Kirchhoff's Law of Thermal Emission: What happens when a law of physics fails an experimental test?

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Kirchhoff's Law of Thermal Emission asserts that, given sufficient dimensions to neglect diffraction, the radiation contained within arbitrary cavities must always be black, or normal, dependent only upon the frequency of observation and the temperature, while independent of the nature of the walls. With this in mind, simple tests were devised to demonstrate that Kirchhoff's Law is invalid. It is readily apparent that all cavities appear black at room temperature within the laboratory. However, two completely different causes are responsible: 1) cavities made from good emitters self-generate the appropriate radiation and 2) cavities made from poor emitters are filled with radiation already contained in the room, completely independent of the temperature of the cavity. The distinction between these two scenarios can be made by placing a heated object near either type of cavity. In the first case, the cavity emission will remain essentially undisturbed. That is because a real blackbody can do work, instantly converting incoming radiation to an emission which corresponds to the temperature of its walls. In the second case, the cavity becomes filled with radiation which is not characteristic of its own temperature. Contrary to current belief, cavity radiation is entirely dependent on the nature of the walls. When considering a perfect reflector, the radiation will not be black but, rather, will reflect any radiation which was previously incident upon the cavity from the surroundings. This explains why microwave cavities are resonant, not black, and why it is possible to acquire Ultra High Field Magnetic Resonance Imaging (UHFMRI) images using cavity resonators. Conversely, real blackbodies cannot contain any radiation other than that which is characteristic of the temperature of their walls, as shown in Planck's equation. Blackbody radiation is not universal, Kirchhoff's Law is false, and cavity radiation is absolutely dependent on the nature of the walls at every frequency of observation. Since they were derived from this law, the concepts of Planck time, Planck temperature, Planck length, and Planck mass are not universal and are devoid of any fundamental meaning in physics.

According to the Kirchhoff's law this radiant energy is independent of the nature of the radiating substance and therefore has a universal significance.

Max Planck, 1959 [1, p. 18]

1 Introduction

Kirchhoff's Law of Thermal Emission was formulated in 1859 [2,3]. It is often presented as merely stating that, at thermal equilibrium, the emissivity of an object, ϵ_ν, is equal its absorptivity, α_ν. However, this relationship, known as the Law of Equivalence, was first proposed by Balfour Stewart [4], just before Kirchhoff's own law was formulated. Kirchhoff's Law extends much beyond Stewart's and states that, given thermal equilibrium, the radiation contained within an arbitrary cavity will always depend only on its temperature and on the frequency of observation, but will be completely independent of the nature of the walls [2, 3]. The senior author has stated on numerous occasions that Kirchhoff's Law is not valid (see [5, 6] and references therein) as it has no proper theoretical [7] or experimental proof.

1.1 Max Planck and Kirchhoff's Law

Max Planck attempted to prove the validity of Kirchhoff's Law in the opening sections of *The Theory of Heat Radiation* [8, § 1-52], but the derivation is filled with errors [7]. These include redefining blackbodies. It was not appropriate to ignore absorptivity at the interface of a blackbody, as this violates Kirchhoff's very definition of a blackbody: the ability to absorb radiation over an *infinitely small thickness* [3, § 1]. In contrast, Planck [8] permits radiation to enter the wall of the cavity without absorption at its surface and never lets it escape based on infinite transmission. Thus, Planck's 'proof' of Kirchhoff's Law uses transmissivity and, at times, improperly ignores absorptivity. Additionally, his proof relies on the use of polarized light [8, § 1-52], when heat radiation is never polarized [7].

Furthermore, Planck assumes that perfectly reflecting cavities will always be filled with black radiation at the correct temperature, provided that any existing radiation in the cavity can be thermalized with the insertion of a small carbon particle. He insists that this particle contributes no heat energy and acts only a catalyst [8, § 51-52]. However, it can easily be demonstrated that the catalyst argument violated the

1st and 2nd laws of thermodynamics [9]. The particle must do work to transform heat energy into radiation and fill the cavity. It could never act as a catalyst. Furthermore, as will be demonstrated below, whenever a cavity has a high reflectivity, the radiation it contains depends on its external environment, not on its own temperature. In this respect, Kirchhoff's Law [2, 3] is easily proven false.

1.2 Perfectly Reflecting Cavities

Throughout his text on *The Theory of Heat Radiation* [8], Max Planck places all of the energy in the radiation field and leaves none in the walls of the cavity. Obviously, if this is done, the solution cannot depend on the nature of the walls. However, the approach is not justified. Real cavities have energy in their walls and the most important example is the perfectly reflecting cavity, wherein thermal equilibrium is governed by the energy in the walls, not within the radiation field [9]. The walls, by definition, have no means of interacting with radiation and, therefore, the radiation field cannot be used to set thermal equilibrium in such a cavity. To argue otherwise is a violation of the 0th law of thermodynamics [9]. Perfectly reflecting cavities are responsive to the radiation which is incident upon their openings. The reflection can be either specular, white, or a mixture. Still, any transformation on the incoming light in a perfectly reflecting cavity will occur in a manner completely devoid of any relationship to the temperature of its walls.

This reality is well-known in microwave technology and is the basis for the existence of resonant cavities. Conversely, if Kirchhoff was correct, then any radiation incident into a microwave cavity would become thermalized and immediately change the temperature of the cavity. Signal would be lost as the radiation became blackbody at the final temperature of the cavity. However, the reality is that microwave cavities used in electron spin resonance and much of telecommunications are resonant devices. They are made of nearly perfect reflectors over the frequency range of interest. The same situation is encountered in Ultra High Field Magnetic Resonance Imaging (UHFMRI) wherein resonant cavities are utilized to acquire images [10, 11]. The use of such cavities clearly demonstrate that Kirchhoff's Law cannot be valid, as MRI depends on the conversion of signal from the spins into voltage, without the loss associated if the cavity was acting as a blackbody. MRI uses the ability to build up standing waves in resonant cavities during testing, transmission, and reception, in a manner independent of cavity temperature [10, 11].

The arguments advanced relative to resonant cavities in the microwave and at MRI frequencies is not solely geometrical. Absorption of incident photons, transformation into thermal vibrations, and re-emission into thermal photons does not occur in perfectly reflecting cavities. Kirchhoff and Planck cannot claim otherwise, when they assert that all cavities contain black radiation [2, 3, 8].

The radiation within perfectly reflecting cavities is determined by history and environment, not temperature. When considering thermal equilibrium in the context of a perfect reflector, the cavity must always be devoid of thermal radiation, if one wants to consider the enclosed space as part of the system, and if the 0th law is to be honored. When a system comprised of perfectly reflecting walls and the associated cavity contains radiation, it can only be considered to be in thermal equilibrium if one assigns the radiation to the surroundings, not to the cavity. If one wishes to assign the radiation to the cavity, then it can never be considered to be in thermal equilibrium. Furthermore, there is no means of bringing forth such equilibrium. That is why perfectly reflecting cavities can never be considered to contain black radiation in accordance with the temperature of their walls. Again, to argue otherwise is a violation of the 0th law.

1.3 Analysis of blackbodies

Though enumerable references exist relative to the quality of blackbodies, it remains true that blackbodies are specialized cavities which entirely depend on the nature of their walls (see [5] and references contained therein). Laboratory blackbodies are made from materials that have an elevated emissivity over the range of interest, as is widely known throughout metrology. That statement alone is sufficient to illustrate that Kirchhoff's Law cannot be valid. Planck himself, in obtaining his equation, was dependent on the work of the best experimentalists in order to obtain the proper emission at lower frequencies [12–14]. If Kirchhoff was correct [2, 3], that should not have been required.

In any case, for the sake of brevity, the discussion relative to this presentation can be limited to a single reference without any loss in content. In 1954, De Vos published his *"Evaluation of the Quality of a Blackbody"* in the journal *Physica* [15]. This article has become a classic in blackbody radiation. It highlights both the problem at hand and also conveniently presents a reference for building a cylindrical blackbody, as done in this work, by simply boring a small hole into a material of interest.

In this article [15], the quality of a blackbody made of materials with various emissivity is determined by examining the change which takes place upon incident radiation when it is allowed to enter a cavity, exit, and then be monitored with a detector placed at various angles. For cylindrical cavities, De Vos is concerned with the ratio of the length of the hole to its diameter. He demonstrates that the cavities appear to become increasingly black as this ratio is increased [15]. However, what has not been achieved in the paper is to demonstrate that the cavities will be black, independent of incident radiation.

In fact, De Vos is concerned with the degree to which the surface of the cavity is either specular or white [15]. He is not concerned with whether or not a surface can actually emit any photons at the correct temperature! In the end, De Vos' work provides only limited insight into blackbody radiation [15]. It does analyse to what extent the surface property of a cavity affects the transformation of incoming light into fully diffuse reflection [15]. However, if a cavity is not constructed of a near ideal absorber, it will be grey, not black. The extent to which its emitted light is diffuse will only become important when it is driven out of thermal equilibrium through heating, a situation which, though commonly used, is not in keeping with the requirement for thermal equilibrium. Once again, this is why laboratory blackbodies are made from nearly ideal emitters.

2 Materials and Methods

Infrared images were obtained using a CompactPro thermal imaging camera (Seek Thermal, Inc., Santa Barbara, CA 93117; Thermal.com) interfaced with an Android (version 4.4.2) cell phone as shown in Fig. 1A.

The camera had a focusable lens and a 32° field of view. It is equipped with a 320×240 thermal sensor and has a temperature range of -40 to 330°C. The camera is capable of obtaining either still images or video. It was utilized in either white or black mode.

Cylindrical blackbodies where constructed by drilling a small hole into $12.5 \times 12.5 \times 50$ mm blocks of copper, aluminium, brass, and steel (Specific Gravity Metal Blocks, EISCO, Haryana 133001, India - available on Amazon.com). The expected emissivity of the copper, brass, and steel holes should be on the order of 0.03-0.1 [16]. The type of steel was unknown, but stainless steel can have a relatively elevated emissivity on the order of 0.7 and if heated in a furnace can reach an emissivity of 0.95 [16]. A $20 \times 50 \times 50$ mm graphite block (Otoolworld 99.9% Purity Graphite Ingot Block EDM Graphite Plate Milling Surface - available on Amazon.com) was used to build the reference blackbody. Its emissivity should be on the order of 0.7-0.9 [16]. Holes were produced with a drill press using a $\frac{3}{16}''$ diameter drill bit to a depth of $1''$. In order to easily visualize the emission from each cavity, relative to the graphite standard, the blocks were linked together using packing tape, as shown in Fig. 1B.

Experiments were initiated at room temperature, by placing the camera at a distance of ~ 20 cm above the table surface and therefore ~ 15 cm above the surface of the block assembly. The eye of the camera was positioned directly over the center of this assembly, as shown in Fig. 1C and D.

In order to document the effect of ambient radiation on the cavities, a galvanized steel rod was placed in an oven and brought to a temperature of 450°F, or 232°C. The rod was then positioned either to the right, left, or at the center above the block assembly.

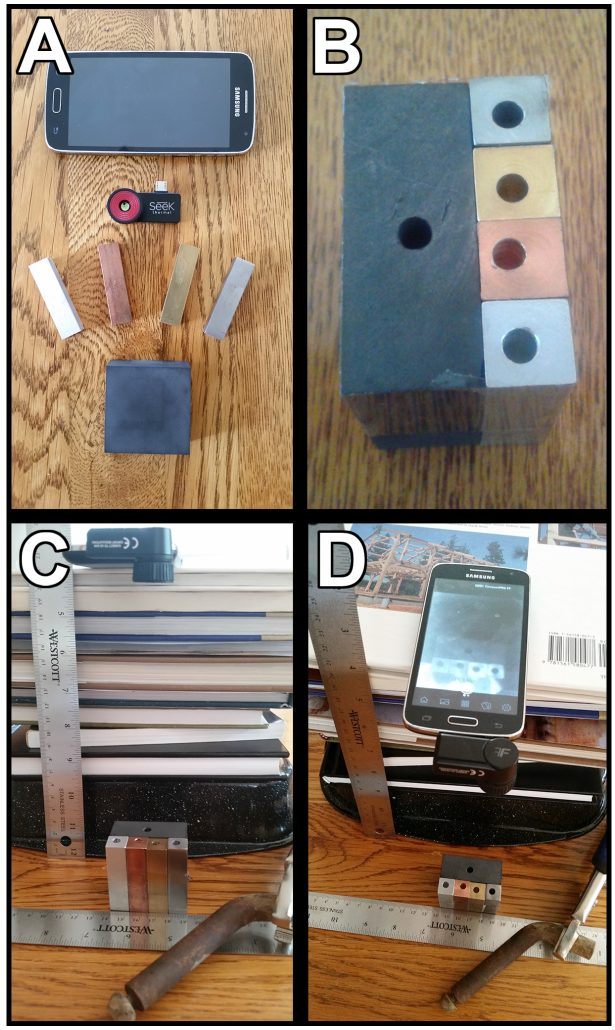

Fig. 1: A) Photograph of the Android phone, Seek Thermal camera, and aluminum, copper, brass, steel, and graphite blocks; B) Block assembly (graphite on the left, steel - top right, brass, copper, aluminum - bottom right). Note that two small scratches are visible near the graphite hole; C) front view of the block assembly and camera mounted on a stack of books and an enameled iron broiling pan; D) top view of the block assembly and camera. In C and D two rulers were added to take the photographs. They were not present during the experiment. The galvanized steel rod can be seen in the lower right of each photo.

3 Results and Discussion

In Fig. 2A a thermal image is presented in black mode, revealing that all the holes appear nearly the same at room temperature. Of course, the block is also within a room filled with radiation at the same temperature. As such, it is important to determine whether the cavities were generating their radiation on their own or simply manifesting the radiation in their surroundings. For the next portion of the experiment, the camera was switched to white mode and the holes all appear black as

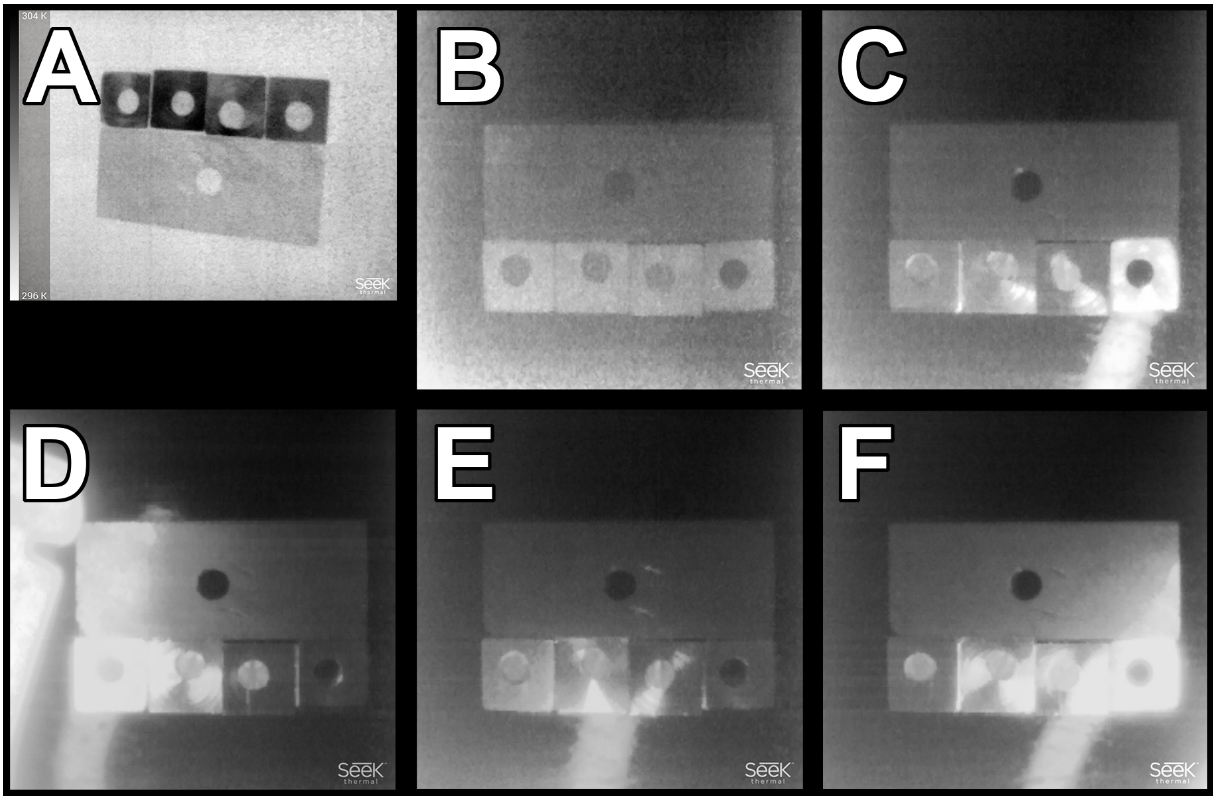

Fig. 2: A) Infrared image obtained from the block assembly with the Seek Thermal camera in black mode. For this image the camera was hand held. All the holes appear to contain the same radiation. As such, on cursory examination, Kirchhoff's Law appears valid; B-F) Infrared images obtained from the block assembly with the Seek Thermal camera in white mode with the camera and block positioned as in Fig. 1C and D. The galvanized steel rod was not near the block assembly; C) The heated galvanized steel rod was placed on the right near the steel hole. Note that the aluminum, copper, and brass holes all appear filled with radiation from the rod. There is also a slight reflection from rod radiation near the graphite hole; D) The heated galvanized steel rod was placed on the left side near the aluminum hole. Note that the aluminum, copper, and brass holes all appear filled with radiation from the rod. The brass hole demonstrates that the radiation is not perfectly diffuse in this hole; E) The heated galvanized steel rod was placed at the center of the block assembly. Note that the aluminum, copper, and brass holes all appear filled with radiation from the rod. The two small scratches near the graphite hole are also reflecting radiation, demonstrating that radiation from the rod is reaching this hole as well; F) The heated galvanized steel rod was placed just to the left of the steel hole. Note that the aluminum, copper, and brass holes all appear filled with radiation from the rod. However, the steel hole also contains some radiation from the rod indicating that its emissivity is not on par with graphite which, in all images, never manifested any effect from rod radiation.

seen in Fig. 2B. Next, in Fig. 2C-F, a heated galvanized steel rod was placed above their surface. The rod had been heated to 450°F, or 232°C. In Fig. 2C it is on the right above the steel hole. With the rod in this position,it is immediately noticed that it cannot fill the graphite or steel hole with radiation, but that these two holes remain pretty much as they were with just a tiny spec of reflection at the graphite hole. This indicates that radiation from the rod is reaching this hole as well, as expected. At the same time, the aluminum, copper, and brass holes are immediately becoming filled with radiation from the rod. Next, the rod was moved to the left, as shown in Fig. 2D. Notice, once again, that there is no effect on the graphite hole and that only a slight reflection is observed at the top of the steel hole. However, all the others are filled with radiation from the rod. In particular, note the pattern in the brass hole manifesting that it is still not able to fully convert incoming radiation into diffuse ejected radiation. This is demonstrating that the hole should be deeper to render the radiation fully diffuse, as suggested in De Vos' classic work [15]. Next, in Fig. 2E, the rod was placed at the center of the block. The three holes from aluminum, copper and brass are again filled with rod radiation, but graphite hole remains unaffected and the steel hole almost unaffected. However, reflection of rod radiation can be observed in the graphite scratches on each side of that hole. As such, radiation from the rod is clearly reaching the graphite hole. Finally, the rod is positioned just to the left of the steel hole. In this position, the steel hole is no longer black. Now, it can be observed that rod radiation is able to partially fill the steel cavity. Nonetheless, the bottom of the hole is darker. It can be concluded that this steel has a much higher emissivity than the aluminum, copper, or brass holes, but is not on par with graphite.

4 Conclusions

For more than 150 years, Kirchhoff's Law of Thermal Emission [2, 3] has governed much of scientific thought in physics and astronomy, despite the fact that it lacked proper theoretical and experimental proof (see [5–7] and references therein). Now it is clear that cavities do not all contain the same radiation independent of the nature of their walls. Perfect reflectors are unable to convert incoming radiation into the Planckian distribution corresponding to their wall temperature. In the absence of wall motion, they are unable to do any work and merely sustain the radiation in their surroundings. If this incident radiation is phase coherent, then perfect reflectors can even sustain standing waves, as required in both microwave telecommunication and Ultra High Field MRI [10, 11]. Had Kirchhoff's Law been valid, then neither of these modalities would exist, as no cavity would become resonant and all incident radiation would become destined to adopt the blackbody profile.

Kirchhoff's Law is demonstrably false. Real blackbodies can do work on any incoming radiation and they do so instantly. They exclusively contain radiation which reflects the temperature of their walls, not the presence of the radiation in their surroundings. It is this ability to do work in the ideal blackbody, and the inability to do work in the perfect reflector, which determines the real behavior of cavities. That is also why laboratory blackbodies are always constructed from materials which possess relatively elevated emissivity values over the frequencies of interest. The production of a blackbody spectrum absolutely requires the presence of a vibrational lattice and is intrinsically tied to the nature of the walls, contrary to Kirchhoff's claim.

As a result, Max Planck's long advocated universality [8, § 164] relative to time, length, mass, and temperature does not exist. The concept is absolutely dependent of the fact that Kirchhoff's Law is valid and this is simply not the case. Physics thereby loses the universal significance of Planck's constant and Boltzmann's constant as well [17]. There is nothing inherently fundamental in these constants. They have no more primacy in nature than a mile would possess over a kilometer. Planck's claim to the contrary is unfortunately unsound. The units of measure will forever remain a product of humanity's definitions and science will always remain constrained by this realization.

What happens when a law of physics fails an experimental test? There is a better understanding of the emissive properties of materials and, with it, the realization that the production of a thermal spectrum absolutely depends on the presence of a vibrational lattice [18]. Humanity can also continue to marvel at the wonders of microwave technology and the sharp images of UHFMRI as a constant reminder that Kirchhoff's Law was false [10, 11]. The realization that the experimental test presented herein invalidates Kirchhoff's Law, mandates a fundamental reformulation of modern astronomy [19–24].

Dedication

This work is dedicated to Joseph Benoît Martin Robitaille.

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