The Physics *of* Everyday Things

The Extraordinary Science Behind an Ordinary Day

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CHAPTER ONE

You Begin Your Day

It is early morning, and you're asleep in bed. Your slow, regular breathing and steady pulse mark the passage of time, bringing you closer to when you must get up and begin your day. Today will be a busy one, with a visit to the doctor followed by a flight to another city for a business presentation. The vintage clock on your wall, a gift from your grandmother, provides a comforting tick, tock *as the small bob hanging from the body swings rhythmically back and forth. Although the clock keeps good time, you rely on the alarm setting of your smartphone to wake you. But the first sensation that will register the start of your day will not be your hearing; it will be your sense of smell. Last night you set the* ***digital***

timer *on your coffeemaker to start its brewing cycle ten minutes before your phone's alarm will go off. Your room soon fills with the aroma of fresh coffee, and you begin to stir.*

The elegant physics of an oscillating pendulum underlies the working of both the clock on the wall and the electronic timer on your coffeemaker, and plays a crucial role in many of the devices you will use as you prepare for the day.

A pendulum is a very simple device, consisting of a string, fixed at one end, with a mass, termed the "bob," attached at the other end. The oscillations of the pendulum bob provide visual confirmation of one of the most important concepts in physics, that of the principle of conservation of energy: "kinetic energy," the energy of motion, can only be converted to "potential energy" (the energy associated with a force acting on an object and the distance over which that force can cause motion) and vice versa. In a pendulum, you can increase the potential energy of the mass on the string by lifting it up, rotating the bob to a higher level while keeping the string taut, doing work against the gravity that pulls down on the bob. Once you release the bob, its potential energy is converted into kinetic energy as it moves in an arc of a semicircle. As the bob swings to the other side, the kinetic energy is converted back into potential energy. Both the starting height and the final height at the other end of the arc are the same—when you release the mass and don't push it, it can never rise to a greater height than where it started.

A pendulum is useful for keeping time. The time it takes for the bob to complete a full cycle as it swings back and forth does not depend on how heavy the weight is, or on how high the mass is lifted to start it swinging (at least, for relatively small excursions back and forth). The greater the height of the mass, the larger the arc as it swings back and forth, and the larger the kinetic energy and speed it will have at the bottom of its arc. The longer distance and the faster speed exactly balance out, so that the time it takes to complete a cycle is the same—regardless of how high the bob is raised. The only factor that controls the time for a cycle is the length of the string. A pendulum whose string is just a little less than ten inches long will take one second to complete a full oscillation. As it swings, some of the kinetic energy of the bob is transferred to the surrounding air, pushing the molecules out of the bob's way. A careful audit will find that the gain in kinetic energy of the air is exactly equal to the reduction of the total energy of the pendulum, which is why mechanical clocks—grandfatherly and otherwise—need periodic winding.

It's as true for the digital timer on the coffeemaker as it is for the mechanical pendulum—to mark the passing of time, one needs a power supply (as everything, even counting seconds, requires a source of energy) and a way to convert that energy into a periodically varying cycle. The coffeemaker is plugged into an outlet connected to an external electric power grid. Conveniently for us, the mechanism by which electric power is generated at a power plant automatically leads to an electric current that oscillates back and forth like a pendulum that can be exploited when making a timer.

Your electric company rotates coils of wire between the poles of large electromagnets, and to see how that leads to an alternating electric current, let's return to the simple mechanical oscillating pendulum. Let the bob at the end of the string have an electric charge, say from a few extra electrons sitting on it. Even if this pendulum has a frictionless pivot point and is swinging in a perfect vacuum, with no air drag, it will eventually slow down and come to rest. Where did the bob's energy go? Into electromagnetic waves, demonstrating a profound symmetry between electric and magnetic fields that will be exploited repeatedly throughout your day.

An "electric current" is defined as the motion of electric charges moving together, and as the electrically charged bob swings back and forth, changing its speed, it is a constantly changing current. The current is large at the bottom of the arc, when the bob is moving at its fastest, and the current is zero at the top of the arc, when the bob is momentarily stationary. Moving electric charges, as in a current, generate a magnetic field (this is known as Ampere's law); the faster they move,

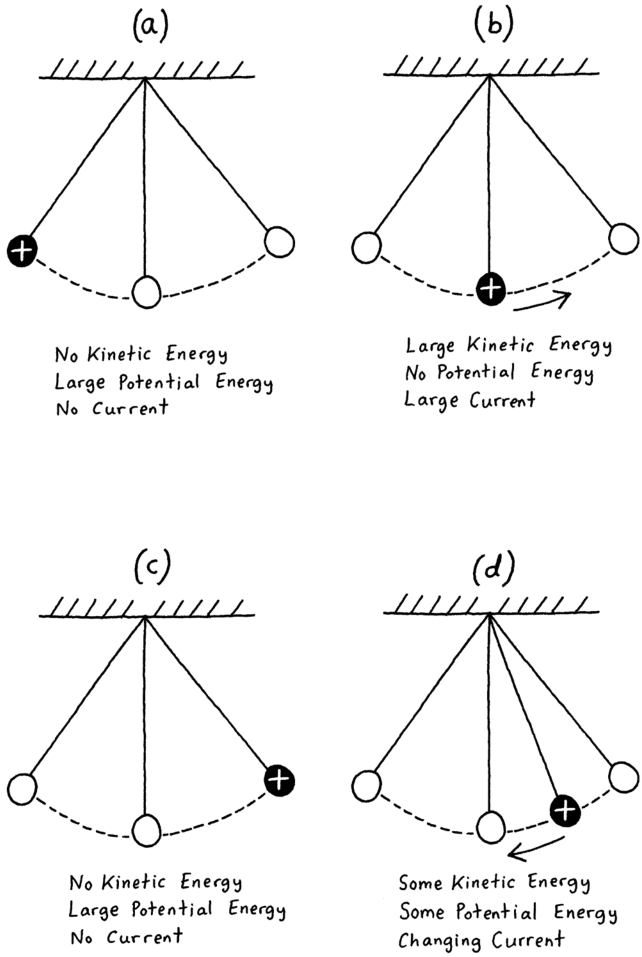
(a)
No Kinetic Energy
Large Potential Energy
No Current
(b)
Large Kinetic Energy
No Potential Energy
Large Current
(c)
No Kinetic Energy
Large Potential Energy
No Current
(d)
Some Kinetic Energy
Some Potential Energy
Changing Current

FIGURE I

the larger the magnetic field. The swinging bob, creating a constantly changing current, generates an equally varying magnetic field. In turn, this changing magnetic field generates a varying electric field (known as Faraday's law). This rhythmic oscillation of electric and magnetic fields is termed an "electromagnetic wave," which will have the same frequency as that of the oscillating bob. These waves carry energy, and thus it takes energy to create them. This is why the oscillations of an electrically charged bob will slowly die out, as its energy of motion is converted into electromagnetic waves. We could see these electromagnetic waves with the naked eye if the pendulum were swinging back and forth very rapidly (say, a thousand trillion times a second), in which case these waves would appear as visible light.

The power company employs the basic physics of electromagnetism when it generates the electric voltage available from the wall outlet, using coils of wire rotating between the poles of a magnet. The voltage provided by your electric company alternates smoothly from a positive voltage to a negative voltage, and back again, forming a wave that is mathematically identical to the variation in position of the pendulum bob as it oscillates back and forth, and is a natural consequence of how the electricity is produced. (This is why our electric power is called AC, for "alternating current.") The power plant is applying Faraday's law, which describes how a changing magnetic field will generate a voltage. As the coil turns, the magnitude of the magnetic field passing through the circular area of the coil varies, and a voltage is generated that sets up a current in the coil.* Think of the coil as a spool of thread with a very large diameter. When the area of the coil is facing the poles of the magnet, most of the magnetic field passes through it (along the length of the spool), but when it rotates by ninety degrees, hardly any of the field passes through the coil's area. A uniform rotation speed yields a smoothly varying voltage that changes back and forth in time, just like the motion of the pendulum bob. In the United States, the coils rotate sixty times a second, which is the frequency of the alternating voltage that is generated.

The fact that the voltage in the wall outlet varies smoothly back and forth sixty times a second means that it takes only 0.0167 second to complete one cycle. To slow this period down to one second, the coffeemaker's timer uses specially designed chips that shift the frequency of the alternating voltage.** One chip divides the incoming frequency by ten, so a voltage wave that oscillates sixty times a second now does so six times a second. Another

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* High-pressure steam is used to turn the coil, and the steam is generated by boiling water via the burning of coal or natural gas or biomatter, or through the energy of nuclear reactions. Regardless of the fuel they use, all power plants use the same physics to generate electricity.

** These chips generate beats by adding a second frequency to the first signal (a process called "heterodyning"). The result is two oscillations, one at a higher frequency that is the sum of the two, and another at a lower frequency that is their difference. Using a filter, one can select for the lower frequency.

chip divides this frequency by an additional factor of six, so the frequency of six cycles per second is reduced to one cycle per second. This slower voltage wave is sent to another chip, which counts the number of times the voltage has its largest positive value (equivalent to watching how often the pendulum bob returns to its original starting position). This "counting" chip monitors the passing seconds, and with a little amount of additional circuitry, this information can be displayed on a digital clock. When you set the timer on your coffeemaker, you are instructing a chip to monitor this counting chip, and when the sum reaches a certain value (the time you specified for the coffeemaker to turn on), it sends another voltage to another part of the electronic system. This voltage is the same as the one created when you press the ON switch manually, and the brewing process begins.

The system for measuring time begins when we plug in the coffeemaker and set the correct time. If the coffeemaker is unplugged, then this preset is lost. So how does an electronic timer work when it is not connected to the external alternating-current power from the wall outlet?

The coffee vapors waft into your room and are recognized by your still-not-fully-awake mind. In addition to setting the timer on the coffeemaker last night, you set the ***alarm clock*** *on your smartphone. The alarm goes off, playing a preset tune stored in the phone's memory chip. You grumble as you*

If the coil in the recharger has the same number of turns (like the winding of thread on a spool) and the same diameter as the coil in the base of the electric toothbrush, then the current induced in the toothbrush coil will be the same as the current that flows in the first coil (assuming that all of the magnetic field from the recharger coil passes through the coil in the toothbrush base). But if the second coil has more or fewer turns, then the current induced will be smaller or larger, respectively, than in the first coil.* This is advantageous, as the alternating current coming from the wall outlet has a peak value of 110 Volts, which is too large to send to the battery in the toothbrush. Transformers are used all the time either to boost the voltage in power lines to improve the transmission efficiency or to decrease the voltage, when the power line reaches your house, to a safer, lower voltage of 120 Volts, suitable for the appliances on your kitchen countertop.

Back in the kitchen, you slice your bagel into two halves. You place each half into the ***toaster,*** *and depress the lever. The spring inside the toaster that holds the slices up is com-*

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* Electrical power is mathematically described as the product of the current and the voltage, and a larger current in the second coil means that the voltage will be smaller. (One is constrained, after all, by conservation of energy, and one can't get more power out of the system than one puts in.)

pressed, and the bagel withdraws into the toaster, where the wires begin to warm, eventually glowing red. The butter is still a bit hard, so you put it in the butter dish and place the dish atop the toaster's openings; the heat will make the butter softer and easier to spread.

The toaster is a technology that would be familiar to your great-grandparents. When you put a piece of bread in a toaster and push the lever arm down, in addition to lowering the slice into the toaster, you are also closing a circuit that allows an electrical current to flow through the wires adjacent to the bread. After half a minute or so, the wires become warm and then begin to glow red-hot. Why? To understand how the toaster converts electrical energy into heat and light requires an understanding of thermodynamics, electromagnetism, and quantum mechanics. All for a piece of toast!

A toaster employs the first law of thermodynamics, which states that for any closed system, the total amount of work and heat must remain unchanged. When you close the circuit by pressing down on the lever, the current is forced through the wire, and thanks to the resistance in the wire, the electrical current's energy is converted into heat.

Let's start with the metal wire itself. To be a good conductor of electricity, a material needs a large number of electrical charges that are free to move. Metals have a large density of mobile electrons and thus make excellent carriers of electrical current, while insulators like plastic or glass have their electrons tied up in the chemical bonds between atoms. The arrangement and detailed chemical interactions of atoms in a solid, subject to quantum mechanical constraints, determine whether any given material is an insulator or a conductor.

Toaster wire is usually composed of an alloy of nickel and chromium (called nichrome), both metals that can carry an electrical current. For quicker toast, the wire should be a good conductor of electricity—but not too good. It's the mixing of two different metals in the nichrome wire, along with any other defects or imperfections, that will lead to the desired heating.

Think of the wire in a toaster as a large staircase with a throng of people all trying to descend at the same time. The more people exiting at the bottom of the stairs, and the faster they are moving, the greater the current. The voltage, which here would be the steepness of the stairs, is what gets people moving down in the first place. A very steep angle would translate to a large voltage, meaning a single person would exit the bottom of the staircase with a greater speed. The individual steps correspond to the atoms in the metal. It's easier to descend the staircase, especially when you are part of a large group, by having everyone line up across the width of the staircase and move down, step by step, in unison. As one row exits at the bottom, another starts off at the top—allowing the staircase to achieve its peak efficiency.

However, people in a staircase, like electrons in a wire, move somewhat randomly rather than marching in lockstep. Moreover, real staircases (and real wires) are not so uniform. If there is a step missing (in a wire this might be an atom out of place, for example) that no one notices until they try to walk onto it, there would be a large tumble. All of this leads to inefficiency, and the whole journey takes longer—which (in toaster-wire terms) translates to a lower current.

In a metal, this is characterized as contributing to the wire's "resistance." There are geometric contributions to resistance, as it's harder to pass a current through long and skinny wires compared to short and fat ones. In some applications, resistance is a significant hindrance. But when making breakfast, it comes in handy.

The resistance of the wire leads to a transfer of kinetic energy from the electrical current to the atoms in the wire, causing them to vibrate more violently than before, a process known as "Joule heating."* This is why nichrome is used in your toaster—it's a good enough conductor to carry a current, but it also has a large

* This same physics applies in space heaters and hair dryers.

resistance, to maximize the Joule heating. With enough transferred kinetic energy, the atoms near the defect can shake so violently that they emit light, which is why the toaster wire glows.

When an atom vibrates, the electrons swing back and forth like a mass on a spring, forming an electrical current that fluctuates inside the atom. That electrical current generates a magnetic field. As the current is continually alternating in magnitude and direction, the magnetic field is constantly changing, and the changing magnetic fields generate electric fields. Think of the charged pendulum bob shown on page 5. The periodically varying electric and magnetic fields combine to form an oscillating electromagnetic wave called "light."

To create that perfectly done piece of toast, the heat of the toaster wire (which can be over 1,000°F) is transferred to the bread. In hair dryers and space heaters, air molecules are pushed past the hot wire, picking up excess kinetic energy, while in the close confines of a toaster, heating occurs mostly from infrared radiation. When the surface of the bread is approximately 300°F, sugars and starches undergo a chemical reaction, becoming brown and changing their flavor and texture. The "toast setting" knob is actually an adjustable resistor that varies the current in the toaster wires. A timer or temperature sensor is used to open the electrical circuit and stop this process, hopefully before your toast burns.