Radiant Thermal Energy Is Not Additive

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Abstract: There are at least 16 different types of energy. Macroscopic types, usually described by classical mechanics, are associated with net linear displacement or deformation of matter, are a function of the mass or extent of the system under study, and thus have extensive physical properties that can typically be added together. Microscopic types of energy, on the other hand, studied most often using quantum mechanics, are typically associated with microscopic oscillations of all the bonds that hold matter together, are pervasive throughout the system, and thus have intensive physical properties that typically cannot be added together. Recognizing that microscopic energy is proportional to the frequency of oscillation of these bonds and is not proportional to the amplitude of oscillation or to mass, helps us understand why climate models currently overestimate the energy absorbed by greenhouse gases and why quantum mechanics is so physically unintuitive.

Introduction: Energy is a very subtle concept (Coopersmith, 2010). In fact, Richard Feynman, one of the best known and most provocative physicists of the 20th century, wrote "it is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount [that can be added together]" (Feynman et al., 1963)(p. 4-2). Feynman received the 1965 Nobel Prize in Physics for his contributions to the development of quantum electrodynamics, which is, essentially, the study of how thermal radiation interacts with matter. With respect to thermal radiation and other energies in the quantum world, Feynman may have been quite correct.

Energy is a physical property of physical objects that can be transferred to other physical objects or converted into different forms, but cannot be created or destroyed (Kittel and Kroemer, 1980). Energy comes in at least 16 different forms or types, and we may describe each type from many different perspectives. Energy is, in its most basic form, "the 'go' of the universe," that which "makes things happen"—that which "causes change" (Coopersmith, 2010). Energy can be thought of as powering the dimension of time because without change, it would be impossible to note or measure time.

Energy comes in two fundamentally different forms: 1) those generally associated with the net linear displacement or deformation of macroscopic matter, such as kinetic, potential, mechanical, mechanical wave, elastic, and mechanical work energies, and 2) those associated with microscopic oscillations of molecular and atomic bonds that hold matter together, such as thermal, heat, chemical,

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electric, magnetic, radiant, nuclear, and ionization energies. We study macroscopic energies primarily via classical mechanics. We study microscopic energies primarily via quantum mechanics.

Macroscopic energies typically depend on position, distance travelled, velocity, acceleration, mass, or extent of the object and are therefore said to have *extensive* physical properties. Energy that is extensive "comes in little blobs of a definite amount" that generally can be added together. Kinetic energy, for example, includes mass (m) and velocity (v) in its definition ($E_k = \frac{1}{2}mv^2$). When you double the mass, you double the energy. When you double the velocity, you quadruple the energy. Macroscopic energies are typically *additive*.

Microscopic energies, on the other hand, involve simultaneous oscillation of all the molecular and atomic bonds that hold matter together. Sometimes these bonds oscillate at high enough frequencies to be "shaken" apart, causing the matter to melt or become dissociated. Every piece of every atom is involved in these oscillations in some way—the smaller the piece, the higher the frequency of oscillation and the higher the energy holding the bond together. These microscopic oscillatory energies are pervasive throughout matter, do not depend on the size or extent of matter, and are, therefore, described as *intensive*. Intensive physical properties are typically *not additive*.

Microscopic oscillations have two physical properties—frequency of oscillation and amplitude of oscillation. Mass may affect the frequency of oscillation but is typically not changing and thus does not need to be included in the equation defining oscillatory energy. These atomic oscillators are frictionless, so that length of travel is not a factor affecting energy. The extent, or amplitude of oscillation is always changing but there is no net change except as a very important function of temperature described below. Thus frequency, the rate of change of the length of the bond, has the primary effect on microscopic energy. If energy powers change, then higher energy powers a higher rate of change. A higher rate of change for cyclical systems is, by definition, a higher frequency. At atomic scales, energy appears simply to be frequency times an appropriate scaling constant. Think of microscopic energy as the pulse, the heartbeat, of matter that gives rise to temperature and goes to zero at absolute zero.

Temperature is not additive: Temperature (T) is a physical property of matter that is an indicator of how much thermal energy is contained within a body of matter, whether solid, liquid, or gas. If you divide that body in half, you will have two bodies with the same temperature (T). If you then combine the two bodies again before either can lose heat, you will once again have a single body with temperature (T). Temperature is an intensive physical property of matter, meaning

that the numerical value (magnitude) of temperature (T) is independent of the size of the system.

If you have two bodies at different temperatures T_1 and T_2, and you put them together in thermal contact and let them reach thermal equilibrium without losing heat to the surroundings, the new body will *not* have a temperature that is the sum of the two temperatures $(T_1 + T_2)$; when it reaches thermal equilibrium, it will have a temperature somewhere between T_1 and T_2. If the bodies are of identical size and material, the new body will have a temperature equal to the average temperature of the two bodies $(T_1 + T_2)/2$. Temperature results from microscopic oscillations of chemical bonds permeating the whole body. This is why temperature is an intensive physical property of matter that is not additive.

Heat capacity, on the other hand, how much heat a body of matter can hold, is a function of mass and is additive. Twice the mass has twice the capacity to store heat and would typically take twice as long to warm up in the presence of the same radiation.

Thermal energy is oscillations of chemical bonds: The chemical bonds that hold atoms together to form matter are not rigid. They are observed to oscillate about an energy minimum between electrodynamic repulsive forces pushing the atoms apart and electrodynamic attractive forces pulling the atoms together (Figure 1). As the thermal energy of oscillation increases, the amplitude of oscillation increases until at some energy threshold (E_{max}) the bond comes apart. One such anharmonic atomic oscillator exists for every normal mode of oscillation of every degree of freedom of every bond in matter. Each oscillator has characteristic resonant frequencies, normal modes of oscillation, each with an amplitude of oscillation that increases with increasing temperature (thermal energy). Because the oscillator is asymmetric, the *average* length
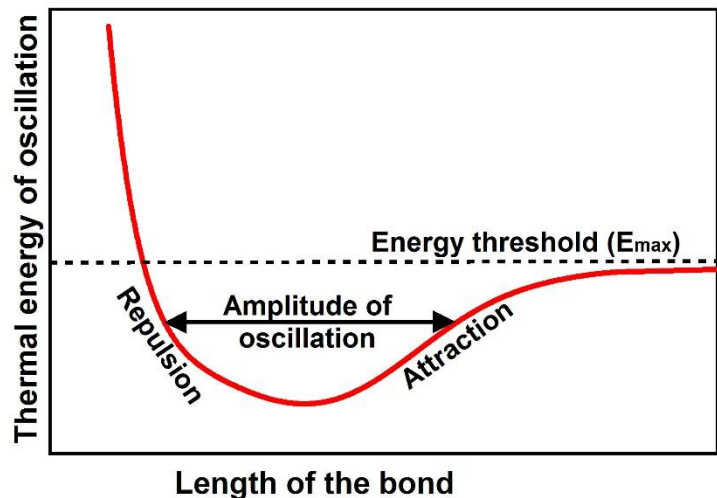

Figure 1. The chemical bonds that hold atoms together to form matter are observed to oscillate about an energy minimum between electrodynamic repulsive forces pushing the atoms apart and electrodynamic attractive forces pulling the atoms together. As the thermal energy of oscillation increases, the amplitude of oscillation increases until at some energy threshold (E_{max}) the bond comes apart.

of the bond increases with increasing thermal energy so that the volume of the matter expands with increasing temperature—something that is well observed.

An atomic oscillator of this type is asymmetric (anharmonic) because the force of repulsion increases very rapidly with decreasing distance as like charges are pressed together whereas the force of attraction decreases much more slowly with distance as opposite charges separate.

An atomic oscillator of this type is frictionless and thus can oscillate for a very long time. The only way to add energy to such an oscillator, or to subtract energy from it, is through *resonance*. When the amplitude of oscillation at a specific frequency of one bond is larger than the amplitude of oscillation at the same frequency of an adjacent bond, the bond with the larger amplitude will "give up" energy to the bond with the lower amplitude until the amplitudes for both bonds are equal. The rate of energy transfer, therefore, increases with increasing difference in amplitudes as is widely observed.

Resonant heat transfer at specific frequencies provides the basis for the way oscillations on the surface of matter radiate thermal energy into air or space, and resonance at specific frequencies is the primary way gas molecules absorb such radiant energy. Within matter, however, physical connections between molecules also allow sharing of frequencies and amplitudes through the physics of conduction.

Oscillatory systems typically have normal modes of oscillation—a fundamental frequency of oscillation and several fixed higher frequencies of oscillation often referred to, in musical systems at least, as harmonics or overtones. The overtones of a harmonic oscillator with a fundamental frequency of oscillation of 440 hertz, for example, are typically integer multiples of the fundamental (880, 1320, 1760, etc.). An anharmonic oscillator, however, has overtones that are generally not integer multiples. Physicists and chemists describe electrons in atoms, ions, and molecules as taking on certain discrete energy levels—values of energy that exist in ground state and in higher energy excited states. If energy of oscillation is directly proportional to frequency of oscillation, then these excited states may simply be higher frequency (higher energy) normal modes of oscillation.

Microscopic energy often is used to describe a threshold: Microscopic energy is often viewed as a threshold that must be crossed to initiate a chemical or physical reaction. Radiant energy, for example, will only initiate a particular reaction when it exceeds some minimum *energy level*, some minimum magnitude of energy. For example, the level of the most energetic solar radiation reaching each altitude determines the structure of Earth's atmosphere (DeMore et al., 1997; Liou, 2002). In addition, there is an *intensity* or amount at each particular level of energy that influences the rate and duration of the chemical or physical reaction (Finlayson-Pitts and Pitts, 1999). As we will see below, this energy threshold is typically the

energy required to break one or more of the chemical bonds holding matter together.

In classical mechanics, we often think of energy as simply a physical state—a body of mass is said to "possess" a certain kinetic or potential energy. Kinetic energy, for example, is defined as one-half the mass times the velocity squared ($E_k=\frac{1}{2}[mv^2]$). If we role a ball with a certain mass down an incline, the ball will "acquire" a certain kinetic energy (E_k) as potential energy (E_p) is transformed to kinetic energy. Since E_k is a function of mass (m), a larger ball with twice the mass, in the same situation, will "acquire" twice the kinetic energy of the smaller ball. There is no reaction here, however. We are not talking about energy that makes chemical change happen. A mechanical analogy to chemical change would be if we place a much heavier body of matter at the bottom of the incline and ask how much kinetic energy will it take for the ball to cause the larger body to move? We must increase the mass of the ball or its velocity, the two variables in our equation, until the kinetic energy reaches some threshold, some level of energy, at which it will begin to move the larger body. Until this level of kinetic energy is reached, the ball will simply bounce off the larger body. Understanding that energy in microscopic cases often refers to a threshold is fundamental for understanding radiant thermal energy.

The photoelectric effect is such a threshold: Classical electromagnetic theory (Maxwell, 1873) predicts that electrons should be released when light shines on metals and that the rate of electron emission should be increased by increasing either the frequency or the intensity of the light, the two relevant variables in Maxwell's equations. Hertz (1887) and Lenard (1902), however, observed that electrons are released only when the frequency of light reaches some threshold, that above this threshold, the kinetic energy of the released electrons increases with the frequency of the light, and that above this threshold, doubling the intensity or amount of light, doubles the number of electrons emitted. Below this threshold, however, no intensity of light is sufficient to cause any electron to be emitted. It has since been observed that it takes certain colors of visible light to release electrons from alkali metals, higher frequency violet to ultraviolet light to release electrons from most metals, and very high frequency, extreme ultraviolet radiation to emit electrons from non-metals. This photoelectric effect is used widely to make measurements in particle physics.

In 1900, Max Planck postulated, in order to write his law for the distribution of power in emission spectra from black body radiators (Figure 2), that energy in radiation (E) is equal to frequency (*v*, the Greek letter nu) times a constant of proportionality (h) that became known as Planck's constant: E=h*v* (Planck, 1914). Albert Einstein (1905) suggested that an electron would be emitted when it

absorbed a quantum of energy with a sufficiently high frequency(v). This quantum of energy became known as a photon (Lewis, 1926) and E=hv became known as the Planck-Einstein relation stating that the energy (E) of a photon is equal to the frequency of oscillation (v) of the photon times a constant of proportionality (h).
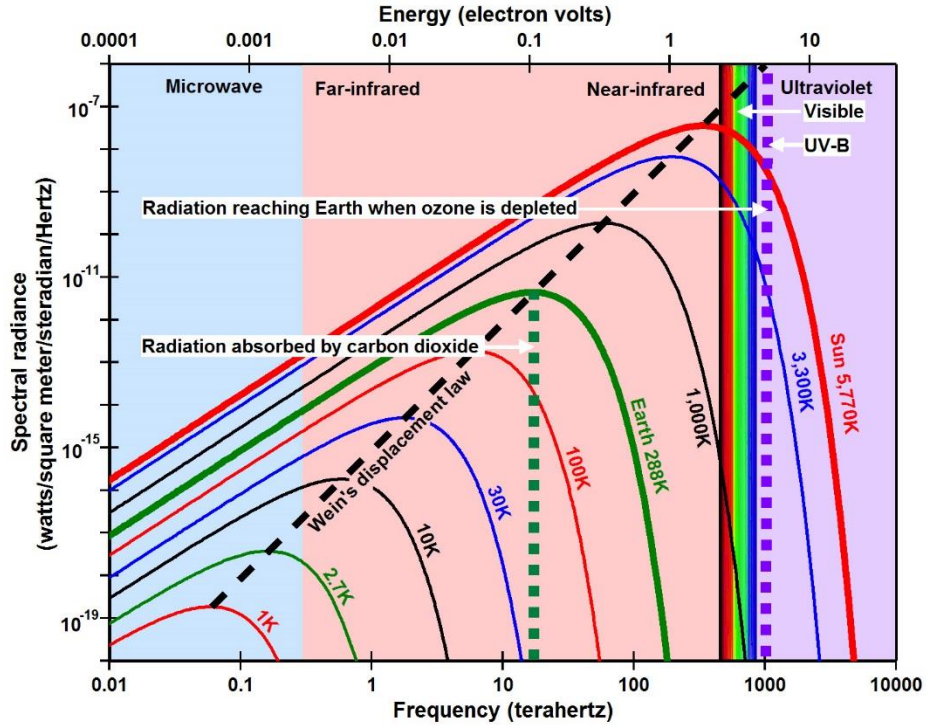

Figure 2. Planck's law shows the amplitude (intensity) of radiation at each frequency of oscillation as a function of the temperature in Kelvin of a black body at thermal equilibrium.

It has subsequently been found that certain values of E represent levels of energy needed to make particular photochemical reactions happen. Today we know that electromagnetic radiation must contain frequencies around 749 terahertz (violet to ultraviolet-A) to cause the photoelectric effect in common metals, 967 terahertz (ultraviolet-B) to dissociate ozone, and 1237 terahertz (ultraviolet-C) to dissociate oxygen.

Energy is simply equal to frequency times a constant: In E=hv, the only variable is frequency (v). Energy (E) in electromagnetic radiation is therefore not a function of intensity, amplitude of oscillation, distance traveled, or bandwidth. A distinctive feature of light in air and space is that frequency (color) does not change with distance, even galactic distance except for Doppler effects. If E= hv, then, the energy of ultraviolet-B radiation leaving Sun is equal to the energy of ultraviolet-B radiation arriving at Earth. What does change is the amplitude of the oscillation at this frequency, which decreases with the square of increasing distance.

If radiant thermal energy (E) is simply equal to the frequency of oscillation (v) times the Planck constant (h), then setting v equal to one shows that the Planck constant is the energy "contained" in one cycle per second. Many people find this truism hard to grasp intuitively. How can frequency contain energy? Because frequency is energy. Well, energy is change. Frequency is rate of change. Higher frequency means higher rate of change. Higher rate of change means higher

energy. Thermal energy, for example, is the "ceaseless jiggling motion" (Coopersmith, 2010) of the bonds holding matter together. Thermal radiation in air and space is induced by this "ceaseless jiggling motion" on the surface of matter.

Thus, radiant thermal energy is simply the microscopic frequency of oscillation in cycles per second times a constant of proportionality (h) that scales microscopic joules to macroscopic joules. In dimensional analysis, it has become customary, especially since the organization of the International System of Units in 1960, to omit the word cycle, specifying the units of h simply as joule seconds. A macroscopic joule, however, is typically thought of as the energy transferred, the work done, when a force of one newton acts on an object in the direction of its motion through a distance of one meter. Linear distance is central to the common definition of a macroscopic joule as is mass. When thinking about microscopic energy in a cyclical process, it is important to recognize that, in one cycle, the length of a bond between two atoms, for example, "travels" a linear distance from fully compressed to fully extended and then "travels" the same linear distance in the opposite direction from fully extended to fully compressed, but the net physical distance travelled is zero. The word cycle describes distance travelled that is inherent in the definition of a macroscopic joule. Omitting the word cycle omits the unit of distance required in the macroscopic definition of energy. We have lived somewhat comfortably with omission of the word cycle because most physicists assume the word cycle when they use units of reciprocal second or hertz. It would be more precise and more physical to retain the unit of cycle so that we understand more clearly why energy (E) of a cyclical process is defined simply as frequency (v) in cycles per second times the Planck constant (h) and why energy in a frictionless atomic oscillator is not a function of amplitude of oscillation.

It makes no physical sense to add frequencies of radiation together:
Electromagnetic radiation is well known to consist typically of a broad spectrum of frequencies (Figure 2) that do not interact in any way except when they are interacting with matter. It makes no physical sense to add frequencies together. You cannot add red light to blue light to get ultraviolet light. Nature does not work that way. If E=hv, then, it similarly makes no physical sense to add energies together. You cannot add the energies of red light and blue light to get the energy of ultraviolet light (Figure 3). Think how large the net energy would be if you added (integrated across) the energies for each shade of color between red and violet! Radiant thermal energy is not additive.

In matter, a seismic or water wave, for example, at a specific location can be approximated by a Fourier series, the sum of a large, if not infinite, series of terms consisting of an amplitude times the sine and/or cosine of different wavelengths or frequencies. It is the bonds or pressure holding solid or liquid matter together that

provide the physical basis for the plus signs, or "*addability*," in the Fourier series. Everything involved with mechanical waves is interconnected. Everything involved with electromagnetic radiation in air and space, on the other hand, is not connected and can be thought of as a Fourier series without plus signs—a series that is not additive. There is some red light, some blue light, some yellow light, etc., that do not interact until the full spectrum interacts with matter, as in a rainbow or prism (Figure 3) or the classic double slit experiment (Young, 1802).

Physicists today are used to thinking of radiation in terms of photons. The oscillatory energy in a photon is commonly thought of as E=hν, the Planck-Einstein relation. Yet E=hν is not additive. If one photon has energy E, 20 identical photons contain 20 times the *amount* or *intensity* of energy E, but the *level of energy* of the ensemble is still E. If you have 20 identical glasses of water, all at the same temperature (the same level of thermal energy) and you add them together into one big pot, you now have a big pot with 20 times more water than one glass, but the temperature of the water in the pot (the thermal energy of the water in the pot) is still the same as the temperature of the water was in each
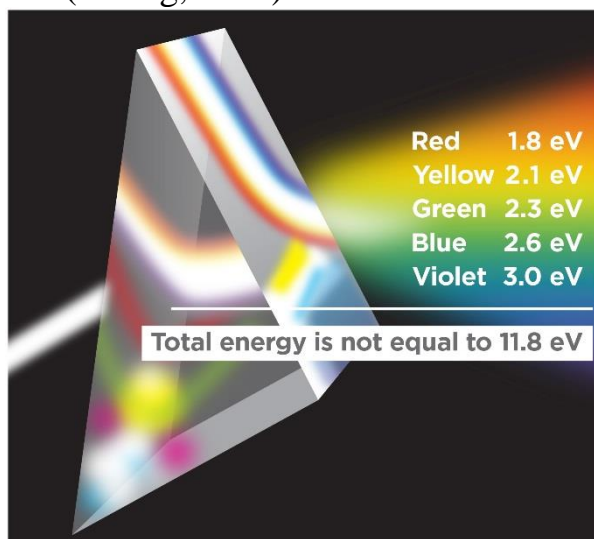

Figure 3. When white light from the left is passed through a prism, its many different visible components are shown, each with their own energy shown here in electronvolts. Energy is a function of frequency only. Each hue has a different energy. The energy of white light is not the sum of the components. Radiant energy is not additive.

glass. You just have 20 times more of that level of energy (E) and it will take 20 times longer to raise the temperature of the water in the pot with the same energy input into one glass. Most physicists today, accustomed to thinking of radiant energy as the sum of the number of photons, find this reality very difficult to accept.

E=hν says that energy is only a function of frequency and that energy is not a function of the number of photons, of bandwidth, of the amplitude of oscillation, or of the intensity of oscillation. It simply says that energy is frequency times a constant of proportionality, which means that low frequency is low energy and high frequency is high energy. The spectrum of electromagnetic radiation extends from low frequency radio signals to very high frequency nuclear radiation (Figure 4). There is no question
1. that infrared radiation is more energetic than radio signals but not energetic enough to cause photosynthesis,
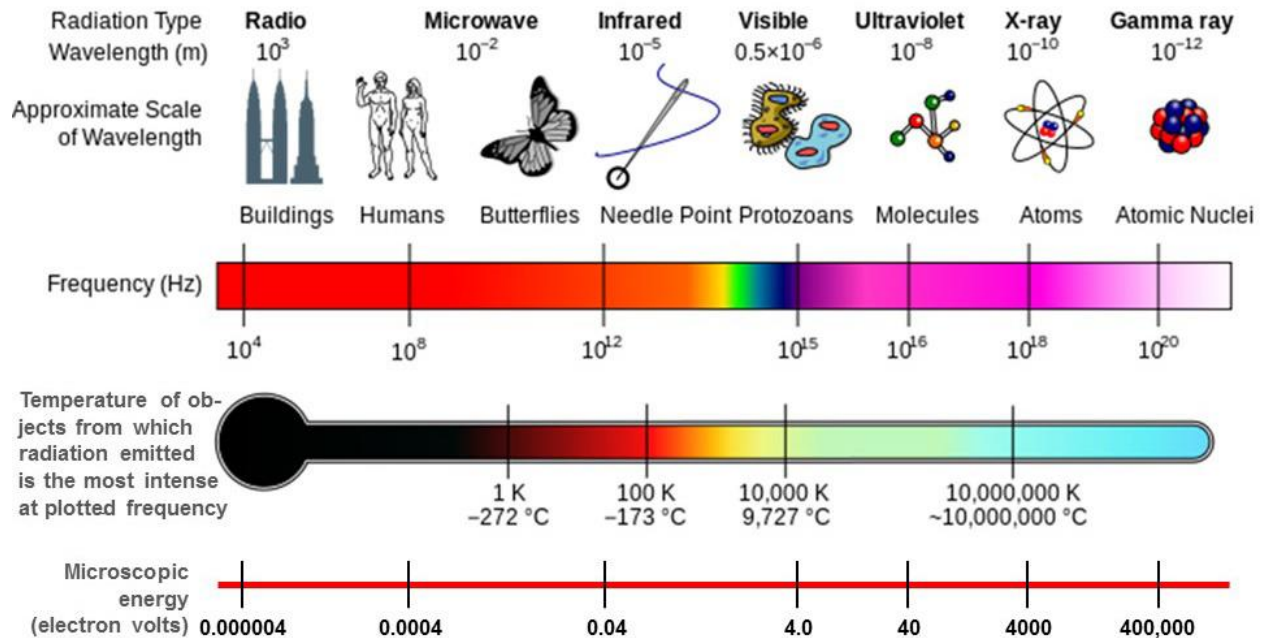2. that visible light causes photosynthesis but does not burn skin,

Figure 4. The electromagnetic spectrum extends from very low radio frequencies to very high gamma ray frequencies. Temperature is shown for objects whose radiation is most intense at the frequency plotted based on Wien's displacement law shown by the dashed black line in Figure 2. Microscopic energy shown is E=hv.

3. that ultraviolet radiation is more energetic than visible light and can burn skin,
4. that X-rays are more energetic than ultraviolet radiation, and
5. that nuclear radiation is much more energetic and can cause much more change, much more damage than any of the lower frequency types of electromagnetic radiation.

Heat is a very broad spectrum of frequencies: Heat consists of a very broad spectrum of frequencies of oscillation that is stored in the bond oscillations, as shown by the observation that the capacity of a material to store heat (the heat capacity) increases with the number of degrees of freedom of the bonds involved (Grossman, 2014).

Max Planck (1914) proposed an empirical equation in 1900, now known as Planck's law, describing, as a function of temperature, the observed spectral radiance emitted by a perfectly radiating and perfectly absorbing body of matter (a so-called black body) that has reached thermal equilibrium (Figure 2). Note that for Earth (green line), at a temperature of 288K (15°C), heat includes frequencies from less than one cycle per second to well over 10^{14} cycles per second while the amplitudes of oscillation also vary over many orders of magnitude.

The filament of an incandescent light bulb has a temperature of around 3300K, emitting a broad spectrum of radiation according to Planck's law (blue line, Figure 2) that we perceive as being very hot. A green light-emitting diode (LED), on the

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other hand, emits frequencies primarily between 545 and 577 terahertz, a narrow spectrum that takes much less power to create and that we perceive as being quite cool. What we perceive as heat is the result of oscillations over a very broad range of frequencies. The amplitude of oscillation at each frequency may vary in many ways, but once thermal equilibrium is reached through conduction, the distribution of amplitudes approaches the smooth curves calculated using Planck's law.

Planck's law must also describe the oscillations on the surface of matter, since it is those oscillations of electric charge that induce electromagnetic radiation. Thus, Planck's law tells us that heat in matter consists of a very broad spectrum of frequencies, each oscillating with a natural amplitude of oscillation specified by Planck's law. Through the process of conduction, therefore, the frequencies and amplitudes of oscillation are all redistributed within the absorbing body until, at thermal equilibrium, they can be described by a Planck curve. Each such curve specifies, for a given black body temperature, the natural amplitude of oscillation on the surface of the radiating body at each specific frequency.

The amplitude of oscillation decreases inversely with the square of distance travelled because what we think of as rays diverge in two dimensions, perpendicular to the line of sight. A laser, on the other hand, increases the natural amplitude of oscillation over a very narrow range of frequencies, moving the amplitude closer to or even greater than E_{max} (Figure 1) for some materials. A laser also nearly eliminates divergence so that its narrow, collimated beam loses little amplitude of oscillation with distance.

Planck's law is an equation that was derived empirically in an effort to explain observations made in the late 19th century, and still made today, measuring the *thermal effect* of radiation on the piece of matter in the sensor, typically a thermopile or resistor. The physical properties of radiation, however, are frequency of oscillation (color) and amplitude of oscillation (commonly thought of as brightness or intensity). Ideally the y-axis should be amplitude of oscillation and the x-axis frequency of oscillation, which is proportional to energy by $E=h\nu$. The traditional way of plotting Planck's law (Figure 2) has power (watts per square meter) on the y-axis as a function of wavelength on the x-axis, but wavelength is inversely proportional to frequency and is therefore a measure of energy. Plotting power (energy per second) as a function of energy assumes that energy is additive, which, as we have seen, it is not for microscopic energy.

Note that the Planck curves do not cross each other. To make a body of matter hotter, you must increase the amplitude of oscillation at each and every frequency, and you must increase the frequency of the maximum amplitude, described by Wien's displacement law (dashed black line in Figure 2). These are the reasons why heat flows by resonance from hot to cold and cannot flow by resonance from cold to hot. These are also the reasons why there is no flow of heat from a body at

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a given temperature to a body at the same temperature. In fact, thermal equilibrium is defined as the state where there is no net flow of heat. Thus, radiation from Earth cannot warm Earth, as is assumed by greenhouse-warming theory—radiation from Earth, even if it has not travelled any distance in air or space, contains the same amplitudes of oscillation and the same frequency for the maximum amplitude as oscillations on Earth's surface. Once radiation has travelled any distance, it contains the same energy but less amplitude of oscillation than the surface of the radiating body. Earth's heat, therefore, cannot physically flow back to Earth as widely assumed (Trenberth and Fasullo, 2012; Wild et al., 2013).

Are photons real physical things? Spectral physicists have documented experimentally, in extremely precise detail (Rothman et al., 2013), that a molecule of gas absorbs energy from an electromagnetic field along spectral lines whose frequencies are equal to the frequencies of the normal modes of oscillation of all the degrees of freedom of all the bonds that hold the molecule together. In other words, the amplitudes and frequencies of oscillation in the electromagnetic field cause resonance of the normal modes of oscillation of the absorbing molecule, transferring energy to the molecule at those resonant frequencies where the amplitudes are greater in the field or transferring energy from the molecule to the field where the amplitudes are greater in the molecule. If we think of the packet of energy transferred as being a photon, then the frequency content (energy content) of the photon is determined by the resonant frequencies of the molecule in the immediate vicinity of the molecule. The photon, therefore, could not have traveled from Sun or from any other radiating body. If it had, there would have to be different photons for each chemical species that absorbs radiation, a highly improbable circumstance.

Also, electromagnetic radiation spreads out with the square of distance. If the electromagnetic field were quantized into photons at its source, it is impossible to pack those photons closely enough as they leave a distant star to appear continuous to an observer on Earth. While the photon concept is extremely useful mathematically and is a cornerstone of quantum mechanics and of the Standard Model of particle physics, it is not clear that photons traveling from a radiating body physically exist. What is clear is that electromagnetic radiation emitted by a body of matter is a frequency field, continuous in three dimensions, which can be measured and mapped out with an appropriate sensor. Disturbances (changes) appear to travel through this field at the velocity of light, which, according to Maxwell (1865), is equal to one over the square root of the product of electric permittivity times magnetic permeability, which is proportional to the time it takes for an electric field to induce a magnetic field, and for the magnetic field to then induce an electric field again (one cycle) leading to a self-sustaining process. In

other words, the velocity of light is proportional to the smallest increment of time at which radiation can regenerate itself.

Can radiation really travel as waves? Maxwell (1873) derived a very important series of equations treating electromagnetic radiation traveling through space as waves. Waves are a physical property of matter and there is no matter in space. Physicists, therefore, postulated that there must be some luminiferous aether, some medium in space through which light waves could travel. Michelson and Morley (1887), however, demonstrated in the laboratory that such an aether does not exist. Yet because of the widespread utility of Maxwell's equations, the concept of light waves in space still exists today, expressed as wave-particle duality in quantum mechanics where you can use either wave equations or particle equations, depending on which is more convenient for the problem at hand. If light is sort of like waves and also sort of like particles, then light is not equal to either. Perhaps the most important physical property of light is that you cannot see it. You see the effects of light, but you cannot see light itself traveling through space. Doesn't it seem a bit peculiar that we try to describe something we cannot see as being like waves or particles that we can visualize quite clearly? Frequency is something we cannot see, and light, as explained in this paper, appears simply to be a broad spectrum of frequencies.

Electromagnetic radiation does exhibit wavelike properties such as reflection, refraction, interference, and birefringence when it interacts with matter, caused by the bonds that hold the matter together.

Energy itself is not quantized in nature, but the effects of energy often are: Frequency in Nature is a continuum extending over dozens of orders of magnitude from radio signals to gamma rays (Figure 4). If $E=h\nu$, then energy is also a continuum and is therefore not itself quantized, but the *effects of energy* are often quantized by the absorbing matter. When a molecule of gas absorbs energy from an electromagnetic field along spectral lines, each spectral line represents a quantum of energy. Each spectral line is slightly broadened, having some finite width containing a narrow continuum of frequencies and therefore a narrow continuum of energies. Hence we can think of a spectral line as a quantum of energy.

Einstein (1905) introduced the concept of light quanta to explain the photoelectric effect, in which, as explained above, certain frequencies of light cause electrons to be released from certain polished metal surfaces. Electrons are only emitted when the frequency (energy) of the light exceeds some threshold frequency (with an energy of E_{max}, Figure 1), typically in the blue to violet range. Similar threshold effects hold for most chemical reactions. Visible light can power

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photosynthesis, whereas infrared radiation does not have high enough frequencies, i.e. does not contain high enough energies, to do that. When a molecule of oxygen (O_2) absorbs frequencies in the vicinity of 1237 terahertz, the molecule is dissociated into two atoms of oxygen (2O). The energy of this frequency (5.11 electron volts or 8.19 x 10^{-19} joules) is sufficient to cause dissociation. Similarly threshold energies apply to electronic transitions and to ionization. To have an effect, radiant microscopic energy must contain sufficiently high frequencies (energies). Thus, the *effects of energy* on matter are quantized, while energy itself is a continuum.

Spooky action at a distance is all around us: Every molecule of everything that we can see, is oscillating primarily at some frequency (color) with some amplitude (brightness). When we look in the direction of that molecule with clear line of sight, the oscillations of that molecule cause three different types of cones in our eyes to resonate. Each type of cone is most responsive to a narrow band of frequencies often referred to as red, green, and blue bands. Our brains then turn the responses of these three types of cones into our perception of the color of that molecule. Our eyes are most responsive to the visible spectrum of frequencies because the size of cells making up the cones resonate best within these narrow ranges of frequencies (Figures 2 and 4). Ultraviolet radiation can damage the receptor cells, so our eyes have adapted by making the lens impervious to normal levels of ultraviolet light. Furthermore, most ultraviolet radiation from Sun is usually filtered out by the atmosphere. The CMOS sensor of a digital camera similarly encodes levels of red, green, and blue that a printer or computer monitor reproduces as a pixel at one specific color (frequency).

The observation that oscillations of a molecule over there cause similar oscillations of cells in the cones of our eyes over here, without anything visible connecting the molecule to the cells, is what Albert Einstein called "spooky action at a distance." In quantum mechanics, this is known as quantum entanglement, which has taken on a rich set of mathematical concepts that may obfuscate the simple possibility that radiation "propagates" by resonance. Oscillations on the surface of the antenna of a radio transmitter are received by a radio receiver, within line of sight, tuned to resonate at that precise frequency. A molecule similarly oscillates at a specific color that causes any appropriate sensor within line of sight to resonate at the same frequency. This is why a crowd of people all observe more or less the same thing when they are looking in the same direction. Thinking of each transmitting molecule as issuing a ray of light to each receiving molecule becomes geometrically complex exponentially.

Heat, on the other hand, is radiated by causing resonance over a very broad band of frequencies described by Planck's law (Figure 2). What travels through

space is oscillations with a specific amplitude at each frequency. You cannot see these oscillations until they interact with matter and anything in the line of sight, such as gas molecules, pollution, or clouds, will reduce the amplitude of oscillation at any frequency with which it resonates. We think of oscillations of charge on the surface of matter, as inducing an electric "field" that induces a perpendicular magnetic field, that induces a perpendicular electric "field," and so on in a self-sustaining way, delivering frequency and amplitude of oscillation to any matter within line of sight. Now that we recognize the primary role of resonance, we may wish to revisit the mathematics of what light is and how it "travels."

Radiant energy in climate is not additive: Computerized climate models calculate radiant thermal energy absorbed by greenhouse gases by adding up (integrating) watts per square meter across all observed spectral lines of absorption within a few narrow bands of frequency (Figure 5) for each greenhouse gas. They calculate that there is far more radiant energy in the infrared than in the ultraviolet because there are more spectral lines of absorption. Radiant thermal energy, however, is not additive and is thought to be a function only of frequency of oscillation, $E = h\nu$ (red line), which says that the energy of ultraviolet-B radiation, with a frequency of around 967 terahertz (commonly specified as a wavelength of 310 nanometers) (red circle), is 48 times greater than the energy of infrared radiation that is absorbed most strongly by carbon dioxide, which has a frequency of around 20 terahertz (a wavelength of 14,900 nanometers) (blue circle).
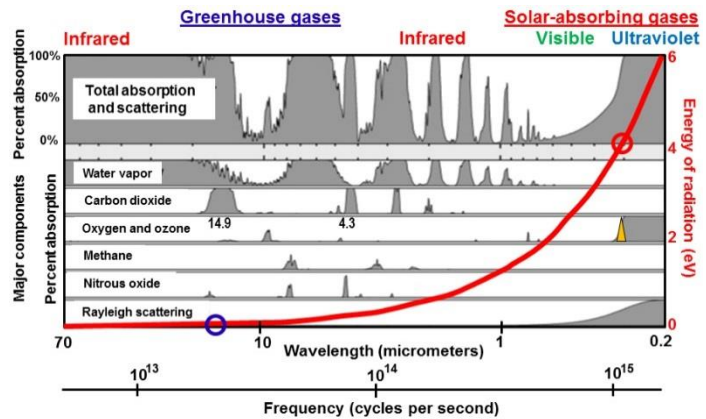

Figure 5. When ozone is depleted, a narrow sliver of solar ultraviolet-B radiation with wavelengths close to 0.31 μm (orange triangle) reaches Earth. The red circle shows that the energy of this ultraviolet radiation is around 4 electron volts(eV) on the red scale on the right, 48 times the energy absorbed most strongly by carbon dioxide (blue circle, 0.083 eV at 14.9 micrometers (μm) wavelength. Shaded grey areas show the bandwidths of absorption by different greenhouse gases. Current computer models calculate radiative forcing by adding up the areas under the broadened spectral lines that make up these bandwidths. Net radiative energy, however, is proportional to frequency only (red line), not to amplitude, bandwidth, or amount.

   Furthermore heat is a very broad spectrum of frequencies (Figure 2) while greenhouse gases only absorb very narrow spectral lines within very narrow bandwidths of frequency. Plus carbon dioxide only makes up 0.04% of the mass of the atmosphere, roughly 0.04% of the heat capacity of the atmosphere. There simply is not enough heat absorbed by greenhouse gases to have a major effect on global warming.

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Global warming has been occurring, however, and Ward (2016a) and Ward (2016b) explain, in detail, the evidence for depletion of the ozone layer, allowing more ultraviolet-B radiation than usual to reach Earth, providing a much more direct, logical, and complete explanation than greenhouse gases for each of the major changes in global warming over the past 100 years and throughout Earth history. Ozone was depleted beginning in the late 1960s caused by manufactured chlorofluorocarbon gases (CFCs). Warming since 2014, on the other hand, was caused by Bárðarbunga volcano in Iceland, the highest rate of basaltic lava production since 1783, and gases associated with basaltic lava are observed to deplete ozone.

Do we have energy right in quantum mechanics? Recognizing that radiant thermal energy is a broad band of frequencies each with an amplitude dependent on the temperature of the radiating body as specified by Planck's law and inversely proportional to the square of the distance traveled from the radiating surface, provides new insight into quantum mechanics and suggests ways to make quantum mechanics much more physically intuitive. Some of the most arcane features of quantum mechanics have come about by many of the most brilliant minds in history trying to force a round peg, thermal radiation, into a square hole, wave-particle duality.

Conclusions: Temperature is an indicator of the amount of thermal energy (heat) contained in microscopic oscillations of all the degrees of freedom of all the bonds that hold matter together. Radiant thermal energy is induced in air and space from these same oscillations on the surface of matter. Thermal energy is transferred by conduction in matter, but also by resonance in matter, by resonance from matter into electromagnetic radiation, and by resonance from radiation back into matter. Understanding that microscopic thermal energy is an intensive physical property that cannot physically be added together, helps us understand why current climate models overestimate the importance of infrared radiation in global warming and provide new ways to look at quantum mechanics. Energy is not quantized but the effects of energy often are. Quantum entanglement is a physical property of radiation and it is all around us. Resonance rules.

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