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heat in history

Early Study of Heat Transfer: Newton and Fourier

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Editor's Note: Isaac Newton's laws of physics govern most of the objects that can be seen and touched. Less familiar to the general public is Newton's contribution to heat transfer. It is most appropriate to mark the 300th anniversary of the publication of "A Scale of the Degrees of Heat" with Dr. Winterton's elegant article on the subject. The old phrase, "past is prelude," is amply demonstrated by this earliest written example of the science, of heat transfer. It is argued elsewhere that the heat transfer coefficient is an inappropriate, confounded variable (because of its frequently large dependence on temperature). However, the fact remains that the coefficient is used the world over in experimentation and computation. The following, fascinating story of how the heat transfer coefficient came about has Newton as the central character, but also involves Fourier in a major way, as well as Biot.

Arthur E. Bergles
Heat in History Editor, Emeritus

Extracts are given from the original articles by Newton (1701) and Fourier (1807). In the case of Newton a later English translation is used. In the case of Fourier the translation is by the present author. In this way the contributions of the two scientists to the early study of heat transfer are explained and an attempt is made to dispel some misconceptions. Newton is correctly associated with the origin of the understanding of convective heat transfer and Fourier with that of conduction.

The origins of the study of heat transfer are associated with the names of Newton and Fourier, but it is not that easy to find copies of their work. It seemed worthwhile to reproduce short sections of their original articles and summarize their contributions. Reading general heat transfer textbooks one can even find statements to the effect that Newton did not really introduce Newton's law of cooling (it was Fourier) and that Fourier did not really discover Fourier's law of heat conduction (it was Biot). Fortunately, neither of these statements is supported by more detailed study, but they

I would like to acknowledge the efforts made by the library at the University of Birmingham in tracking down some of the more obscure references and also the Bodlean Library at Oxford University for allowing me to consult numerous references that they have on the shelves or in their store.

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do suggest that reference to the original sources would be useful.

In addition to the interests of scholarship in checking back from time to time that references to these classic articles are correct, the articles themselves can be a stimulus to modern thinking. Just following through logically the implications of Newton's original explanation of his law of cooling leads to a result for heat transfer coefficient for laminar flow over a flat plate close to the accepted value. In the case of Newton, this year is particularly appropriate to remember him, being the 300th anniversary of his article.

An indication of the interest in this field is the much more wide-ranging article published earlier in this journal [1].

NEWTON, 1701

Nearly all heat transfer textbooks mention Newton's law of cooling, but many do not give a reference. When a reference is given, it tends to be for the original article of 1701 [2], failing to point out is that the article is in Latin. An English translation appeared in 1809 [3] and has since been reproduced in a number of places [4–6]. One of these [4] is accompanied by a facsimile reproduction of Newton's original Latin article.

Since Newton discovered Newton's law of cooling, one might reasonably expect to find in his article an equation like:

$$Q = hA(T_{\text{wall}} - T_{\text{bulk}}) \qquad (1)$$

where Q is the heat flow rate, h the heat transfer coefficient, and A the surface area; T_{wall} is the temperature of the solid surface and T_{bulk} the temperature of the coolant flowing past. In fact, not only does no such equation appear, there are no equations in the article at all. Newton did not define or use the heat transfer coefficient. Also, as the equation stands, it is no more than the definition of heat transfer coefficient; it only becomes Newton's law when the further assumption is made that h is constant. He did make the key assumption that the rate of loss of temperature of a hot body is proportional to the temperature itself. Compared to this, writing the law in the form of an equation is fairly trivial.

It is important in trying to understand the original article to realize that the science of heat transfer scarcely existed at that time. Topics that are simply taken for granted now, such as the definition of specific heat, or the existence of a generally agreed temperature scale, had yet to be properly studied in 1701. Newton's work was in fact directed toward establishing a temperature scale and finding experimentally a method of measuring high temperatures. Only peripherally was it concerned with what is now known as Newton's law of cooling.

Newton was interested in constructing a scale of temperature that went up to high values. He had a linseed oil thermometer that went up, in modern terms, to 200°C. He was looking for a method of measuring considerably higher temperatures. He decided to do this by using the transient cooling of a red-hot iron bar. Small samples of different metals and alloys could be placed on the bar and the time at which they solidified noted. The temperatures were deduced from the cooling times, essentially as in the modern lumped-parameter method. So Newton invented the lumped-parameter method of transient analysis, a fact that seems to have been generally overlooked (but is noted in [7 and 8]).

The results were presented in the form of a table. The distinction between heat and temperature was not clear at this time; in the table, heat (calor) is being used where we would use temperature. A shortened version is given as Table 1 (the complete table is available at [6]). The

Table 1 Simplified version of Newton's results

Equal parts of heat, E	Degrees of heat, D	Event	Converted to °C
0[a]	0[b]	Thawing of crushed snow	0[a]
12	1	Greatest heat in contact with human body	36.4
33[a]		Water begins to boil	100[a]
34	2.5	Water boils vigorously	
34.5		Maximum temperature of boiling water	
72		Tin melts	218
81	3.75	Bismuth melts	245
96	4	Lead melts	291
136	4.5	Glows by night but not in twilight	412
146		Antimony solidifies	442
192	5	Coal fire	582

[a]Reference points for linear conversion.
[b]Incorrect.

last column in the table is an addition, Newton's equal parts of heat translated into degrees Celsius using the fixed points of melting snow at 0°C and boiling water at 100°C and linear interpolation. (If this is not the first use of melting ice as a fixed temperature, then it must rank very early; Newton's second fixed temperature was body heat). As the temperature rises, the values in the last column are increasingly in error. For example, the melting point of antimony is now considered to be 631°C.

The zero value for the degrees of heat at 0°C is almost certainly a mistake, although it is given in all the English translations; it does not appear in the facsimile Latin original in Cohen [3], and anyway zero is not an acceptable temperature in a geometric scale. Mysteriously the mistake has been transmitted back into the retyped Latin version given in [5].

To explain Table 1 we use Newton's own words [3] (the complete article is also available at [6]):

> In the first column of this table are the degrees of heat in arithmetical proportion, beginning with that which water has when it begins to freeze, being as it were the lowest degree of heat, or the common boundary between heat and cold; and supposing that the external heat of the human body is 12 parts. In the second column are set down the degrees of heat in geometrical proportion, so that the second degree is double the first, the third double the second, and the fourth double the third; and making the first degree the external heat of the human body in its natural state. It appears by this table, that the heat of boiling water is almost 3 times that of the human body, of melted tin 6 times, of melted lead 8 times, of melted regulus 12 times, and the heat of an ordinary kitchen fire is 16 or 17 times greater than that of the human body.
>
> This table was constructed by means of the thermometer and red-hot iron. By the thermometer were found all the degrees of heat, down to that which melted tin; and by the hot iron were discovered all the other degrees; for the heat which hot iron, in a determinate time, communicates to cold bodies near it, that is, the heat which the iron loses in a certain time, is as the whole heat of the iron; and therefore, if equal times of cooling be taken, the degrees of heat will be in geometrical proportion, and therefore easily found by the tables of logarithms.

Newton was able to show, in the range covered by his linseed oil thermometer, that the two methods of calculating temperature gave the same answers (in the range up to 200°C). A further extract from the original article gives the law of cooling:

> Having discovered these things; in order to investigate the rest, there was heated a pretty thick piece of iron red-hot, which was taken out of the fire with a pair of pincers, which were also red-hot, and laid in a cold place, where the wind blew continually upon it, and putting on it particles of several metals, and other fusible bodies, the time of its cooling was marked, till all the particles were hardened, and the heat of the iron was equal to the heat of the human body; then supposing that the excess of the degrees of the heat of the iron, and the particles above the heat of the atmosphere, found by the thermometer, were in geometrical progression, when the times are in an arithmetical progression, the several degrees of heat were discovered; the iron was laid not in a clam air, but in a wind that blew uniformly upon it, that the air heated by the iron might be always carried off by the wind and the cold air succeed it alternately; for thus equal parts of air were heated in equal times, and received a degree of heat proportional to the heat of the iron.

Not only is the law stated as the rate of loss of heat is proportional to temperature (heat in the usage of 1701) and that it is temperature difference that matters (heat above the heat of the atmosphere), but the importance of fluid flow is stressed, i.e., the law applies to forced convection. Further, the law is explained: the air is taking away heat proportional to the temperature of the iron bar because it is heated up to that temperature by contact with the bar. This explanation of Newton's law is illustrated in Figure 1. An extension of this reasoning [9] gives an equation for the heat transfer coefficient in laminar flow over a flat plate that is close to accepted modern results. So Newton's intuition was close to the truth.

The reason that Newton's estimates of high temperature are too low (Table 1) is that he did not take radiation into account, as explained by Grigull [10]. A detailed simulation [9, 11], including the effects of varying specific heat of the iron bar as well as radiation, gives the results in Table 2.

In conclusion, Newton was the first to postulate that the rate of loss of temperature of a hot object, with air blowing past, is proportional to the temperature itself. This is the essence of his law of cooling even if he did not define the heat transfer coefficient. An obvious extension of the idea is to integrate the law for a transient cooling process, i.e., Newton originated the lumped-parameter method of transient analysis. Newton's explanation of why his law works, that the air warms up to the heated surface temperature and takes away heat proportional to the temperature rise, has not been given

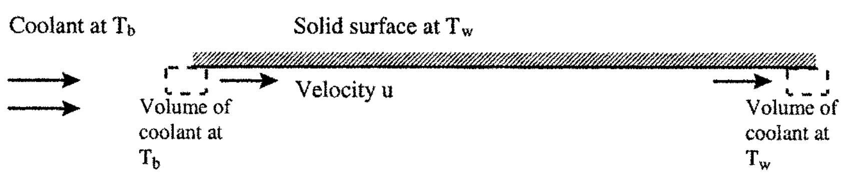

Figure 1 The air traveling along in contact with the bar warms up from T_b to T_w, i.e., the air carries away heat proportional to $T_w - T_b$, which is Newton's law of cooling.

Table 2 Correspondence between Newton's results (converted to °C) and the simulation for air velocity 0.5 m/s, bar diameter 0.05 m, and emissivity 0.9

True temperature (°C)	Newton: Equal parts of heat, E	Newton: E converted to °C	Simulation (°C)	Event
0	0^a	0		Thawing of crushed snow
37	12	36.4		Greatest heat in contact with human body
100	33^a	100^a	100	Water begins to boil
232	72	218	229	Tin melts
272	81	245	259	Bismuth melts
328	96	291	300	Lead melts
525	136	412	396	Glows by night but not in twilight
631	146	442	436	Antimony solidifies
1,192	192	582	582	Coal fire

[a]Reference points for linear conversion.

sufficient prominence. A simple extension of the idea gives results close to accepted modern equations for heat transfer coefficient [9].

Incidentally, it is not correct to assume that Newton was unaware of the possible existence of thermal radiation. In his *Opticks*, referred to in [12], he speculates that there is such a thing as heat radiation and that it is of the same nature as light. This is the 300th anniversary of the original (anonymous) publication of his work on the law of cooling, but there is evidence that the work started rather earlier [13].

FOURIER, 1807

Newton dealt with what we would now call forced convection. The problem of conduction inside a solid was not tackled until much later.

Fourier's article of 1807 [14] was not published and made generally available at the time, but since it was the first version of his theory there is interest in referring to it. Also, although it is very similar to the published version of 1822 [15], it is in places shorter and more simply expressed. For example, rather than assuming an arbitrary change of the dimensions of the prism conducting the heat, he says suppose the prism were half as long. The 1822 version has a long philosophical introduction that does not relate very well to the rest of the work. An English translation of the 1822 article is also available [16].

A number of well-known scientists were interested in the topic of heat transfer in solids at this time. The problem they had in making any progress was that their starting point was always Newton's statement that the heat flow rate was proportional to the temperature difference. Although nothing in Newton's article suggested that this principle could be applied to heat conduction within a solid body (he clearly was talking about convection from the exterior surface of the body to the surrounding air), they assumed that it applied equally to conduction within the solid body. For example, Laplace, in 1808 (page 78 of [17]) states (translated) "This principle, given by Newton, shows that the heat communicated by one body to another contiguous body is proportional to the difference in their temperatures."

Fourier's breakthrough came in recognizing that it was temperature gradient that mattered in conduction, and in clearly distinguishing between what was happening inside the body and what was happening outside. In the extracts that follow we have used Fourier's word "conductibility," although it may not be in general use in either in French or English, to emphasize the confusion that existed prior to his work.

Fourier's complete article [14] is long, a book rather than an article. He defines temperature, heat, and specific heat much as one might in a practical manner these days. Temperature is based on expansion of liquid in a thermometer (he recognizes the anomalous expansion of water). We now give some extracts. The translation is by the present author.

Section 16. On the external conductibility (*i.e., convective heat transfer coefficient*) and on the transfer of heat.

Let us suppose that a body with a plane surface of a certain extent (a square decimeter) is somehow maintained so that all points of the surface are at a constant temperature 1, and the surface is in contact with air at zero temperature, or placed in a vacuum. The heat which flows continuously through the surface and passes into the surroundings will be constantly replaced by the heat which keeps the temperature of the body constant. The quantity of heat passing through the surface, in a specified time, is continuous and always the same. The quantity of heat passing through a unit area for a fixed temperature gives us an exact measure of the external conductibility, i.e., the facility with which the surface transfers heat to the air, or allows heat to escape into the vacuum. The value of the quantity of heat which is dissipated through the surface is influenced by various factors.

The value is influenced by the spontaneous radiation from the surface and by the heat which is given to the air. We suppose that the air is continuously replaced with a constant, known velocity. If the speed of the current increases, the part of the heat that is given to the air also increases; the effect would be the same if the density of the medium increased. If the constant excess temperature of the body over that of the air and the surroundings, which we expressed by 1, changed to a smaller value, the amount of heat flowing would diminish as well. Observations made by Newton and several other physicists show that this quantity of heat dissipated is, everything else being the same, proportional to the excess of temperature of the body over that of the air and the surroundings. Each of the two constituent parts, the amount given to the air and that radiated from all points of the surface, is separately and without measurable error proportional to this excess of temperature.

So, designating the amount of heat that is dissipated through the surface in a given time when the heated surface is at a temperature 1 and the surroundings are at a temperature 0 by h, we can conclude that this quantity would have the value hz if the temperature of the surface was z, all other circumstances being unchanged.

The value h of the quantity of heat that is dissipated through a heated surface is different for different bodies, and varies for a given surface according to the circumstances. The effect of radiation reduces as the surface is more polished; if the polished finish is removed, one increases considerably the value of h. For example, a heated metallic body will cool much more quickly if one covers its outer surface with a black coating able to completely dull the metallic shine. One obtains a similar effect by applying various coverings to the surface. The quantity h seems to have values little different for different metals with polished surfaces, other factors staying the same.

The rays of heat which escape from the surface of a body are transmitted across spaces empty of air, to reach colder bodies. These rays also penetrate atmospheric air and travel through it without heating it measurably; their direction is not affected by movement of the intermediate air; they can be reflected and join together at the focus of a metallic mirror.

When the heated body is placed in still air at a temperature 0, the heat, which is communicated to the air, makes the layer of this fluid next to the surface lighter. This layer rises faster as it receives more heat and is replaced by an equal mass of air at the temperature 0. A current of air is thus established. Its direction is vertical and its speed increases as the temperature of the body increases. This is why, if the body cools progressively, the velocity of the current diminishes with the temperature, and the law of cooling is not the same as when the body is exposed to a current of air at constant velocity, which is the assumption throughout this article.

The value h of the quantity of heat lost by the surface is proportional to the extent of the surface. This quantity varies also according to the nature of the fluid environment. The rate of cooling of a body plunged into a liquid is much faster than if the medium was a gas, but it is not controlled by the ratio of the densities, in fact the quantity of heat dissipated is different for different gases.

We take for the measure of the external conductibility *(i.e., convective heat transfer coefficient)* of a solid body a coefficient h expressing the quantity of heat that passes during a specified time (1 minute) from the surface of this body into atmospheric air, assuming that the surface has a specified area (1 square decimeter), that the temperature of the body is 1, that of the air is 0, and that the heated surface is exposed to a current of air of specified and constant velocity.

We note that there is a complete, quantitative definition of heat transfer coefficient. A curious feature is that Fourier, writing in French, uses h as the symbol for heat transfer coefficient. Certainly this is sufficient reason for modern usage of the symbol h. If it was good enough for Fourier, it is good enough for the rest of us.

There is explicit reference to Newton (though this does not appear in the 1822 version). The article is correct in that Newton's law of cooling applies in forced convection and explains why in very similar terms to Newton's article, so obviously Fourier was familiar with Newton's work. The main extension to Newton's law of cooling is that Fourier has written it down as an equation, has assumed that heat loss is proportional to surface area, and has defined the constant of proportionality. There is a surprisingly good qualitative account of natural convection and an explanation of why Newton's law does not hold in this case. There is a good account of several aspects of radiation heat transfer. The only incorrect point is in assuming that radiation follows the same law, i.e., is proportional to temperature difference. This last mistake is not surprising. If one considers just black-body radiation over the range 0 to 100°C (with surroundings at 0°C), the deviation from exact proportionality in the heat transfer coefficient is only 20% and experimentally Fourier and other workers of the time would be trying to detect this against possibly a larger forced-convection contribution. The problem is the same as that faced by Newton—how to measure very high temperatures. Without some method of doing this, the law of radiation heat transfer was unlikely to be discovered.

In the following extract Fourier considers what happens inside the solid body. The figures have been redrawn. The original figures (which have no captions) combine the geometric representation of the body with a graph of the temperature distribution in a manner that seemed confusing.

Section 17. On the interior conductibility (*i.e., thermal conductivity*). Note on the uniform flow of heat.

Solid substances differ again by the property they have of being more or less permeable to heat; this quality is their intrinsic conductibility (*thermal conductivity*). To define this and have an exact measure, consider the following question which relates to the uniform flow of heat.

Suppose that a solid prism of a certain material has an unspecified length and that the section perpendicular to the axis has a specified area (a square decimeter). All points at one end of the prism, section a, under a continuing action, are kept at a temperature 1. All points at the other end, section A, are kept at a temperature 0. The distance aA is given (1 decimeter). We ignore the heat which is dissipated through

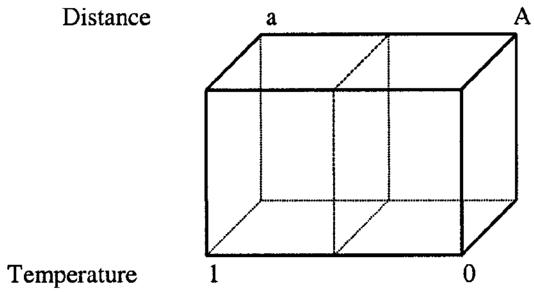

Figure 2 Heat conduction between the two end surfaces of a prism.

the exterior surface of the part of the solid area between the two sections a and A, i.e., we suppose there is no loss of heat through this surface (see Figure 2).

With the problem defined as above, a flow of heat will arise from a to A which will traverse the entire length of the prism. This flow of heat, which will change during the first moments, will tend continuously to a uniform and permanent state. If this last state was formed initially, then it would continue unchanged. Now it is easy to see that in this permanent state the temperature must decrease linearly from 1 to 0. Suppose that the prism were divided into an infinite number of equal slices by planes perpendicular to the axis, and that temperatures had been assigned to these different slices such that the excess of temperature of each slice over the following slice was the same throughout the extent of the prism for any two consecutive slices, then the system of temperatures would experience no change. Now the quantity of heat that passes from one section of matter to another depends (other factors being constant) on the excess of temperature of the first body over the second; so if the slices of the same prism have all the same thickness, and in addition the difference of temperature between two consecutive slices is constant, each of these slices will communicate as much heat to the one that follows as it itself receives from the preceding slice; so the prism will conserve its present state.

If one changed the nature of the prism, keeping all the dimensions and the distance between the two sections the same; if one replaced, for example, copper by iron, the effect just described would be different. The temperatures of the intermediate sections would be the same as in the previous case, but the quantity of heat flowing, in a given time, between two slices, would be different. The interior conductibility of each of the two substances (iron and copper) would be exactly represented by the amount of heat that flows, in a given time, in each of the two cases (see Figure 3).

Suppose now we have a second prism of the same material as the first, whose length ax is half the length aA, with still a constant temperature 1 at section a, still of area 1 square decimeter, but the temperature at x is now 0. The distance ax is $\frac{1}{2}$ decimeter. Imagine that this new prism is divided into an infinite number of equal slices that have the same thickness as in the first prism. The difference of temperature between two neighboring slices will still be the same throughout the length of the solid, once the temperatures have become steady; from which one can easily conclude that it will be double that which it was in the first prism, for the temperatures are represented in the first case by the ordinates of the straight line 1 and in the second case by the ordinates of the straight line 2. Therefore if one compares two neighboring slices of the second prism with two neighboring slices of the first prism, these four slices all have the same thickness; but the two systems differ in that the excess of temperature is twice as large for the second as for the first, so the quantity of heat transmitted, which is, everything else being equal, independent of the absolute temperatures and proportional to the excess of temperature of one body over the other, will also be twice as large in the second prism as it is in the first. In general, to compare the quantities of heat which flow, under steady conditions, in different prisms of the same substance, it is necessary to suppose that two consecutive slices have the same thickness in both systems, and compare the excess of temperature. The ratio of these differences is that of the quantities of heat flowing in a given time. A result of this is that the quantity of heat that crosses a given section of a prism, during a given time, does not depend solely on the excess of temperature of the two extreme surfaces, but also on the distance at which these two surfaces are placed. The quantity of heat flowing becomes double, triple, quadruple, etc., when the excess of temperature of the extreme surfaces becomes double, triple, quadruple, etc. It is, all the dimensions staying the same, in direct proportion

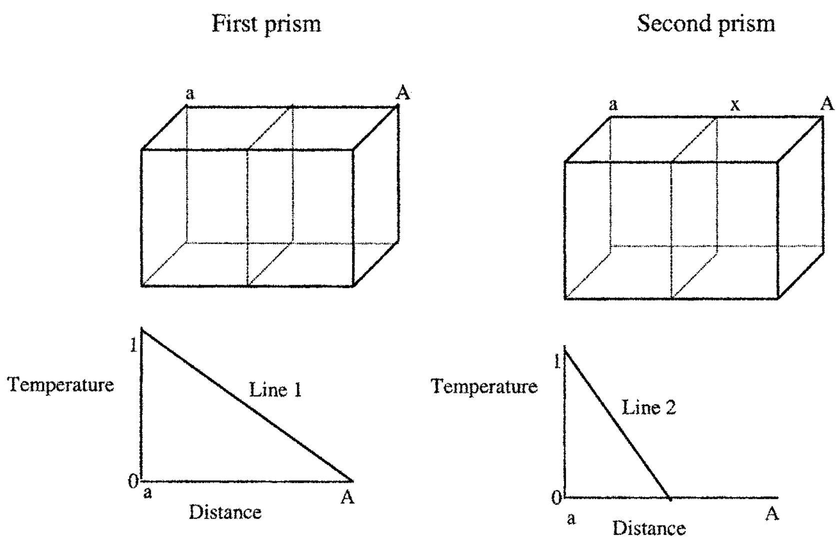

Figure 3 Effect of halving the length of prism over which the temperature drops from 1 to 0.

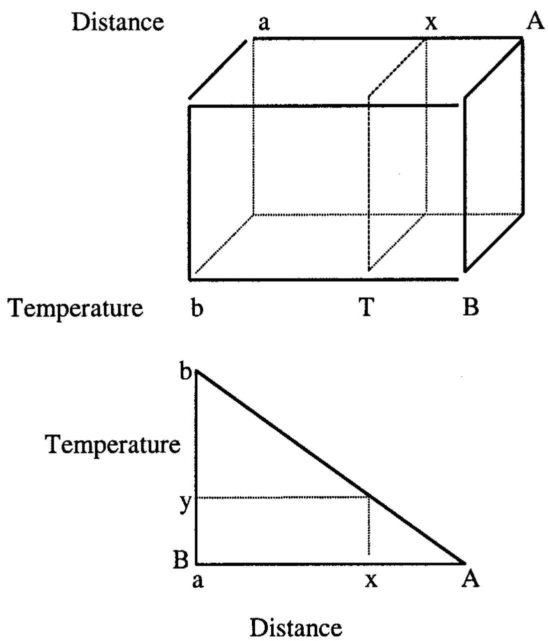

Figure 4 Generalization of the effect, leading to the definition of thermal conductivity.

to the difference of the temperatures. The quantity of heat flowing becomes double, triple, quadruple, etc., when the gap between the two surfaces becomes twice, three times, four times smaller; it is in inverse proportion to the separation of the surfaces.

When the temperatures of the different slices of the prism have become steady they are proportional to the ordinates of a straight line, and the quantity of heat flowing is represented by the slope of this line (see Figure 4). If one denotes by a the perpendicular distance from the first section to the origin, by b the temperature of this section, by A the abscissa that corresponds to the opposite section, and by B the temperature of this section, and finally by T the steady temperature of an intermediate section which corresponds to the abscissa x, the system of steady temperatures will be represented by the equation

$$T = b + (x - a)\frac{(B - b)}{(A - a)}$$

The quantity of heat that flows in a given time through a certain section of the prism is given by the expression

$$-K\left[\frac{B-b}{A-a}\right] \quad \text{or} \quad -K\,\frac{\Delta T}{\Delta x}$$

in denoting the differences by Δ, and K being a constant coefficient. If one supposes $b = 1$ and $B = 0$, and if $A - a$, or Δx, is unit length, the quantity of heat flowing will be expressed by the coefficient K.

This coefficient is the true measure of the interior conductibility *(thermal conductivity)* of a substance; it represents the quantity of heat flowing in a steady state in a given time (1 minute) across a prism formed of this substance, when the two extreme sections of a square decimeter in area and separated by 1 decimeter are maintained at fixed temperatures of 1 and 0, the exterior surface of the prism being impermeable to heat.

It is perhaps unnecessary to repeat Fourier's argument, but one could summarize it as follows. He considers the flow of heat along a uniform-cross-section bar and imagines the bar to be divided into slices of equal thickness. He assumes:

1. Heat flow rate from one slice to the next to be proportional to the temperature difference ΔT between them
2. Steady state

Assumption 1 is taken directly from Newton (but Newton was talking about convection from the solid surface and never considered what happened inside the solid). Only temperature difference matters, not the absolute temperature level. The Fourier law follows directly, as illustrated in Figure 5.

We now consider the case where the distance is reduced to one-half of the previous value, i.e., the surfaces at 1 and 0 temperature are separated by half the distance. The thickness of the slices is the same. The temperature difference across each pair of adjacent slices is doubled. So the heat flow rate is doubled (Newton). The conclusion is that the heat flow rate depends on $\Delta T/\Delta x$.

The treatment in the 1822 article is similar, but Fourier has decided to adopt modern basic SI units (somewhat ahead of the United States) and so talks about a unit length of 1 m and a unit area of 1 m^2.

A short while later, in the 1807 article, Fourier introduces the local heat flow rate as being proportional to dT/dy and goes on to give the solution for a uniform-cross-section bar losing heat by convection from the sides. Later he gives a whole range of solutions, including transient conduction and the general differential form of the heat conduction equation. For some of these solutions he had to invent Fourier series. Looking through the entire work is a rather sobering experience. It is a remarkable intellectual achievement and one has the superficial impression that it could be republished as

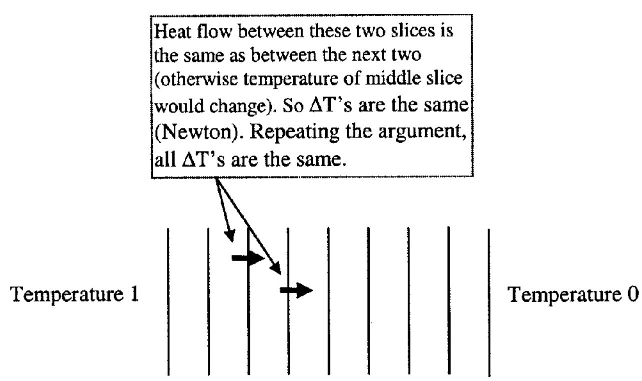

Figure 5 A summary of Fourier's argument for the steady state in plane geometry. With all the ΔT's the same, the temperature variation must be linear.

a modern textbook on heat conduction and that little had been achieved in analytical treatment of heat conduction between Fourier's work and Carslaw and Jaegers' book in 1947 [18].

THE CONTRIBUTION OF BIOT

A last point to consider is the contribution of Biot, since there have been claims that he should be credited with the Fourier heat conduction law. Biot published an article on heat transfer at much the same time [19]. The article deals mainly with experimental measurements of temperature along a bar heated at one end. He used an iron bar around 2.2 m long and 30 mm thick. It was curved at one end over a 230-mm length to allow it to be plunged into a constant-temperature pool of mercury at 82° Réaumur (the Réaumur scale had ice melting at 0°R and water boiling at 80°R). Holes were drilled in the bar at 100-mm intervals, filled with mercury to ensure good contact, and thermometers inserted. Steady temperatures were reached after 4 h and measurements taken after 5 h. The thermometers at the farther end of the bar showed no significant temperature rise.

The results, for the excess of bar temperature over ambient temperature, are shown in Figure 6, along with the exponential law that Biot fitted to the data. Biot did not give this graph in his article; instead, he gave a table of the data. The exponential law was fitted to the second and fourth readings. In his table he shows that the other readings fit the exponential law to within 0.5°. In Figure 6, a log scale is used for temperature which has the advantage that the exponential law appears as a straight line; it also reveals that the data are systematically deviating from the law at large distances. Biot ignored this and used the exponential law to work out what the temperature of the heat source would have to be in order to get a 1° increase in temperature at the farthest thermocouple position. He calculated that the source would have to be at 23,984° Réaumur (i.e., 29,980°C). This result, and his general statement that it was impossible for the heat to reach the far end of the bar, did not help his credibility.

Biot's exponential law, temperature $T = yC_1^{-x}$, with y and C_1 constants and x distance, is the same as Fourier derives for an infinitely long bar ($T = C_2e^{-mx}$), but Biot gives no derivation. Although there is some qualitative discussion of some of the heat passing down the bar and some being lost to the surroundings, he basically states that the data follow the law without analysis.

The contrast with the contemporary Fourier article could not be more glaring. Biot's article is very short and has no analysis in the form of equations. Fourier's article could pass as a modern textbook on conduction heat transfer. Fourier's analysis (for a square bar) proves that the parameter m in $T = C_2e^{-mx}$ is equal to

$$\sqrt{\frac{2h}{KL}}$$

where $2L$ is the thickness of the bar.

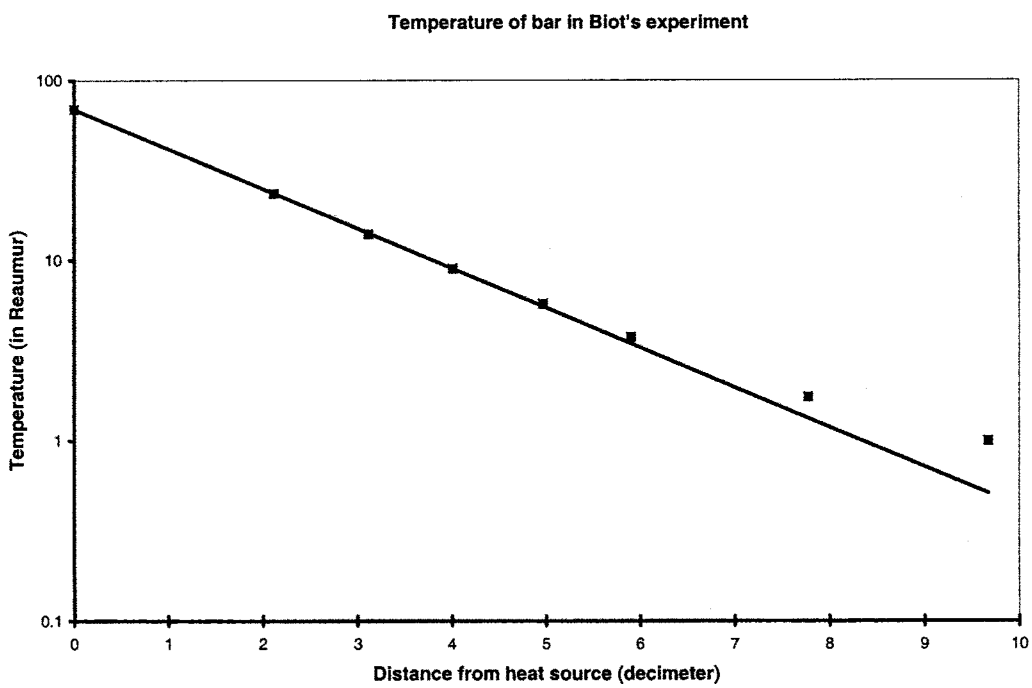

Figure 6 Biot's experimental results for the temperature variation along the iron bar, together with an exponential law (solid line) fitted to the data.

As far as Biot was concerned, m would be little more than a constant fitted to the results. Fourier's theory, applied to a finite bar, would give a much closer fit to the data in Figure 6.

Some years later, Biot wrote a textbook on physics [20]. The section on heat transfer does not go much beyond his earlier article. Again there is very little theory or analysis. If he wanted to prove that he had discovered the law of heat conduction, he would certainly have included the material in this textbook. Not only does he not do this, he refers to Fourier as the person who has made advances in the field.

Part of the confusion results from criticism of Fourier at the time. Such a major body of novel analysis was bound to excite some objections, many of them mathematical. Not only Biot but Lagrange and Laplace were unhappy about aspects of the work. However, their criticism was more to the effect that aspects of the work were wrong than that they themselves had thought of it first. No one now takes these criticisms seriously. Details are given in [14] and [17].

In conclusion, Fourier was the first to distinguish clearly between what was happening inside the solid (conduction) and what was happening outside (convection). He deserves credit as the originator of the heat transfer coefficient, h. He was the first to state that conduction depends on temperature gradient (the Fourier law) and not on temperature difference as such. Although it was not discussed in detail in this article, he originated most of what now exists as heat conduction theory.

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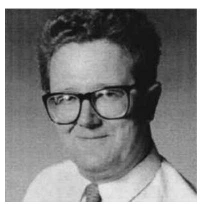

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