Kirchhoff's Law of Thermal Emission: Nothing but an Illusion

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Strangely, ideas can become so engrained in our consciousness that we can fail to question their validity, even when confronted with obvious contradictions. Such is the case with Kirchhoffôs Law of Thermal Emission. Gustav Kirchhoff is well known for his laws of current at each node (Ɇi_{in} = Ɇi_{out}) and voltage for each loop (ɆV = 0). However, his Law of Thermal Emission is less familiar to the electronics community. Yet the law has become a cornerstone of modern physics, despite modern technology refuting it daily.

The consequences are profound, impacting not only upon microwave communications but virtually every aspect of physics, from the nature of fundamental units, to condensed matter, to the stars and the Big Bang. In all of this, electrical engineers hold the key.

Kirchhoff's Law

Kirchhoffôs Law was formulated in 1859, advanced purely from theoretical arguments and without any experimental confirmation. After more than fifty years, Hilbert complained that a proper theoretical formulation of Kirchhoffôs Law still did not exist. Kirchhoffôs initial two proofs were found to be lacking. Max Planck tried to advance a proof of Kirchhoffôs Law, but that derivation was fraught with problems. As such, it could be said that Kirchhoffôs Law forever lacked all necessary scientific proof.

So, how could it be that Kirchhoffôs Law of Thermal Emission has survived to this day? To answer that question, we need to understand everything that is built upon this law. First, let us introduce Kirchhoffôs Law, in order to place everything in proper context.

Kirchhoff claimed that, given thermal equilibrium, every opaque cavity must contain normal or blackbody radiation, dependent only upon temperature and frequency of observation whilst being completely independent of the nature and form of the walls.

Initially he expressed his law as follows: $E/A = e$, where E and A corresponded to emission and absorption, respectively. Parameter ñeò represented a universal function of temperature and frequency, $e = f(T,v)$, which would eventually be presented by Max Planck. Yet, as soon as Kirchhoff presented this expression, he changed absorbance, A, to absorptivity, a, which he set to 1 for all blackbodies. However, even for Max Planck it was evident that Kirchhoffôs function would become undefined when absorptivity was set to 0, a characteristic of perfect reflectors, a situation of interest to modern-day electrical engineers.

So, what had Kirchhoff done?

He claimed that the character of the radiation contained within all opaque cavities was always of the same nature, regardless of the nature and form of the walls. But, to be valid, his law must be true at both limits; namely, for the perfect absorber (a = 1) and the perfect reflector ($a = 0$). Clearly, this was not the case. As a result, Kirchhoffôs claim was false relative to the universality of cavity radiation. Much of the physics community and, more specifically, the astrophysics community, still maintain that Kirchhoffôs Law is real. In fact, much of modern astrophysics would collapse if this were not the case. This is where electrical engineering can play a role in correcting physics.

Resonant cavities exist

In Kirchhoffôs day there was no such thing as network analysers and phase coherent radiation. Even Max Planck could never have anticipated such technological developments or the importance that resonant cavities will come to play in the modern world. Some say that if radiation is incident upon a spherical cavity, see Figure 1, the radiation will bounce around the cavity until it is eventually absorbed and becomes black or normal.

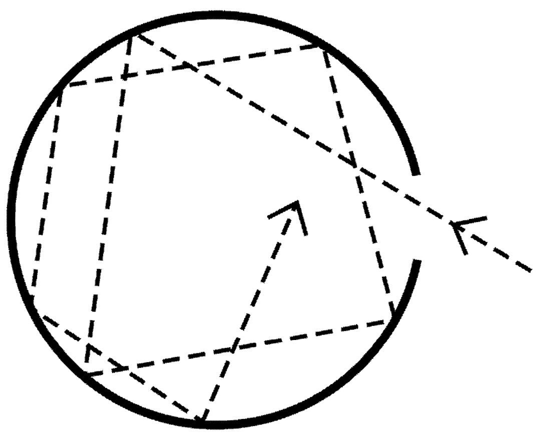

Figure 1: Schematic representation of radiation incident upon a spherical cavity

This will occur in a manner independent of the nature of the walls, advancing the same arguments from the mid-19th century. But, if you speak to electrical engineers, they might choose to make their cavity from a nearly perfectly reflecting silver mirror. They might then take a source of phase coherent radiation and guide that radiation into the cavity, thereby building standing waves. They certainly hope that the radiation will not become black and, fortunately for modern society, it will not. With minor considerations concerning dimensions, they will have built a resonator.

It is well-recognised throughout microwave engineering that resonant cavities exist. Furthermore, in optics these cavities and reflective surfaces can display phenomenal characteristics, as super-mirrors exist. Laser cavities built from specialised materials can achieve Q values of 10^{11}. That is far from anything Kirchhoff could ever have anticipated in 1859.

You might think: ñWho cares if Kirchhoffôs Law is wrong?ò. Engineering, science and technology have certainly advanced despite the error. That is true, of course, but engineering is losing a great opportunity to correct physics and astronomy. Perhaps, it would be better to assert: ñHey! We exist over hereé and our cavities are not black!ò

First, letôs acknowledge that resonant cavities do exist, not only in the radio and microwave ranges, but all the way up to the optical field. Ultra-high field MRI has always been dependent on cavities that are resonant and not black. When sampled with a network analyser, these cavities can be tuned to the frequency of interest and, thereby, ensure that UHFMRI images can be obtained. There are now well over sixty such scanners in the world and, although many do not realise it, those scanners are affirming that resonant cavities are not black.

In a sense, humanity has a choice. We can argue for the validity of Kirchhoffôs Law, based on conjectures and ill-conceived ideas, or we can recognise that UHFMRI scanners exist. The same holds true for all of microwave communications, a field so dependent on the existence of resonant cavities.

Astronomers and Kirchhoff's Law
Some will argue that the point is being missed with the resonators. They will claim: ñIt is the need for thermal equilibrium that makes Kirchhoffôs law validé Your resonators are not in thermal equilibrium!ò Actually, they go a little further. There is nothing like claiming that someone has violated the Second Law of Thermodynamics in order to prevail, and thatôs usually the path many select.

ñIf your cavities are not black at thermal equilibrium, you will be in violation of the Second Law!ò It all sounds very good on the surface, until one starts thinking about the details.

When Kirchhoff and Planck analysed blackbody cavities, they required two things: (1) temperature equilibrium must exist and (2) the entire systemôs energy must be contained within the radiation field. This leads directly to the Second Law arguments.

Consider a cavity constructed from a perfect absorber/emitter, something like graphite or soot. Since the wall material acts as a perfect emitter, the entire systemôs energy will be placed into the radiation field – no energy will remain in the wall; otherwise, the emitter would not be perfect. As a result, some argue that, if you take such a cavity and place it symmetrically against the opening of an arbitrary cavity at the same temperature, the second cavity must also contain black radiation; see Figure 2.

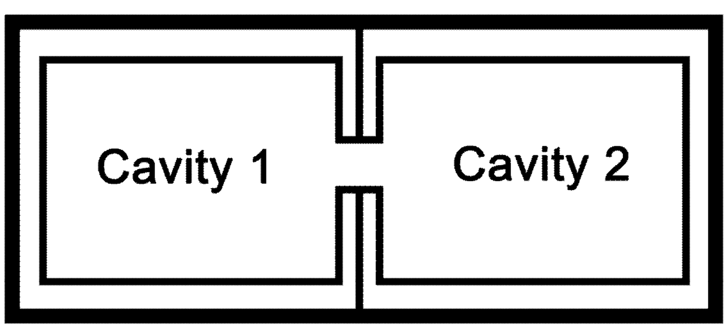

Figure 2: Schematic representation of a perfectly emitting cavity (all of the energy defining the temperature of the cavity is contained in the radiation field) and a perfectly reflecting cavity (all of the energy defining the temperature of the cavity is

contained within its walls) placed side by side such that energy can be exchanged either through their opening or through direct thermal contact of the walls. The entire system is surrounded by an adiabatic wall (depicted as a thicker outer line), such that no energy can enter or leave the two systems under consideration

If not, work could be done in violation of the Second Law. Namely, a photon could move from one cavity to the other without a temperature gradient, in order to balance the radiation fields, and work could be extracted from the photon energy.

It all sounds very convincing, until it is recognised that the temperature of the second cavity was not established solely through its radiation field (it was not a perfect emitter), but also by the amount of energy contained in its walls. As a result, in order to honour the Second Law, when a photon crosses the opening, an equivalent energy must move from the wall of the second cavity into the wall of the first. No net displacement of energy has occurred, and no violation of the Second Law. The second cavity is permitted to be devoid of radiation, while still at the same temperature as the first, provided that all its energy is contained within its walls. Kirchhoff and Planck were unaware that the walls of their cavities could not be neglected.

For a perfect reflector, often approached by silver, those walls contain electrons in conduction bands, and those electrons have associated energy that remains trapped and unavailable for thermal emission. Good reflectors make poor emitters for this very reason.

A thought experiment

Beyond this analysis and our everyday experience, it is easy to demonstrate through a simple thought experiment that not all cavities contain blackbody radiation reporting their temperature.

Start with a small, perfectly reflecting cavity placed within a sealed larger perfectly emitting cavity, as in Figure 3.

Figure 3: Schematic representation of a thought experiment. A large outer cavity acts as an ideal blackbody (emissivity = 1, reflectivity = 0) and is initially immersed in a helium bath at 4K. Within this cavity, a perfectly reflecting cavity (emissivity = 0, reflectivity = 1) rests of the floor with one of its sides initially remaining open

Make the inner cavity six-sided and temporarily leave one side open, requiring that the small cavity remain in physical contact with the interior lining of the large cavity. Now, place the entire system in a helium bath at 4K. Both cavities will move to the same temperature, and the larger cavity will emit photons at that temperature. Since one side of the little cavity is open, then both cavities will be filled with the same 4K radiation.

Now, seal the opening of the small cavity by replacing the wall. It will now trap the 4K radiation, as it can produce no new radiation on its own. At this point, lift the large box out of the helium bath and allow it to come to room temperature. Because the small cavity is in thermal contact with the large cavity, its walls will also move to room temperature. However, while the large cavity now contains radiation corresponding to room temperature, the small cavity still contains 4K radiation, even if it is in thermal equilibrium at room temperature. No laws of thermodynamics have been broken. The only thing that has occurred is that Kirchhoffœs ñLawò has been proven false. Not all cavities in temperature equilibrium contain radiation corresponding only to their temperature in a manner independent of the nature of their walls.

The lesson is clear. In the real world, not all cavities are filled with black radiation, irrespective of thermal equilibrium arguments. Another point can be made. Perfect reflectors (since, by definition, they canœt absorb radiation) canœt reach thermal equilibrium based on radiation fields. In fact, they are innocuous to those fields. That is the feature upon which the use of resonators depends.

Perfectly reflecting cavities can only reach thermal equilibrium through conduction or convection. They are completely uncoupled from any radiation they might contain, as we observe every day throughout modern science. Kirchhoff and Planck cannot require that such cavities are characterised by the radiation field they contain.

What does this all mean?

At the onset, it should be made clear that Planckôs formulation of the blackbody solution remains correct for actual blackbodies. It is simply a matter of not all cavities containing black radiation, a fact which is well established throughout the electronics world.

At the same time, there is one more important aspect to consider, relative to actual blackbodies, namely, that such objects can do work. They can convert any incident energy, either in the form of incident light or heat in their walls, into a thermal spectrum that manifests their own temperature. This ability to do work is critical and something that was never considered when blackbodies were treated by Kirchhoff and Planck.

Conversely, rigid perfectly reflecting cavities canôt do work. That is why they can be used in microwave communications and laser technology. Perfectly reflecting cavities can be used to build up standing waves, without allowing the incident energy to be converted into another form (no conversion to heat or alternative frequency). In the end, it seems that Kirchhoffôs Law of Thermal Emission was just an illusion.

This has important consequences for physics and astronomy. First, in falsely arguing that Kirchhoff was correct, Max Planck sought to bring universality into physics. Because he believed in Kirchhoffôs Law, he thought that the constants *k* and *h* had universal implications. He felt that there were universal values of length, mass, time and temperature: ñIn contrast with this, it might be of interest to note that, with the aid of the two constants h and k which appear in the universal law of radiation, we have the means of establishing units of length, mass, time and temperature, which are independent of special bodies or substances, which necessarily retain their significance for all time and for all environments, terrestrial and human or otherwise, and which may, therefore, be described as ónatural unitsôé These quantities retain their natural significance as long as the law of gravitation and that of the propagation of light in a vacuum and the two principles of thermodynamics remain valid; they therefore must be found always the same, when measured by the most widely differing intelligences according to the most widely differing methodsò.

In fact, whilst many think that the introduction of the quantum of action was Planckôs crowning achievement, it could more properly be argued that it was this universality of constants that Planck most cherished. Now, with Kirchhoffôs Law proven invalid, all claims of universality will fade away. Constants like *k* and *h*, while important in Earthly physics, hold no special place elsewhere in the universe. Earthly physics remains bound by the measures that it has adopted *a priori*.

This also has implications in astronomy, as the existence of gaseous stars and the Big Bang critically depend on the validity of Kirchhoffôs Law. In the case of the stars, it is known that they emit thermal spectra which characterise the white light of the Sun. To generate that white light, Arthur Eddington had recourse to Kirchhoffôs Law. He believed (and most still do) that the Sun, devoid of a true surface, can generate a thermal spectrum based solely on thermal equilibrium arguments. Eddington argued that the Sun can be considered enclosed and acting as a slowly leaking sieve. In this sense, it could be treated as any other cavity and, according to Kirchhoff, its emitted radiation must be black.

Taking a different approach, Stephen Hawking has argued that black holes could generate blackbody radiation at their event horizon from pair production. Cosmologists argue that blackbody radiation was produced by the primordial atom and freed at the recombination event. Unruh argues that blackbody radiation could be produced by acceleration relative to an infinite thermal bath. All these scenarios completely reject Kirchhoffôs most fundamental requirement: thermal equilibrium with an opaque enclosure. As such, many believe that they can generate thermal photons from nothing. Blackbody spectra can now be generated from processes that have no relation with how a photon is generated from a piece of graphite on Earth, an actual blackbody. Yet, the production of a thermal photon in graphite must require something very fundamental, namely the vibration of atomic nuclei within the confines of a structural lattice, as the engineering community has already recognised. Such a mechanism, so vital to blackbodies on Earth, is completely absent from the current models of the stars, black holes, the Big Bang and Unruh temperatures. This has all happened because most within physics still believe in the illusion that is Kirchhoffôs Law. But, engineers do not build from illusions. So, when you are working with resonators and microwave cavities, remember to tell everyone: ñHey! We exist over hereé and our cavities are not black!ò