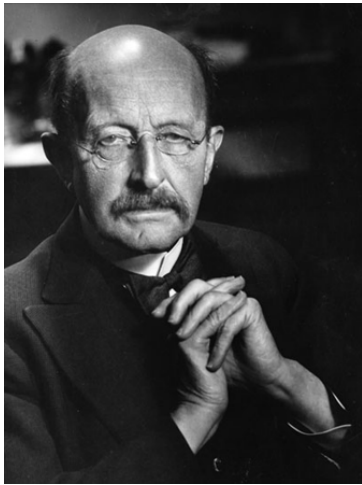


# Chapter 16

## Quantum Theory

### Now For Something Completely Different



Max Planck,

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Max Planck, 1945-1946

“When I began my physical studies (in Munich in 1874) and sought advice from my venerable teacher Philipp von Jolly...he portrayed to me physics as a highly developed, almost fully matured science...Possibly in one or another nook there would perhaps be a dust particle or a small bubble to be examined and classified, but the system as a whole stood there fairly secured, and theoretical physics approached visibly that degree of perfection which, for example, geometry has had already for centuries.” *Max Planck* ( )

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**We have seen just how unusual the ideas** of Relativity were and, how slowly they were adopted by the physics community. In some ways, the insult to common sense that was Relativity is secondary to the injury that became Quantum Mechanics. By the 1920's, like a slow-motion, one-two punch, physics realized that it had been rocked by the tag-team of those two new subjects which called into question basic facts about nature, but also the status of Reality and Knowledge. Between Relativity and Quantum Mechanics, Ontology and Epistemology—what *is* and what we can *know*—took their biggest hits since Plato.

## 16.1 Goals

The goals

## 16.2 A Little Bit of Max Planck

One would be hard-pressed to identify more people in the history of 20th century physics more respected by his or her colleagues than Max Planck. The story of the beginnings of quantum mechanics are essentially solely identified with Planck and Einstein and in this chapter we'll become familiar with their early adventures into the strangeness of quantum mechanics.

Planck was the epitome of German order and precision. He came from a family of academics in law (his father was a prestigious Professor of Constitutional Law in the University of Kiel, and then Munich) and theology (both grandfather and great-grandfather were theology professors at the University of Göttingen) so his path was paved by the expectation that he would be patriotic, honest, moral, fair, and generous... and an academic himself. He was an accomplished musician, and like Einstein, took great comfort in piano and organ... nearly taking music as a career. However, after some physics and mathematics courses at the University of Munich, he became hooked on physics. He described his reasons for choosing physics in his *Scientific Autobiography, and Other Papers* in 1949,



Figure 16.1: planckyoung

“ The outside world is something independent from man, something absolute, and the quest for the laws which apply to this absolute appeared to me as the most sublime scientific pursuit in life. ”

More irony. Quantum mechanics taught us that the outside world is anything but “independent” and “absolute.”

Planck excelled and received his PhD at the age of 21 and quickly moved through the hierarchical German academic system, eventually making it to the peak: the University of Berlin in 1888 as the Director of the Institute for Theoretical Physics—at the age of 30! He held this position until he retired in 1928. His specialty was thermodynamics and he was renowned for his clear lectures and brilliance in this, at that time, confusing field. Far from the study of just temperature and the mechanics of heat, thermodynamics had become a theory of statistical treatment of still hypothetical atoms. This wasn't Planck's personal preference—not until he abandoned the idea that the Second law of Thermodynamics was not an absolute rule

of nature, but a statistical one. And that switch was in order to solve the problem that is the subject of this chapter.

As we'll see, understanding how objects radiate heat was a theoretical conundrum at the close of the 19th century and it was in solving it that Planck secured his name in the textbooks. But he didn't quit when his formula fit the new data from the laboratories in Berlin. In addition he forced himself into a tortured few months of trying to find a physical interpretation of what his mathematics was telling him. And that was the birth of the "quantum."

Planck was 42 years old when he made his historic leap and defined modern physics. He was awarded the 1918 Nobel Prize for this work and confessed that for a long time he didn't understand his own theory, and then distrusted its conclusions.

He was the permanent Secretary of the Mathematics and Natural Science Section of the Prussian Academy of Sciences from 1912 until 1943. In 1929 the Max Planck Medal was established as the highest award of the German Physical Society, and Planck himself and Albert Einstein were the inaugural recipients.

Science was extremely important to the German government and society and as the acknowledged leader of all of German science, Planck was a respected advisor to the German government. He was also revered for his fairness by his colleagues and it was no surprise that he personally involved himself in trying to persuade Adolf Hitler away from his racial laws. He failed and when the Academy was reorganized by the Nazis, Planck resigned. He remained in Berlin during World War II, explaining

“ I've been here in Berlin at the university since 1889 ... so I'm quite an old-timer. But there really aren't any genuine old Berliners, people who were born here; in the academic world everybody moves around frequently. People go from one university to the next one, but in that sense I'm actually very sedentary. But once I arrived in Berlin, it wasn't easy to move away; for ultimately, this is the centre of all intellectual activity in the whole of Germany. ”

Remember, by the war he was 80 years old.

His life was full of personal tragedy. He lost his first wife in 1909. They had four children, twin daughters and two sons. Both of his daughters died during childbirth in 1917 and 1919. His youngest son was killed during World War I in 1916. He had one son with his second wife, but remarkably he was tortured and executed by the Gestapo as he had been a part of a plot to assassinate Hitler in 1944.

Planck's home was destroyed in an allied air raid in 1945 and he lost all of his possessions, including his notebooks of a lifetime. When the allies arrived in Berlin he was rescued as an elderly, homeless refugee.

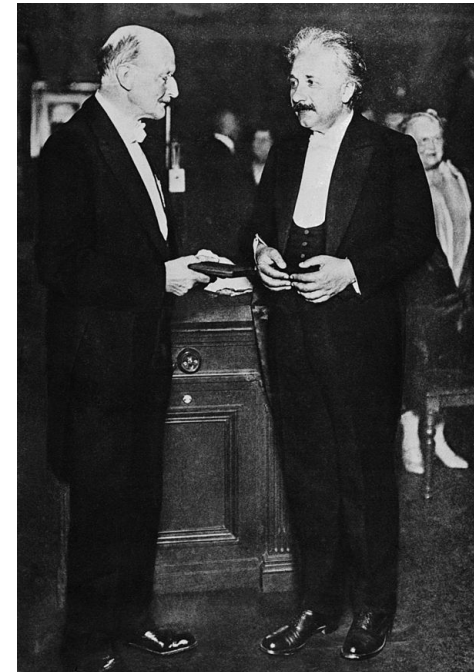


Figure 16.2: planckmedal

Remarkably he became president of the Kaiser Wilhelm Gesellschaft in 1945 and worked until the end of his life to try to re-establish German science. Remember, it was Planck alone who took the unknown patent clerk's odd scribbles seriously in 1905. Such was his innate fairness and devotion to science.

“ In the temple of science are many mansions, and various indeed are they that dwell therein and the motives that have led them thither. Many take to science out of a joyful sense of superior intellectual power; science is their own special sport to which they look for vivid experience and the satisfaction of ambition; many others are to be found in the temple who have offered the products of their brains on this altar for purely utilitarian purposes. Were an angel of the Lord to come and drive all the people belonging to these two categories out of the temple, the assemblage would be seriously depleted, but there would still be some men, of both present and past times, left inside. Our Planck is one of them, and that is why we love him.  
Albert Einstein on Planck's 60th birthday celebration. ”

### 16.3 Things Were Heating Up

Complicated ideas are sometimes reduced to catchphrases and quantum theory is no different with its famous motto of “wave-particle duality.” Like many bumper-sticker phrases, while a lot is left unsaid, a hint of the truth still shows through. The realization that light waves and light particles somehow share a common reality emerged as an unexpected and unwelcome outcome of ordinary scientific problem-solving.

Waves were well-motivated as we've seen. Thomas Young's demonstrations in the early 1800s seemed to settle the matter of the nature of light: **waves**. Maxwell's theory of electromagnetism was a story about: **waves**. By 1900, light is a: **wave**. Absolutely. No question.

**Wait.** *So, if light is a wave, then it's not a particle.*

**Glad you asked.** *Of course, you're right. Showing that light behaves like waves would seem to be simultaneously a disproof that it could also behave like particles. Nobody questioned the logic of this. Until you know who: our patent clerk.*

Few cities in the world were as self-confident as turn-of-the-20th-century Berlin. Increasingly, following Germany's 1870s political unification, world-leading progress in industry, arts, science, and militarism

were just a part of life. There was at once a vibrant intellectual environment, within a simultaneously conservative and authoritarian society. It was these latter aspects which troubled the young Einstein and the former which nonetheless pulled him to the city. Unusually connected with progressive industry, science attracted the “best and brightest” to physiology, chemistry, and physics, with successful members of one field often trained in another—Helmholtz, for example, trained as a practicing physician and physiologist and functioned as a physicist.

## 16.4 Everything Radiates. Everything.

George Carlin says that you can’t “preheat” an oven,<sup>1</sup> but this seemingly trivial observation is subtly incorrect. Carlin’s oven may not be ready for cooking, but it’s still emitting heat.

In the mid-19th century, it was realized that heat emission was just a long wavelength (infrared) version of Maxwell’s electromagnetic radiation, with a  $\lambda$  just a little longer than that of the color red. Gradually it became apparent that all objects radiate at all wavelengths, not just in the infrared region. “Warm” objects radiate a lot in that region, while “cold” objects radiate less—but not zero. Let’s roast marshmallows.

### 16.4.1 Thermal Radiation

Suppose you’re on a camping trip with an open fire pit burning large, hardwood logs very hot. After the fire has been put out, without even touching, you can tell which logs are still hot. They glow—emitting electromagnetic waves in the visible region and just to get near them is to feel a lot of heat. Nonetheless, since it’s electromagnetic radiation, Maxwell’s equations should describe it, right?

As they cool in the crisp night air, they cease to visibly glow—now it looks like a log—but it would still be warm for some time afterwards. You could detect this reduced warmth by touching it, which might still be unpleasant, but you could sense the temperature without touching—just by putting your palm close to the its surface. The log is *still* emitting electromagnetic radiation, this time at a frequency that your eyes can’t detect, but your skin can. Again... *this* should be describable by Maxwell’s equations! In essence, the log is both a visible light and an infrared “light” antenna (bright and hot) and when it cools, largely an infrared antenna (mostly just hot).<sup>2</sup>

What happened? Of course we say that the log “cooled,” but a microscopic observer in the log would say that the agitated molecules of the its atomic lattice slowed down their vibratory motions. Because these molecules involve electric charges and, as we have seen, the acceleration of charges produces electromagnetic radiation, as they vibrate they emit waves that you call predominantly heat and light. The lattice motion slows down, and the dominant frequencies of the radiation change.

<sup>1</sup> Just like you can’t “preboard” an airplane!

<sup>2</sup> You can still see the log, but that’s because once it’s cooled it’s reflecting light into your eyes, not because it’s emitting its own visible light.

But, by the next cold morning had it stopped radiating? No, the molecular motions haven't stopped, but the radiation is much different in character. The log has resumed its dark, now charcoal-like appearance and its temperature has equalized with the air. It's not ice cold...it's still radiating in the IR region, just less.

### 16.4.2 Blackbody Radiation

Suppose, once the log was hot the previous night you had gingerly picked it up and placed it in an enclosed, insulated box, with un-shiny walls. Now, just like overnight, the log continues to emit electromagnetic waves of energy...but they don't disappear into the atmosphere, they encounter the walls, which warm up and *themselves* emit back into the enclosure and the log and so on and so on. It doesn't cool, since the box is insulated from the outside. The log and walls are radiating like mad and it would be classically appealing to imagine a *linguine* mixture of electromagnetic sine waves inside the box at thousands of different wavelengths all to-ing and fro-ing such as in Fig. 16.3.

The box walls and the log will eventually reach a state in which they each emit as much radiation as they absorb. If there is no reflection, the absorption becomes total at all wavelengths and its emission is only due to the thermal motions of the wall's surface: such completely absorbing (and emitting) objects are traditionally called "blackbodies." If you cut a small hole in the box and carefully measured the wavelengths of the radiation that escaped, you'd be taking an unbiased sample of the radiation that's filled the box and "bouncing" all around.

Now suppose that instead of a log, you heat a chunk of porcelain, or a shaft of steel, or anything else *to the same temperature as your log* and you did the same procedure: put it in the box and make a measurement of the radiation leaking through the hole. You'd find *precisely the same resulting wavelengths leaking through the hole*, regardless of the material in the box or *of* the box. The only thing that matters? The temperature. Such radiation seems to be a universal phenomenon.

For centuries, makers of china, blacksmiths, sword-smiths...craftspeople with an oven and a need to bring products to certain temperatures learned that they can accurately guess at the temperature of a glowing object by looking at its color—sword<sup>3</sup>, porcelain, or whatever. Like our log and its friends in our box, the trick of relating color to temperature was found to be a universal phenomenon...*it doesn't matter what the material is*, radiation patterns will be the same for objects at the same temperatures.

When some phenomenon appears to be universal, regardless of substance and apparently dependent on only one common variable, Nature's trying to tell us something important. So in the late-1800s, ovens with holes of the sort described above were created in order to precisely measure and characterize this radiation. Why was a problem that needed to be solved. To say that Maxwell's theory was inadequate is a

#### Definition: Blackbody Radiation.

Thermal radiation from a body in equilibrium between emission and absorption.

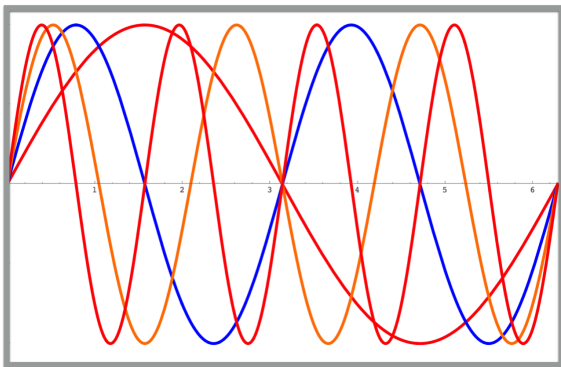


Figure 16.3: pasta2

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<sup>3</sup> The art of forging samurai swords is, by legend, 1300 years old. Among the instructions are to heat the sword "until it turns to the color of the moon about to set out on its journey across the heavens

huge understatement. It was a disaster. Everyone all failed to explain this most everyday of phenomena:  
how objects radiate warmth.

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**Box 16.1** A Word About Temperature(s)

If you watch the weather on TV, you know that we're confused about how to measure temperatures. The rest of the world is not confused, just us since we continue to use an old temperature scale named after the German and Newton contemporary, Daniel Fahrenheit. He was one of the first to use mercury as the medium that would expand and contract with temperature since it would register all the way to the boiling point of water, which alcohol thermometers could not. There's a bit of murkiness about what he did and what was redone after his death. Here's the gist:

What do you do to your sidewalks when it's icy? You put salt (well, these days a different crystal) on them since salt water freezes at a lower temperature than plain water, so your salted ice sidewalk becomes water unless it's *really* cold. How cold does that work? Well just about 0 degrees Fahrenheit and that was the low "set point" that he used to define his scale. Another was when regular water freezes, and the highest was the temperature of a healthy human body. With those three reference temperatures, he then extrapolated to the point at which water boils. The actual numbers that he assigned and those that we use today are different. We use the difference between water's freezing—32°F—and boiling—212°F—to be exactly 180 degrees. This makes the conversion to . . . yes, that other scale . . . easier. If I refer to Fahrenheit temperatures at all, I'll write something like "50°F."

The Celsius scale of temperature is named after the Swedish astronomer Anders Celsius, who lived a little after Newton who defined the set points of freezing and boiling plain water and named them 0 and 100.<sup>4</sup> If I refer to a temperature in Celsius, I'll write "−273.15°C." The scientific temperature scale takes into account that there is a temperature limit, a floor that is "absolute zero"—nothing can be colder than absolute zero: the Kelvin scale.

The temperature at which all molecular motions would stop is an unreachable, theoretical limit that's useful for use in physics, chemistry, astronomy, and engineering. It's called the Kelvin scale and it's defined to have the same single-degree unit as that in the Celsius scale, but the zero of the Kelvin scale is that useful absolute zero. That's about −273.15°C The rough numbers to remember are that room temperature is just about 300 K (that's the real way to refer to Kelvin, you don't use the word "degrees," you just say "50 Kelvin" or "50 K." 300 K corresponds to about 27°C and 80°F. For dramatically hot temperatures, I'll sometimes just refer to "5,000 degrees" because, really, the difference between Celsius and Kelvin is small at that level (but I'll really mean Kelvin!). Converting among temperatures is pretty easy, if you're used to it. We'll not do much of this and if you need to, you can always ask Mr. Google.

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<sup>4</sup> We now call this scale Celsius, but prior to 1948, it had been called "centigrade" with "100" figuring into the Latin prefix, "centum."



### 16.4.3 Radiation At Different Temperatures

There were essentially two issues that physicists thought should be understandable about radiating objects using the new electromagnetic theory: the *total amount* of energy radiated at a given temperature and the *frequency spectrum* of the radiation—how much energy is radiated at each frequency (or from  $c = \lambda f$ , the wavelength distribution).

**Wait.** *I don't think I understand what the "frequency spectrum" means.*

**Glad you asked.** *Think of it this way. You can learn the outcome of a baseball game by looking at the final score, which adds up all of the activity for the whole nine innings. That's like the total amount of energy. But there's "structure" in that total score, namely how those totals are distributed within each inning. So the individual inning results are sort of like the frequency spectrum.*

Let's think about our hot log with these two things in mind. Let's pretend that we've got two,  $1 \text{ cm}^2$  square devices—like the size of a postage stamp—that each measure the energy of radiation that falls on them, but one, "H," is only sensitive to heat and the other, "V" is only sensitive to visible light.

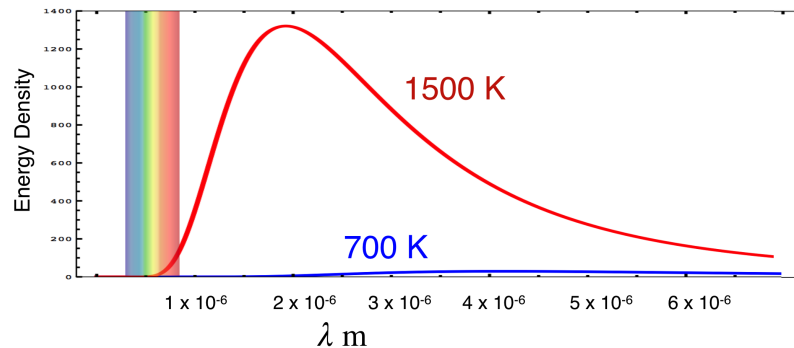


Figure 16.4: blackbody1500700

**Wait.** *Those must be very special detectors.*

**Glad you asked.** *Well, as pieces of technology, yes. But you come from the factory with those very detectors as standard equipment. Any  $1 \text{ cm}^2$  patch of your skin is blind to visible light, but very sensitive to heat radiation, while your eyes are largely blind to heat, and exquisitely tuned to be sensitive to visible light!*

Let's put V and H in each hand and stand a meter away from the hot, glowing log, which we'll assume is at a temperature of about 1500 K. Both devices are recording like mad! But how much radiant energy does V detect as compared with H?

Figure 16.4 shows the modern description of the intensity of the radiation on the vertical axis (don't worry about the actual units) and the radiation wavelength on the horizontal axis in meters (these wavelengths are closer to microns,  $\mu\text{m}$ ,  $10^{-6}\text{ m}$ ) for two radiating bodies. The red curve is the radiant intensity as a function of wavelength that would be emitted by our 1500 degree log. The overlaid vertical colored stripe shows the visible wavelength region which you can see just barely clips the total spectrum in its visible red tail.

Not much radiation contributes to our visible, glowing log-light, and what there is is going to be mostly red in color. But boy. There is a lot of the energy output in the 2 micron region—beyond the visible—but smack among the “infrared” wavelengths. This is a special value for us, since for wavelengths longer  $2\mu\text{m}$  radiation falling on human skin isn't reflected but rather begins to penetrate the epidermis stimulating nerves that signal the sensation that we detect as warmth. In this case of our log, at 1500 degrees without touching the surface, you'd detect a lot of warmth.

As the log begins to cool what happens to the radiation? Let's imagine that it has been reduced by almost a factor of two, to 700 degrees and the blue curve in Fig. 16.4 shows the intensity at that temperature. That relatively small temperature reduction results in a huge reduction in the amount of radiation.

## 16.5 Early Research

You've maybe heard that all hell broke loose in physics in the year 1900? *This* is that hell.

Just before the seminal work that caused the ruckus, scientists had learned how to predict just three things: how much total energy is radiated by a heated object, the peak wavelength radiated by a heated object, and the distribution of radiation for short wavelengths (high frequencies). These are called: Stefan's Law, Wein's Displacement Law, and Wein's Law. Wilhelm Carl Werner Otto Fritz Franz Wien (1864-1928) received the Nobel Prize for his work on radiating bodies in 1911.<sup>5</sup> These three descriptions weren't a fundamental description of what is happening, but essentially “curve-fitting” descriptions of the data. Nobody was satisfied with this.

<sup>5</sup> ...or for having the longest name in recorded scientific history

### 16.5.1 Stefan's Law

Josef Stefan inferred 1879 that the amount of energy radiated per unit area per unit time (called a "flux") was proportional to a simple, but large function of just the temperature of the radiator. Today, we call this Stefan's law:

$$u(T) = \sigma T^4.$$

This fourth power of the temperature is a lot. If the temperature doubles, then the energy output increases by a factor of 16 ( $2^4$ ). You instinctively know this already. Think about how different your skin feels if exposed to the air for an hour on a 90 degree day in August as compared with one in October at 45 degrees. The constant of proportionality, now called Stefan's Constant, has the modern value of  $\sigma = 5.670400(40) \times 10^{-8} \text{J}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ . (Notice that the units are energy per unit time per unit area per  $T^{-4}$  as you would expect.) This is a general relationship between the energy and the temperature and so  $\sigma$  is independent of the material.

The reason it's an interesting story is that after studying laboratory-based arc lamps and comparing with light from a telescope, he then *took the temperature of the sun* by measuring the energy that was captured in an area on the Earth. He found that the Sun's surface temperature must be approximately 5,430°F.<sup>6</sup> Further, in 1885 his empirical relationship was derived theoretically by his student Ludwig Boltzmann who concocted it from thermodynamic and electromagnetic theory.

So: increasing the temperature of any object ( $T^4$ ) increases the total energy that object radiates enormously! Why?

### 16.5.2 Wein's Displacement Law

The second thing that was known through experiment and some mathematical imagination by Wilhelm Wien in 1893 was at what wavelength the peak in the power curve would occur:

$$\lambda_{\text{peak}} = \frac{b}{T}$$

where  $b = 2.90 \times 10^{-3} \text{ m}\cdot\text{K}$  and is called Wein's Displacement Constant and is shown in Fig. 16.5.

You can see that the peak of the 1500 degree curve in Fig. 16.4 occurs at just about 1.8 microns which matches his prediction in Fig. 16.5. From Stefan's measurement that the Sun has a surface temperature of 5,430°C we can calculate what wavelength corresponds to the highest intensity and we'd get:<sup>7</sup>

$$\lambda_{\text{peak}} = \frac{2.90 \times 10^{-3}}{5703} = 0.509 \mu\text{m}$$

<sup>6</sup> A more modern value is closer to 5780 C.

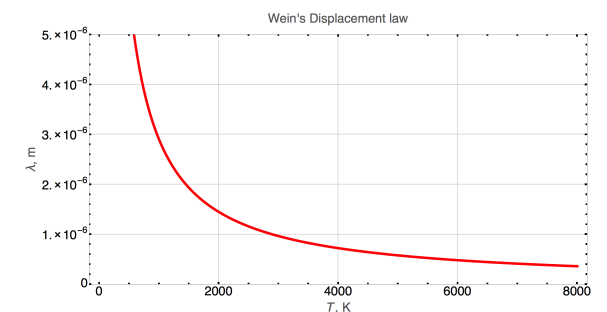


Figure 16.5: weinsDisplacement

<sup>7</sup> 5,430C is about 5703 K.

<sup>8</sup> The great John William Strutt (the future Lord Rayleigh) had a problem when he was a student—he was brilliant and at the top of his class at Cambridge. But, his problems are not like our problems: as a future Baron Rayleigh, a scientific career was considered a significantly lower-class occupation and was not popular with his family. Nonetheless, he pursued his calling and, as a wealthy man, didn't need an academic career and could devote himself to independent experimental and mathematical research, which he did at his family estate. See, not our kind of problems. He was the first to explain, among many other things, why the sky is blue and he shared the 1904 Nobel Prize for his discovery of the element argon.

<sup>9</sup> Ludwig Boltzmann was a theoretical physicist who also worked during the late 19th century on problems of thermodynamics. He was a strong believer in an atomic picture of matter and was belittled severely for these views. Nonetheless, he developed statistical theories of how atoms would behave in a gas and derived thermodynamic parameters from this model. The toll of abuse that he suffered was too much for him and he committed suicide while on vacation with his family. Tragically, his death was less than a year after Einstein essentially demonstrated the validity of the atomic hypothesis. Had he held on just a little longer, he would have learned of the obscure patent clerk and his model would have been vindicated. A part of his model was a constant called now Boltzmann's Constant that relates energy and temperature in the relation  $E = k_B T$ . The value is  $k_B = 1.3806488 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$ .

<sup>10</sup> The story of quantum theory is often told as if the eventual solution was pursued as a reaction to the failure of the Raleigh-Jeans formula. In fact, their work was published *after* Max Planck had solved the problem. Yet, nobody doubted that some missing ingredient to the Rayleigh-Jeans model was all that was necessary in order to rid it of its embarrassment and nobody accepted the bizarre, real solution, including its father.

which is right in the middle of our visible sensitivity. It's green-yellow-orange-ish. (The atmosphere changes some of this before we see it.)

Here again, we have an interesting hint and some cute predictions. But they didn't have a model of what's going on.

### 16.5.3 Wein's Law

Yup. Another Wein's Law, this one is the "distribution" law. This is a little more complicated and is strictly curve-fitting:

$$u(\lambda, T) = \frac{1}{\lambda^5} a e^{-b(\lambda T)}.$$

The constants were gathered by comparing the mathematical shape with experimental results and the consequent curve does a pretty good job of matching the observation. But only at the highest frequencies, or shortest wavelengths... in the ultraviolet region. For heat radiation, the infrared, it was not correct.

### 16.5.4 What Would Maxwell Say?

In 1900 Lord Raleigh<sup>8</sup> attacked the blackbody radiation problem in a program of research which lasted until after 1905. With James Jeans, they applied the most sophisticated application of classical electromagnetism, mechanics, and thermodynamics ever attempted. They used a model in which atoms vibrated in a radiator's walls and so, radiated setting up electromagnetic standing waves of many frequencies. By using the accepted ideas of how energy is distributed among components of a system that the energy density distribution of these waves came out to be:

$$u_R(f, T) = \frac{8\pi f^2}{c^3} k_B T$$

where  $k_B$  is called Boltzmann's Constant<sup>9</sup> and  $f$  refers to the frequency of the radiation. This formula fit the data in the low frequency (large wavelength) region—where Wein's formula failed. But, it is obviously nonsense! The energy increases according to the square of the frequency—without bound! There is no upper limit and the energy could approach infinite quantities which was an unwelcome embarrassment. Within the rules of Maxwell's electromagnetism and the energetics of thermodynamics and mechanics, this calculation is unassailable. It has to be right, or the rules are wrong. The Rayleigh-Jeans Formula became the poster child for the failure of classical physics.<sup>10</sup>

## 16.6 The Blackbody Spectrum

Let's skip ahead a little and see what the actual energy distribution from radiating substances looks like.

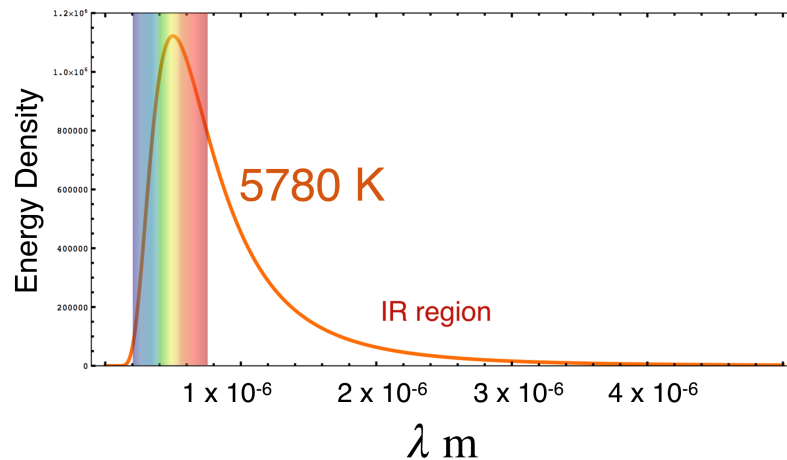


Figure 16.6: blackbodySun

Figure 16.6 is particularly instructive for a number of reasons. It shows the energy density (an energy per unit volume within the blackbody cavity) at different wavelengths for a blackbody at 5780 K, the Sun's temperature. What this means is the following: Look at the curve which peaks at a wavelength just under  $\lambda \cong 0.5 \times 10^{-6}$  m. (This is a half of a micron,  $\mu\text{m}$ , or it's also 500 nm, or  $5000\text{\AA}$ . As you can see, this is in the visible wavelength band and the blend of almost all of the colors looks almost white to us.) Follow the orange curve to the right, to that 2 micron point which is where we feel the pleasant warmth of our Sun. Stefan's law tells us that if the Sun were just a little hotter, human life would probably not have developed since it would have been too hot on Earth. That we have evolved a vision sensitivity in the wavelength range dominated by the Sun's emission spectrum seems pretty natural.<sup>11</sup>

<sup>11</sup> Further, some animals such as snakes and bats have sensitivities further to the infrared than we, indicating an evolutionary preference for detection of heat (the infrared region), while others, like penguins, can sense into the ultraviolet region.

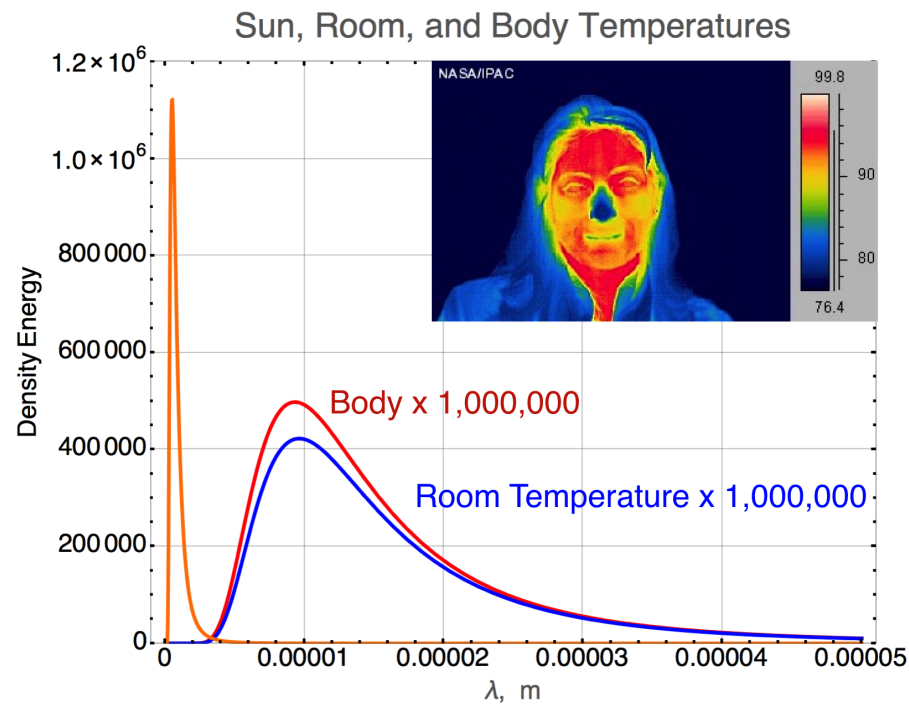


Figure 16.7: bodysunroom

You know, you're the little heat-oven. From Stefan's Law, Eq. 16.5.1, your heat output is quite high because of that fourth power of temperature. If your body area is about a meter squared and your body temperature is about 310 K, then your radiation is about 500 Watts. That's a lot of heat! But you're not in isolation, you absorb a lot of heat, so you don't generate all of your output from Big Macs alone (which would require about 10 a day). No, your equilibrium temperature negotiation with your environment given that you absorb, emit, and wear clothes is about 50-100 Watts. That's right. You're effectively a reading-lamp-worth of heat.

There is another temperature scale of interest to us, namely “body temperature,” where we are most comfortable which is about 310 K (about 98.6°F). Figure 16.7 shows the same solar spectrum along with that of a blackbody at around human body temperature...multiplied by a factor of 1,000,000 (!) in order to show its wavelength distribution on the same scale. Notice that it peaks at about  $\lambda \cong 10\mu\text{m}$ , which is just about at the wavelength at which humans radiate most strongly.

Figure 16.7 shows radiation from a body temperature of 310 K compared with that of room temperature, which is customarily chosen to be around 300 K (remember, about 80°F). No wonder a roomful of students can warm up a classroom, each of you radiating like a 50 Watt light bulb.

## 16.7 The Quantum Is Born

It's not unusual to find that physicists, theoretical and experimental, often continue to work on problems that fit their own specialties. Like most people, they are comfortable in some areas, and less so in others. Max Planck—at the top of his career just before 1900—was an expert in thermodynamics and less enam-

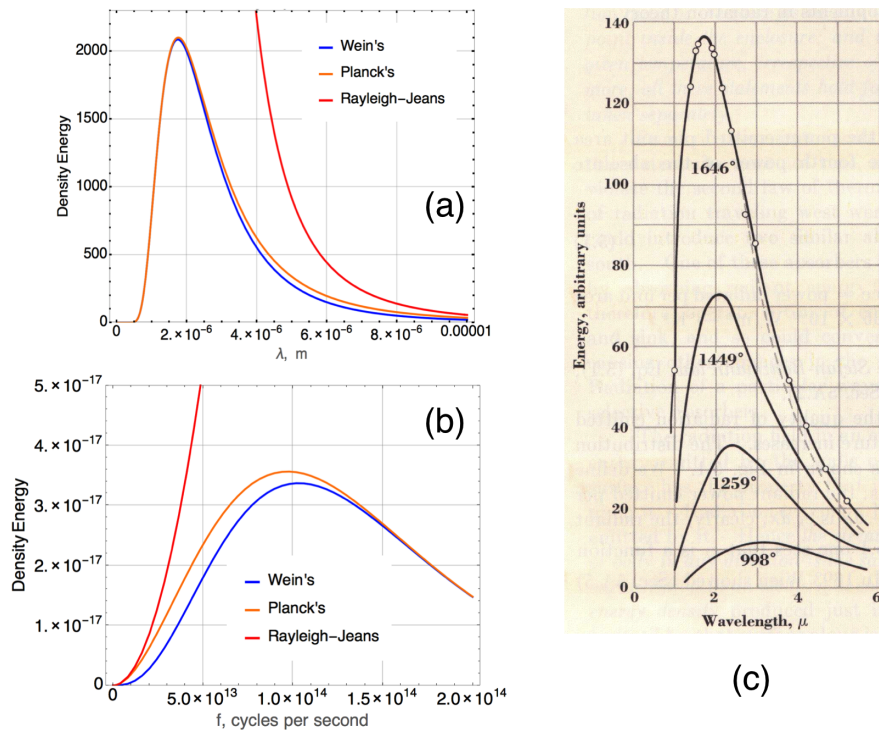


Figure 16.8: everything

ored of the use of statistical methods in physics championed by Boltzmann. As a result, he came to the problem of blackbody radiation with different tastes and approaches than those employed by Raleigh and others. In December of 1900 after a series of fits and starts, he managed to account for the full curve that fit the intensity of radiation as a function of wavelength. He announced it in a meeting in his home institution in Berlin and then one of his experimental colleagues spent the whole night comparing it with the most recent infrared data that were fresh from experiments in the basement: it was bang-on. The curves that I've shown in the previous sections are from Planck's formula and Fig. 16.8 (c) are data and Planck's prediction from that 1900 meeting showing perfect agreement.

So, great. A curve that fit the data. At first, this success was, in a way, mechanical: he introduced an oscillator model like Rayleigh and added some mathematical steps (following Boltzmann) which were very difficult to interpret, but which seemed necessary. He was a fine physicist and was devoted to going

<sup>12</sup> The problem arose in the IR region, and it's easy to see why. Wein's model was based on measurements, so new data wouldn't have been in his fitting. Second, the IR measurements came later since it was very hard to make precise measurements of objects that were by their very nature near room temperatures. It's why IR telescopes are hard to build and operate... if you're trying to detect minute amounts of radiation at nearly the same temperatures as your surroundings, then it's very hard to distinguish the new radiation from the inherent warmth of your detector!

beyond just producing a formula that fit data—he needed an actual physical interpretation to go along with it and was determined to find one.

So now we have three different models to describe thermal electromagnetic radiation: Raleigh-Jeans' model, based on Maxwell, Wein's empirical curve, and Planck's model. Wein's fit well, but as the experiments got better, it began to not work.<sup>12</sup>

Figure 16.8 shows exactly this situation. The Planck formula works perfectly! Let's look more closely. Figure 16.8 (a) on the upper left compares all of the predictions for 1646 K, which correspond to the top data represented as the circles in Fig. 16.8 (c) on the right. I've also shown side by side the predictions as a function of frequency, Fig. 16.8 (b). What do we see:

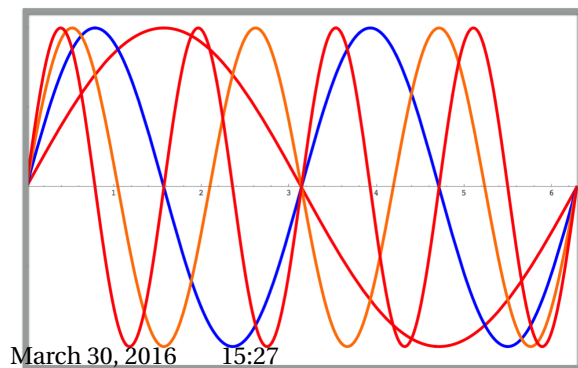
- The Raleigh-Jeans formula fits the Planck model at the longest wavelengths, or the lowest frequencies and fails at short wavelengths and high frequencies.
- The Wein formula fits the Planck model in the opposite regimes: good, for short wavelengths and high frequencies, and bad for the opposite.

How to explain this? Maxwell's theory is surely not wrong! Is it?

### 16.7.1 Max Planck's Interpretation

So Max Planck had a problem. He'd found a way to solve this thorny, old puzzle but at the price of a strange assumption that he had to make in order to make it work. It's important to realize that he had much going for him: his model fit the data over **all** of the wavelengths that were measurable; it reduced to the classically-acceptable Raleigh-Jeans formula at small frequencies, and the Stefan-Boltzmann result fell out when all of the intensity was added up at each wavelength. Further, he could predict Avogadro's Number, Boltzmann's Constant, and the electric charge. The exchange for all of this success was the introduction of a bizarre idea and the tiniest fundamental constant into physics yet devised.

First, why did the Raleigh-Jeans model break down? Inherent in this "classical" description of how radiation would fit into a finite sized box was that all frequencies are allowable with equal probability. Figure 16.9 is a sketch of what I mean. The rules of Maxwell's theory say that the ends of an E&M wave must be nodes at the walls. So the red curve is the longest wavelength wave that could fit in the box, and from there we could imagine adding more and more waves with shorter and shorter wavelengths—and so higher and higher frequencies!—without end. In the figure we add the yellow curve and then the blue curve and then more and more, each one at a higher frequency than the one before. That's the "linguine" that I referred to above. So since there's no limit to the shortness of wavelength, or more easily seen now,



March 30, 2016 15:27

Figure 16.9: pasta2



no limit to the highest frequency that can fit, the energy in the box would rise to infinity! That's what the red curve in Fig. 16.8 is doing. Planck's idea tamed that high-frequency behavior, which was dubbed the "ultraviolet catastrophe" by the more dramatic of physicists.<sup>13</sup>

His model was that the walls of the blackbody-box indeed contained little oscillating charges—just like Raleigh and Jeans had done—but that they were restricted in the wavelengths at which they could oscillate. He had no physical reason as to why they would be restricted, it was a hypothesis and he built it into his model.

This is sort of hard to visualize, so think about this. Sound is a wave phenomenon and our ears are capable of picking out any frequency, pleasing or not. Frequency analyzers are equally capable of detecting any frequency—sound is not restricted to particular tones. But pianos are. When you strike a key on a piano you produce only particular notes, or frequencies but that in no way says anything about what frequencies sound is capable of, just what pianos are able to make. The walls of a blackbody box are like the piano. Planck postulated that the walls could produce only particular frequencies, but that light and all E&M waves could be any frequency. Just not in a blackbody box.

He called these (piano-like) special radiation bits "bundles" which were later dubbed, "quanta"<sup>14</sup> by Philip Lenard.<sup>15</sup> And he found that he needed to insist that energies of his radiation bundles were directly proportional to their frequency.

This is the beginning of Quantum Theory, which will evolve in the 1920s into a more sophisticated "Quantum Mechanics." The hallmark idea of Quantum Theory is that light—and all electromagnetic radiation is "quantized" into these bundles. Radiation is not continuous. One of the simplest,<sup>16</sup> but most profound equations in the history of physics is this statement ("Planck's law"):

$$E = hf. \quad (16.1)$$

The constant of proportionality is now called Planck's Constant, and he estimated its value in his model. It's tiny and the modern value is:  $6.6260755(40) \times 10^{-34} \text{J} \cdot \text{s}$ . Planck's Constant serves as a measure of when quantum weirdness begins to matter and when we can continue to use Maxwell's equations. That's it's so it'sy-bitsy explains why we don't see quantum behavior every day. The energies in our lives are much larger. It's the same idea as to why we don't see relativistic effects in our everyday life where speeds are much less than those of light.

So Equation 16.1 says three important things.

- First, it declares that if you give me a frequency, I'll tell you the energy precisely. For example an IR frequency of 1 micron corresponds to  $1.98782207 \times 10^{-19}$  Joules. Not  $1.98782206 \times 10^{-19}$  or  $1.98782208 \times 10^{-19}$  or anything else.

<sup>13</sup> Why "ultraviolet"? The UV spectrum is that on the other side of the visible, the shorter wavelengths than blue or violet... a sort of short-hand for generically, "short wavelengths" or "high frequency."

<sup>14</sup> Here is the origin of the word "quanta" or "quantum." It is Latin in origin for "*quantus*," meaning "how much."

<sup>15</sup> Lenard became a Nazi and doggedly tried to prosecute Einstein for his "Jewish Physics."

<sup>16</sup> Did I say that some of the most profound solutions would come in very simple mathematical equations? Did I?

- Likewise, if you want radiation of  $1.98782207 \times 10^{-25}$  Joules, then you must be content with radiation that has a wavelength of 1 meter. Not half a meter or 1.2 m, but 1 meter.
- Finally, zero energy corresponds to a frequency of  $f = 0$  identically. We'll see later that this is not possible.

Further, one can build up different amounts of energy in only two ways: change the frequency,  $f$ , or have more bundles. In fact, the more general way to write Planck's law is

$$E = nhf \quad (16.2)$$

where  $n$  is an integer, ranging from 0 to any finite value. For any finite frequency, the radiated energy is finite and equal to  $hf$ ,  $2hf$ ,  $3hf$ , ...and so on.

This is strange. If we extrapolate the quantum idea to life, it makes playgrounds strange.

The idea is as if the frequency of a child's swing is only adjustable in discrete amounts. Picture it going back and forth, each time it returns I give it a little push to restore the amplitude lost to friction. Now to make the ride more exciting, I push the swing just a little harder. But nothing changes. A little harder still, nope. Again and again, more and more and then... then all of the sudden the swing suddenly goes further. And it stays there. More pushing, no change... and so on. The pushes are discrete until the right "quantum" of push is applied corresponding to the energy going from  $nhf$  to  $(n+1)hf$ . This weird  $hf$  is a tiny, tiny energy and could indeed be mistaken for zero in anything but an atomic environment. So we'd not see quantum effects in our swing-pushing, since they'd be tiny.

This is why the Raleigh-Jeans formula matches the Planck formula at the smallest frequencies. That's where the energies in the presumed blackbody wall-oscillators are the tiniest so the differences between classical and quantum behavior is too small to detect. Why? Because Planck's constant is so small.

Planck fought against his own interpretation.<sup>17</sup> In that fight he was in good company, since nobody liked his idea. Nobody, except Einstein. It's important to realize in hindsight that Planck's approach is a little contrived. Without a physical basis, he tied the hands of the blackbody wall oscillators and chose not to mess with the Maxwell interpretation of E&M radiation.

This is not the mark of someone behaving unscientifically...it's the mark of someone facing nearly insurmountable conceptual difficulties while inventing a new subject. His scientific stature surely even raised the stakes for him personally, as when one is as distinguished as he was, a mistake could carry a significant embarrassment. But, in spite of that risk, Planck followed the physics as far as he could, publicly, and forthrightly.

<sup>17</sup> Although he suspected that he had stumbled onto something significant and on a stroll with one of his young sons indicated that he had had "a conception today as revolutionary and as great as the kind of thought that Newton had."

### 16.7.2 How Does It Turn Over?

I've not touched yet why Planck's curve in Fig. 16.8 turns over at the higher frequencies, where the Maxwell-description blows up. This too comes from Equation 16.2.

The requirement of Maxwell's theory that all frequencies of radiation are equally likely suggests that for a given energy, we could populate it with all frequencies. Figure 16.10(a) is a cartoon of that idea. Every frequency works to create energy  $E$ .

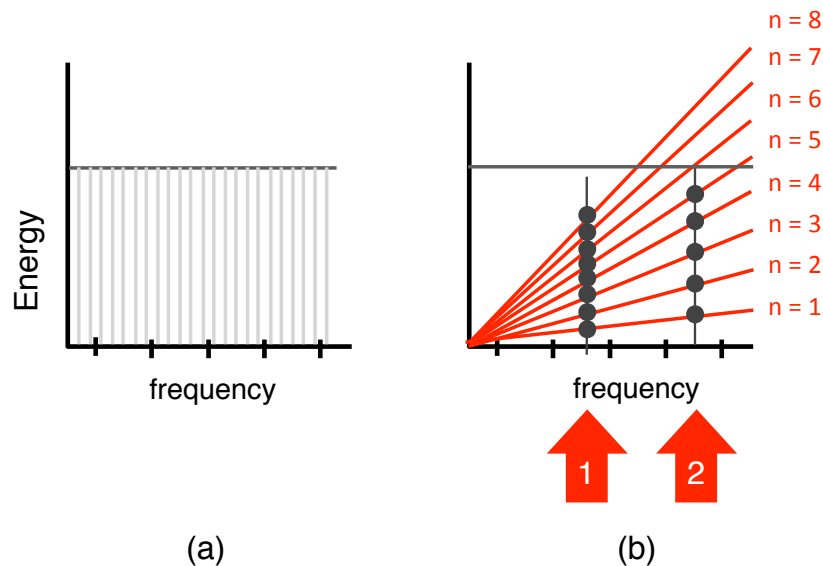


Figure 16.10: planckexplain

Notice that Planck's law is just the equation of a straight line, passing through the origin. This straight line would have a tiny slope, Planck's constant, but it's straight nonetheless. In Fig. 16.10(b) are plotted many such straight lines from Planck's law, each corresponding to a different value of  $n$ . At the smaller frequencies, like the one labeled 1, many different values of  $n$  contribute. But at a higher frequency, like the one labeled 2 notice that many fewer values of  $n$  are necessary in order to get to energy,  $E$ . It takes

fewer quanta of higher energy than at lower energy, so the curve in Fig. 16.8 turns over and falls at the lower wavelengths and higher frequencies since fewer values of  $n$  are involved.

## 16.8 The Quantum Grows Up

We've already met Einstein's singularly unusual way of looking at the world through relativity. In that same year that he was not working very hard at the Patent Office, he was literally changing the world in one time-gulp: remember, in 1905, now called his "miracle year," he published his relativity theory, proved the existence of atoms by explaining Brownian Motion, and correctly reinterpreted Planck's formula as a description of light. Einstein was the first Quantum Mechanic.

### 16.8.1 Photoelectricity, Revisited

Remember that one of the results of Hertz's experiments was the inadvertent discovery that illuminating some metals with ultraviolet (UV) light prompted a current to flow from its surface. This current could be accelerated in an electric field and was found to be negatively charged and so likely to be made up of J. J. Thomson's electrons. But, the characteristics of this "photocurrent" were inconsistent with what one would expect employing a Maxwellian electromagnetism description of the illuminating UV light. For example, the electric field,  $E$ , of the UV light should apply a force to the electrons (remember,  $F = eE$ ) and shake them out of their orbits. The *stronger* the field—the more intense the light—the higher the force and the *faster* the electrons should be ejected. But that's not what happened. Instead:

- If one changed the intensity of the illuminating light, the kinetic energies of the emitted electrons *did not change*
- If one changed the intensity of the illuminating light, the *current did increase*, as if there were more electrons.
- If one increased the frequency,  $f$ , of the light, *the kinetic energies increased*.
- If one switched the light source on and off, the photocurrent *started/stopped immediately*.

All four of these results were counter to what would be expected if UV light acted as waves.

While the early observations were qualitative, by the early 1900s physicists were beginning to make very precise measurements of the characteristics of photoelectricity and the precision continued as surface preparation and vacuums improved. By the late 1800s it was clear that the following was the sequence of events in establishing a photocurrent: one shines UV light on a highly polished surface of (predominantly, an alkaline) metal in a good vacuum. Beginning with a very low frequency, nothing is observed until at

some particular frequency,  $f_0$ , a small photocurrent begins to flow from the surface. As the *frequency* is increased beyond that minimum, the kinetic energies of the ejected electrons grows:  $E(\text{photoelectrons}) \sim$  some function(frequency).

Not only did the observations appear to contradict a wave-like behavior for UV light, it also ran counter to the notions of what held electrons in the metal. It was believed that either the electrons were freely moving inside or that they were bound in oscillators. In either case, the application of a wave of light energy should cause them to absorb that energy and eventually break free, either of the surface or of the oscillator. Calculations suggested that the delays that would be expected would be of the order of seconds or even a minute or so. And yet, the near-instantaneous release of photoelectrons was measured to be on the order of nanoseconds.

So, the problems with photoelectricity caused problems for both Maxwell and Lorentz' electromagnetism as well as the most promising notions of the electronic structure of matter. It should be noted that there was another way to get electrons to be ejected from metallic surfaces...by heating them. This "thermionic" emission mechanism had a similar tendency for the electrons to not be emitted until a minimum amount of energy in the form of heat was applied. This minimum energy is called the *work function* and was the same for similar materials as the low-frequency threshold for photoemission. This led to the conclusion that the photoelectrons and thermionic electrons originate from the same material structure. All of this was going on while Planck was solving thermal radiation. Hmm.

## 16.8.2 Einstein's Take on the Quantum

It was into this fray that Einstein leaped with his first crucial paper of June 9, 1905, "*On a Heuristic Point of View Concerning the Generation and Transformation of Light.*" (His first relativity paper was second that year, the Brownian motion paper, third.) Remember, he had been a "closet" devotee of Maxwell's theory because of its success in explaining the *propagation* of free electromagnetic waves in optical and other frequencies, Einstein was unstinting in his praise. It works. By itself.

But when light *interacted with matter* strange things happen: namely, blackbody radiation and the photoelectric effect. Einstein picked on the weak spot in Planck's argument that had somehow linked together quantized radiators with continuous radiation and drilled right into it proposing that not only would the radiators oscillate according to quantized frequencies, *but that that the quantization would remain...*that light is a kind of lumpy, resultant wavefront—not the more familiar continuous wave.

That is, Einstein insisted that electromagnetic radiation is not continuous, but is itself also quantized—particles. The particles of radiation eventually got the name, **photons**, although not from Einstein and not immediately—it was the 1926 invention of the American chemist, G. N. Lewis.

**Wait.** *How can a wave be a particle?*

**Glad you asked.** *This quantum picture of light doesn't spring easily to mind! Previously "obvious" wave-like observations would have been done with bright light, which in Einstein's picture, is light containing an enormous number of photons. We'll understand how this happens in a bit once Quantum Mechanics is invented. Even though a thoroughly confirmed description of nature, it's still conceptually problematic for all of us. It's one of the best examples of having to trust what the mathematics tells us, even when inconceivable by humans.*

Einstein argued, the wavelike properties are more apparent as a kind of cooperative relationship among the photons. Bright (meaning, Intense) light hides the granularity. But, when one is dealing with the emission of single or few oscillators, then the lumpiness becomes apparent. For the moment, let's follow Einstein's argument about photoelectricity.

### 16.8.3 Photoelectricity Explained

If we take  $f$  to be the frequency of the light, Einstein was proposing that the energy of the particles of light was identical to Planck's formula for the his wall-oscillators. The energy of a single quantum of light—a photon—comes from Planck's law:

$$E = hf.$$

The energy of an intense beam of light of frequency  $f$  would come from the collection of individual photons

$$E = nhf.$$

And the intensity of a beam light is in turn a measure of the number,  $n$  of individual photons in that beam.

|                   |                    |
|-------------------|--------------------|
| Classical Picture | Einstein's Picture |
|-------------------|--------------------|

|   |                                  |
|---|----------------------------------|
| Intensity of light $\propto  \mathbf{E}^2 $ | Intensity of light $\propto nhf$ |
|---|----------------------------------|

He explained photoelectricity by also blending the pictures of waves and particles. The UV light that falls on a photoelectric surface? Those hit the electrons in the metal and behave as if they are *particles*. Plus there is a direct correspondence between the classical, Maxwell nature of light and the quantum nature: intensity and photon number.

The interaction kinematics is precisely “fixed target scattering” that we considered in Chapter ?? with one difference. In order to knock an electron free, the photon needs a minimum energy since the metal binds the electron. If a photon does not have enough energy to liberate an electron from its atom, it can't. But according to Planck, the energy is proportional to the frequency. So if some light isn't sufficient, just raise the frequency. Then, energy conservation would demand that

$$\text{energy of photon} = \text{energy required in order to free an electron} + \text{KE}_{\text{left}} \quad (16.3)$$

$$E = hf = \phi + \frac{1}{2} m_e (v_{\text{left}})^2 \quad (16.4)$$

where  $\phi$  is the so-called “work function” of the material, the amount of binding.  $\text{KE}_{\text{left}}$  is the kinetic energy that the ejected electron has after it's been freed. When turned around to be the maximum kinetic energy of an ejected photoelectron that could be ejected,

$$\text{KE}_{\text{left}} = hf - \phi.$$

This linear dependence on frequency in Eq. 16.8.3 was Einstein's prediction.

It was not until about 1914 that the linear relationship predicted by Eq. 16.8.3 gained ground and, in a series of famously precise and careful experiments in 1916, it was (reluctantly) determined to be correct. I say reluctantly, as it was Robert Millikan at the University of Chicago who performed them, first calling Einstein's idea “bold, and not to say, reckless” and then later lamenting in his publication, “Einstein's photoelectric equation... cannot in my judgment be looked upon at present as resting upon any sort of a satisfactory theoretical foundation...”

He learned to console himself with his Nobel Prize for measuring the charge of the electron.

### 16.8.4 The Compton Effect

Nobody would ever accuse Einstein to be a *reluctant* revolutionary, as certainly Max Planck was. Rather, he was well aware of the revolutionary aspects of all of his 1905 work, and especially the quantum idea. In 1916 he kicked it up a notch to conclude that the light quantum would not only kick out electrons, but if it hit a molecule, then that molecule would recoil mechanically and that the photon that recoiled would itself have less energy, like pool balls, and so its frequency would be reduced.

So we can just use plain-old energy and momentum conservation for the scattering process, just like we had in Chapter ??:

$$A + B \rightarrow A + B$$

$$\text{X-rays} + \text{atom} \rightarrow \text{scattered X-rays} + \text{recoiling atom} \quad (16.5)$$

Energy conservation would be the simple:

$$E_0(\text{photon}) + E_0(\text{atom}) = E(\text{photon}) + E(\text{atom})$$

Here's what we would know:

- the photon's initial energy and frequency:  $E_0(\text{photon}) = hf_0$
- the atom's initial rest energy:  $E_0(\text{atom}) = m_0(\text{atom})c^2$
- the photon's final energy and frequency:  $E(\text{photon}) = hf$

If one could reliably prepare x-rays of a known frequency and measure frequencies of an x-ray beam, the particle hypothesis for photons could be tested. The  $E$  energy could be determined by measuring the frequency of the scattered x-ray beam.

This process is the first time that special relativity and quantum theory were combined together! That's because in order to calculate the momentum of the incoming photons, Einstein had to take his relativistic energy equation to places...that it had never gone before.

Remember the relativistic formula for the total energy of an object having momentum,  $p$

$$E = \sqrt{p^2 c^2 + m_0^2 c^4}.$$

Although unimaginable in 1905, if a body has no rest mass, then  $m_0=0$  and

$$E = pc.$$

A photon has energy and it has a momentum and that mixes up particle and wavelike characteristics:

$$E = pc = hf = hc/\lambda, \text{ so :}$$

$$p = \frac{hf}{c} = \frac{h}{\lambda} \quad (16.6)$$

Equation 16.6 is the expression for the momentum of a single photon. It's related to its wavelength or its frequency! Talk about mixing metaphors!

So we can add to what we know:



- $p_0(\text{initial photon}) = hf_0/c$
- $p(\text{final photon}) = hf/c$

and a momentum conservation equation could then be written.

If this pool ball picture is right, then since the outgoing atom would carry away energy, then the outgoing photon would have less. So  $E < E_0$ , which means that  $f < f_0$  or  $\lambda > \lambda_0$ .

### Arthur Holly Compton

By 1923—eight years after Einstein’s idea of the photon momentum, and seventeen years after his original prediction of photons, Arthur Holly Compton, an American, succeeded in slamming the door tightly against any doubt of the particle nature of light.<sup>18</sup> He studied the elastic scattering reaction

$$\text{X rays + Carbon} \rightarrow \text{X rays + Carbon} \tag{16.7}$$

$$\gamma + e \rightarrow \gamma' + e'. \tag{16.8}$$

This is a standard notation, where the Greek letter gamma ( $\gamma$ ) always represents a photon and the primes indicate here that the scattered particles have different characteristics—different states—from the initial ones. The use of X rays was in part to facilitate the measurements of the final state, as we’ll see. But, they are also sufficiently high in energy that the electron in the carbon target is essentially at rest relative to the incoming photon. This greatly simplifies the mathematics of what to expect. It is strictly “billiard ball” kinematics, albeit with tiny, bizarre billiard balls.

<sup>18</sup> When I was seven or eight years old, I would occasionally play with a neighbor’s visitor in the suburbs of Chicago. I can remember my parents marveling at the fact that his grandfather had a Nobel Prize. My sometimes-friend’s name was “Compy.”

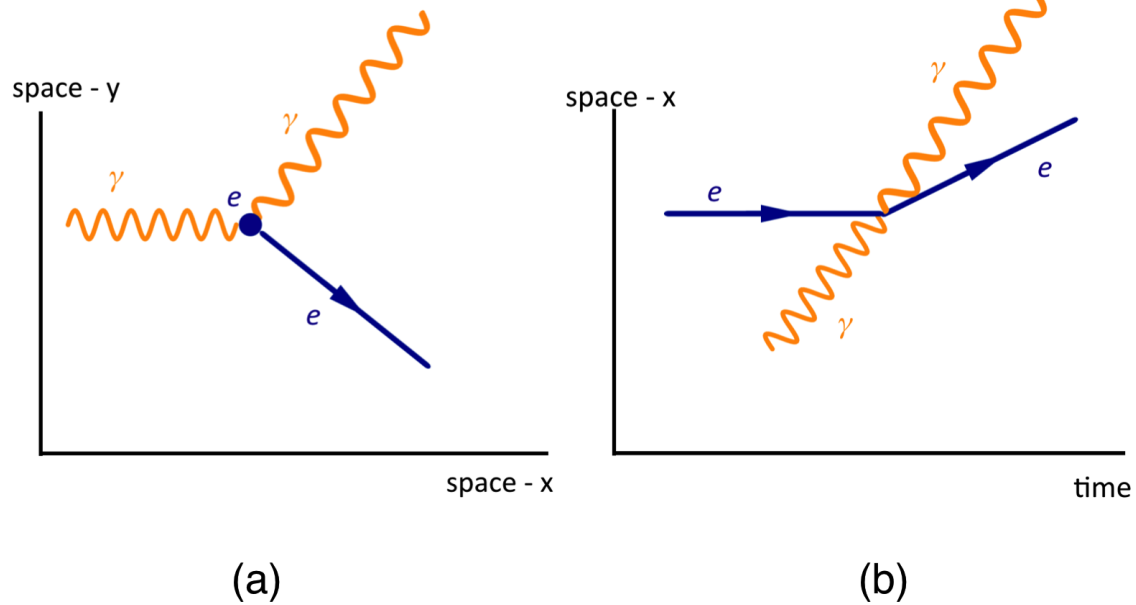
## Particle 1

### photon

|          |                                      |       |                                |          |            |
|----------|--------------------------------------|-------|--------------------------------|----------|------------|
| symbol:  | $\gamma$                             |       |                                |          |            |
| charge:  | $0e$                                 | mass: | $m_\gamma = 0 \text{ MeV}/c^2$ | spin:    | 1          |
| category | boson, aka intermediate vector boson |       |                                | category | elementary |

Figure 16.11 shows our three diagrams for this process—now called “Compton Scattering.” And the results are shown in Fig. 16.11.

Figure 16.11: compton diagrams



The results were conclusive. In Fig. 16.11 the solid curve is the prediction of Einstein’s model and the data fall right on top at a wavelength that’s a little longer than the initial beam’s. It took this long for Einstein’s vindication about the quantum nature of light. Acceptance came slowly: in 1916, Planck nominated him for membership in the Prussian Academy of Sciences, writing in part,

“ That he may sometimes have missed the mark in his speculations, as for example in his hypothesis of light quanta, cannot really be held too much against him. For it is not possible to introduce fundamentally new ideas, even in the most exact sciences, without occasionally taking a risk. ”

Even his Nobel Prize in 1921 was somewhat subdued in nature: “The Nobel Prize in Physics 1921 was awarded to Albert Einstein ‘for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect.’” In fact, this was a scandal for the Nobel Prize organization. There had been a dispute in the committee borne of antisemitism and animosity towards Einstein’s pacifism. As a result there was *no prize awarded in physics in 1921*, even though the world knew that Einstein was due at least one, if not more than one Nobel. Instead, the 1921 prize to him was awarded in 1922. He rarely mentioned it himself, and did not attend the award ceremony. His divorce decree from Mileva in 1919 stipulated that when he won the Nobel Prize, that the award money would go to her and their children.

## 16.9 What’s the Meaning of This?

I know you’re wondering how the photon can be representative of the waves of electromagnetic radiation and at the same time (!?) be a particle. We’ll see some of the explanation—that we physicists, cling to as an excuse for our inability to picture this apparent contradiction—in the next chapter. But we can see the waviness and particulate features in experiment with the aid of modern photodetection techniques.

### 16.9.1 Modern Examples of Photoelectricity

You know, you should always wash your hands. And since the first installation in the O’Hare Airport in 1980’s, in most U.S. airport restrooms it’s pretty easy. You just put your hands underneath the spigot and water comes out. Magic? No, it’s photoelectricity. There are three kinds of photoelectricity, all of which impact our lives in a regular way now. They are

- Photoemissive. Light falls on a surface and electrons are ejected. These are typically metals.
- Photoconductive. Light falls on a material and liberates electrons, but they don’t fly off, rather they become an electrical current within the material. These are semiconductor materials.
- Photovoltaic. Light falls on the top of a two-layer material and causes a voltage to appear between the layers. These too are semiconductor materials.

These are all devices that convert light into electricity in one way or another. The first one in the list is the historically oldest—it’s the story that we just went through: shine light of the right frequency on some surfaces and electrons will be emitted. It’s not as widely used as the other two since photoemissive detectors are actually pretty large and cumbersome. We use them in laboratories to detect the passage of

particles as we saw in Chapter ???. What's neat about them is that by setting up voltages between "stages" in the vacuum of a phototube the little bit of electron current that originally comes from collected light can actually be amplified many times (the "gain" is a measure of that multiplication and a factor of  $10^5$  is not unusual) and a measurable current can result from even a small amount of light and can happen reliably within 10s of picoseconds. So we can glue or press phototubes on pieces of special plastics that emit light when a charged particle goes through them and then collect that light in the phototube. Infrared vision goggles also are photoemissive devices. Some materials (semiconductors) are even sensitive to infrared light and so one can "see" heat in the dark with such devices.

Photoconductive devices can be infrared detectors. These are the devices in the faucets in airport restrooms. If you look under the faucet you'll see a little redish (maybe) window. It contains an infrared LED which is constantly beaming low-power, invisible infrared light under the faucet. When you put your hands in the beam, it reflects back into the window where there's also an infrared photo-receiver. This in turn operates an electric switch and eventually, a valve and the water turns on. Likewise your TV remote control is often infrared with the emitter in your hand and the receiver in the set or cable box. But photoconductive materials can also be in your phone. CCDs are a particular kind of engineered materials which are sensitive to light and create current in your camera.

Photovoltaic devices create a voltage when light falls on them and they are the workhorse of photo panels on dwellings. Solar cells are increasingly made of photovoltaic materials: sunlight becomes power for your home all because of Planck and Einstein.

While the photoelectric effect described by Einstein is only strictly the first mechanism, all of these require quantum physics in order to work and so 1905 was the birth of many modern devices, so ubiquitous that today you hardly realize their sophistication.

### 16.9.2 What's Coming

The "quantum revolution" had a handful of intellectual and experimental boosts. Insight by one or two people caused the scientific world to shudder as revolution seemed to happen over and over again. I noted that Einstein received the Nobel Prize only for photoelectricity. While relativity was indeed revolutionary, his ideas of the quantum were held against him for many years. They were just too unbelievable to be...believed. So when the Nobel Committee finally got around its racism, only apparently the most audacious of his many worthy ideas qualified for acknowledgement. He should have received additional<sup>19</sup> Nobel Prize for Special Relativity, General Relativity, Brownian Motion, and his idea of quantum statistics which we'll touch on later. He had an unprecedented five Nobel-worthy successes. Photoelectricity needs to stand for all of them.

<sup>19</sup> A number of scientists have received two Nobel Prizes, the first being Madam Curie who received one in Chemistry and one in Physics.