of a wall, there's no force on the wall. (Right) If the pressure is stronger on the left, then the wall experiences a force (black arrows) that pushes it to the right.

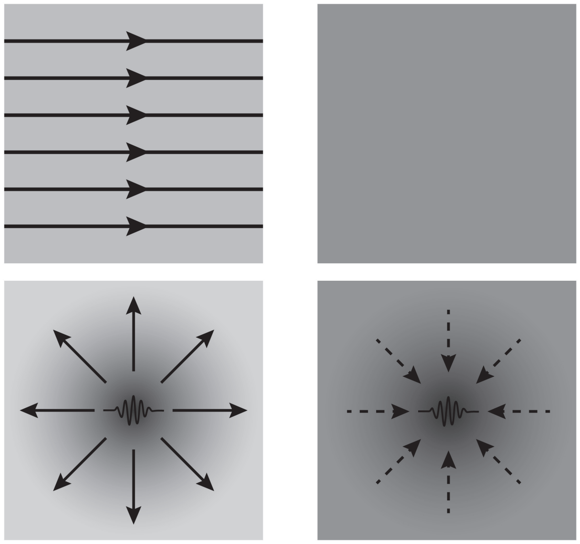

Figure 44: (Left) A pointing field can create a force either when constant (top) or when variable, as around a wavicle (bottom). (Right) A nonpointing field cannot create a force when constant (top) but can do so when varying around a wavicle (bottom). Arrows indicate the direction of the force; on the left, they also indicate the direction of the pointing field, and on the right, they indicate how the nonpointing field varies.

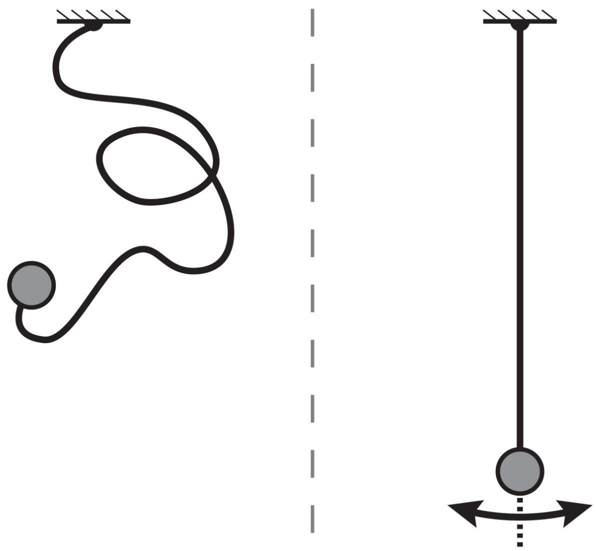

Figure 45: (Left) Without gravity, a pendulum won't swing. (Right) The gravitational field acts as a stiffening agent on the ball's position.

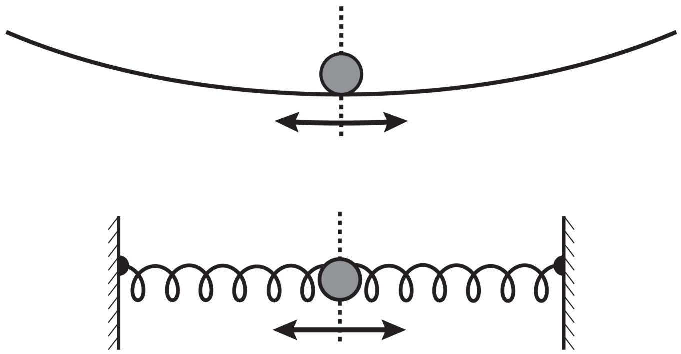

Figure 46: (Top) If a ball is placed in a bowl in the presence of gravity, its position will be stiff. (Bottom) If the ball is held in place by two springs, its position will be stiff even in the absence of gravity.

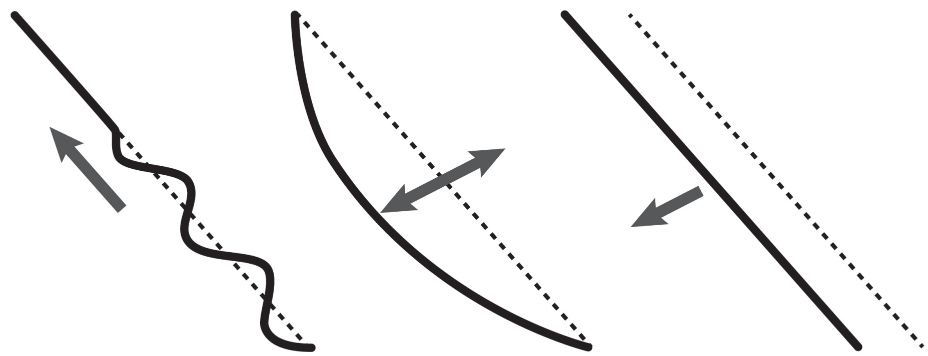

Figure 47: (Left) A traveling wave on a string; it may have any frequency. (Center) A standing wave on a string with pinned ends, like that on a guitar string; it vibrates with the string's resonant frequency. (Right) If a string with free ends (or an infinite string) is lightly pushed, it will drift away. In each case, dashed lines indicate the string's initial position.

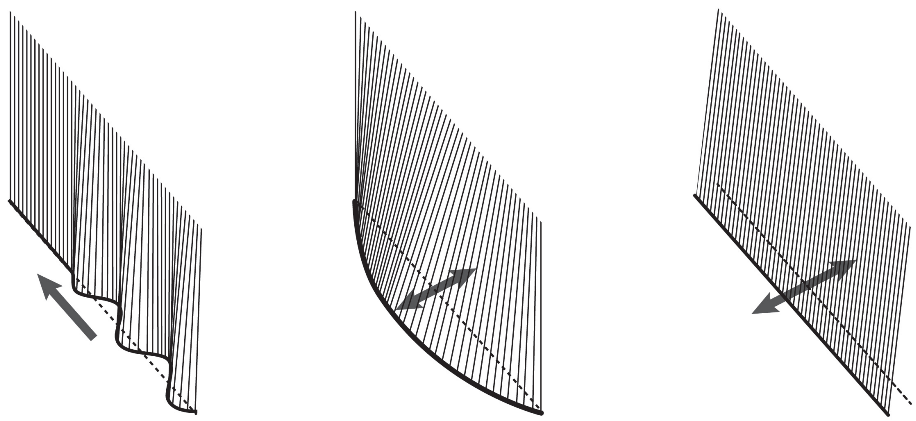

Figure 48: As in Fig. but with a curtain attached to the string. Left) Traveling waves are only changed in detail. Middle) The standing wave with fixed ends is changed only in detail. Right) A string without pinned ends, or an infinite string, no longer drifts; as long as there is gravity, it now vibrates as a whole.

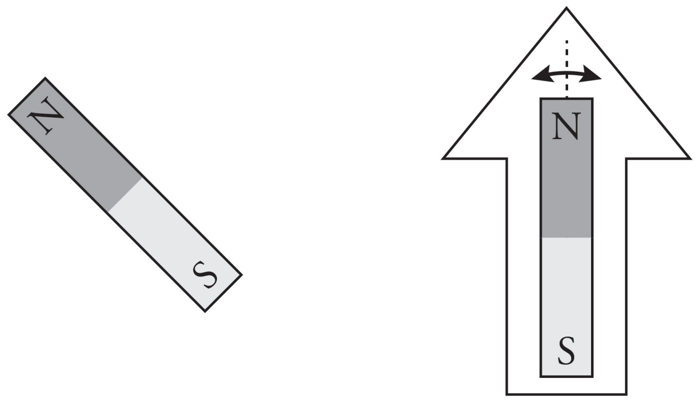

Figure 49: (Left) If the magnetic field nearby is zero, a magnetized needle's orientation angle is arbitrary; it can point in any direction. (Right) In the presence of a nonzero uniform magnetic field (large arrow), the needle aligns itself with the magnetic field, and its orientation angle is stiff.

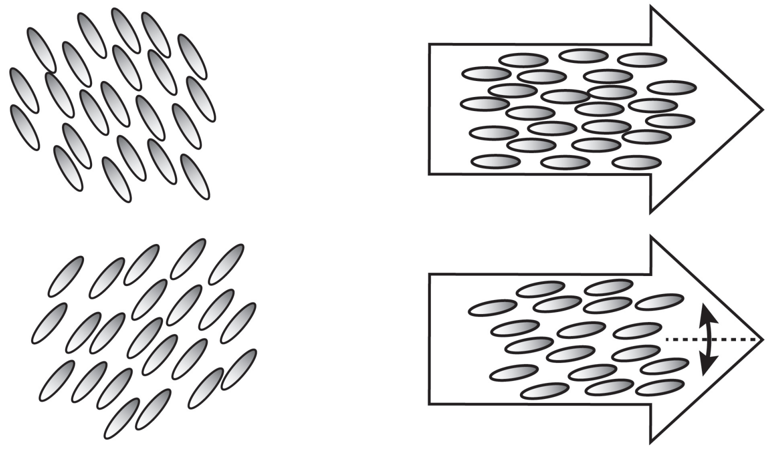

Figure 50: (Left) A liquid crystal's elongated molecules can move around but tend to align. The orientation of their alignment is a floppy field; two equivalent orientations are shown. (Top right) In a nonzero uniform electric field (large arrow), the molecules will align with the electric field. (Bottom right) The orientation field is now stiff; if the molecules are uniformly tilted away from the electric field, a restoring effect draws them back into alignment and a standing wave results (black arrows).

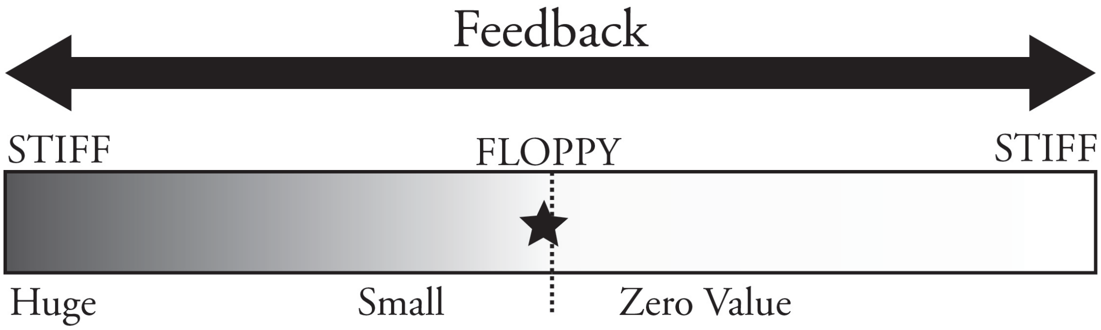

Figure 51: Though feedback from the fields it stiffens pushes the Higgs field toward extremes, it has ended up just left of the center line, as shown by the star, where both the Higgs field's value and stiffness are nonzero but very small. (Not to scale.)

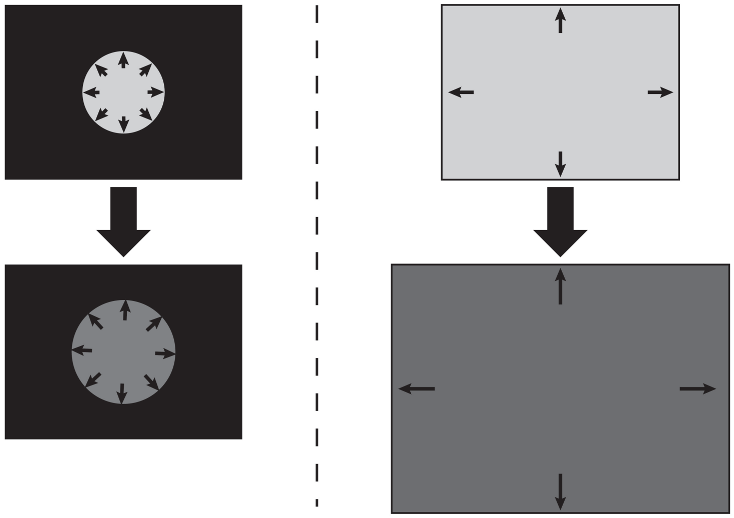

Figure 52: (Left) The Big Bang was not an explosion that blew an expanding hot fireball into a cold void. (Right) Instead, it produced a universal firestorm, hot everywhere; it cooled as space expanded.

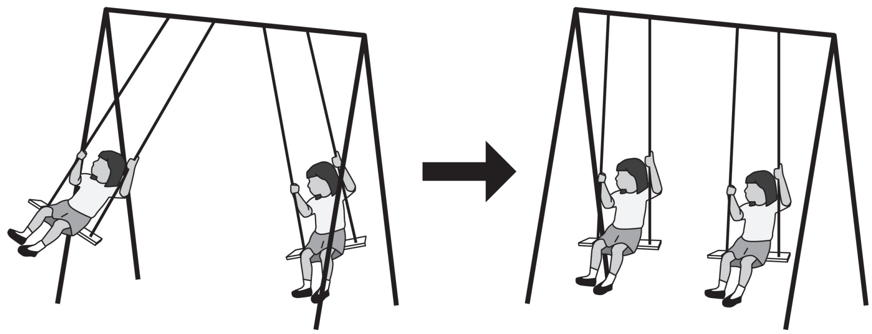

Figure 53: (Left) Immediately after their parents stop pushing them, two twins may swing differently. (Right) But dissipation soon brings them to a stop, leaving them identical.

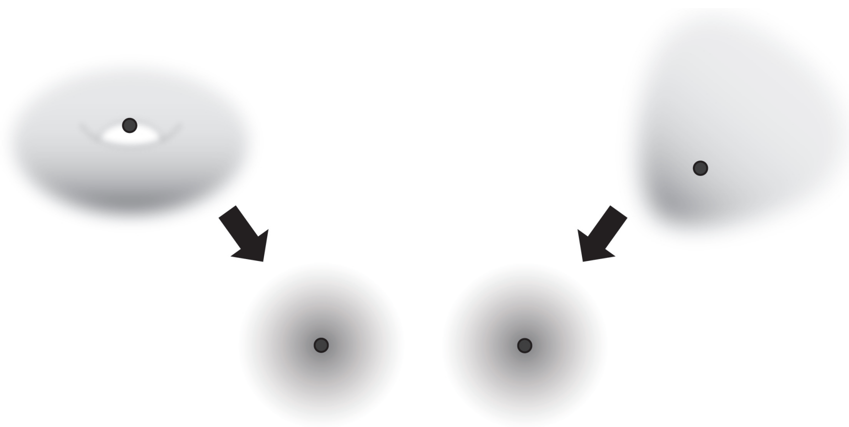

Figure 54: Two electron-proton pairs. (Top) At first they are very different. (Bottom) But after dissipation by emission of photons, they reach their minimal-energy arrangement, the ground state of hydrogen, and become identical.