Where heat goes

Where heat goes

- Conduction
  - from inside power device, to case, then heat sink
  - from packaged IC through traces and laminate
  - from board through connectors and supports to backplane and case
- Convection
  - component heat sink, with or without local fan
  - heat within entire enclosure redistributed, and partially removed to the outside, by using fans
- Radiation
  - usually not a major contributor to heat loss, unless system at elevated temperature

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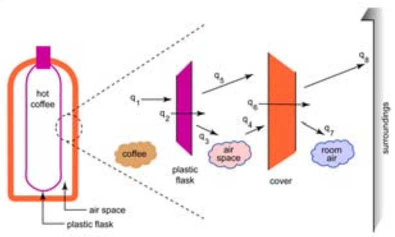
We've looked at where heat comes from: now we need to consider where the heat is going. There are only three basic ways in which heat is going to be removed from the active areas to the ambient, by conduction, by convection and by radiation. We have already looked implicitly at conduction when considering the paths within the solid body of a component. Typically the device is going to be coupled in some way through its case to the heat sink and through to the board, through both the copper and the laminate. Conduction also occurs from the board through connections and supports to the back plane and case. These are physical connections, and with many military and some high power products there is considerable focus on improving the conductivity of the structure because this is a very effective way of getting heat out.

Heat also moves by convection, a term that is used for transfer through a fluid medium. For most applications the fluid is air, which transports heat absorbed from components, either using natural convection – which is movement generated by heated air being less dense than cold air, and creating movement – or using local fans. Within the entire enclosure, heat generated by components and board will be redistributed and partially removed to the outside, also by using fans.

The third general way in which heat is moved is radiation, but this is not usually a major contributor to heat transfer – unless a system is running very hot indeed, this is unlikely to contribute more than 10% of the total heat loss.

Pathways for heat transfer



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after Incropera and DeWitt, *Fundamentals of Heat and Mass Transfer*

We've looked at conduction, convection and radiation as three modes of heat transfer, but in most cases there is more than just the one mode. To take a simple example of this, we have here a flask of hot coffee which, as you know, will be losing quite a lot of heat. Some of this transfer will be by radiation, some by conduction, and some by convection.

For the coffee there are a number of pathways for heat transfer:

- Free convection from the coffee to the inner surface of the flask;
- Conduction through the flask
- Free convection from the flask to the surrounding air held within the plastic cover
- Free convection from the air to the cover
- Net radiation between the outer surface of the flask and the inner surface of the cover
- Conduction through the cover
- Free convection from the cover to the air in the room, and finally
- Net radiation exchange between the outer surface of the cover and the surroundings.

We can't do much about the first of these, but we can modify the materials and the design in order to minimise them as far as possible. You will remember that, in the original Dewar flask, instead of air the space between the two flasks was actually filled, if that's the right term, with vacuum to reduce the conductivity.

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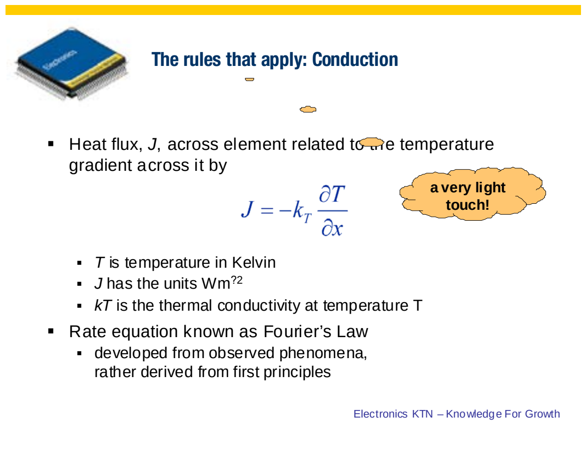
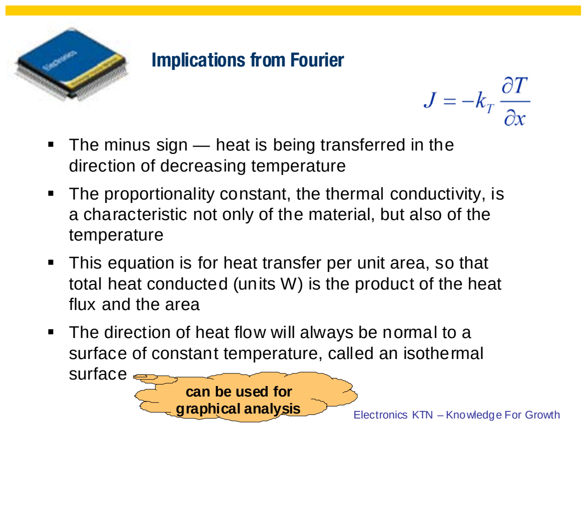
Where heat goes



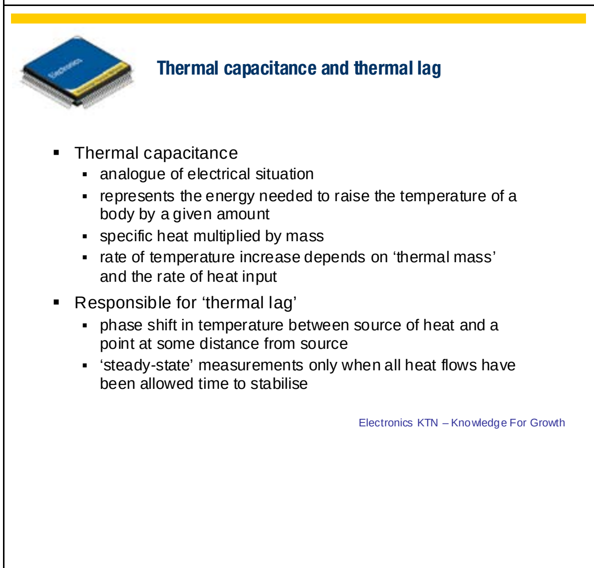
All three of these heat transfer mechanisms have associated rules. We are looking at this with a very light touch, and keeping the mathematics to a minimum, but it is important to understand where certain equations came from, and what their meaning is.

The rate of heat flow, to which we referred as the heat flux, conducted through any element is related to the temperature gradient by the rate equation known as Fourier's Law. This law is interesting in that it was developed from the observation that the amount of heat transferred depended on the rate of temperature difference, rather than derived from first principles.



We can draw some useful conclusions from the equation. First of all the minus sign, which indicates that heat is being transferred in the direction of decreasing temperature or, in other words, it is going from a hotter to a cooler place. The K_T figure, the proportionality, is a characteristic of the conductive material, but note that it is a function of the temperature, and not constant. And both the heat flux and the proportionality constant are per unit area, so that the resultant is the thermal flux, or the density of heat transfer.

The equation can of course be developed into a partial differential equation in two or three dimensions, when it tells us that the direction of heat flow will always be normal to a surface of constant temperature. This is referred to as "isothermal surface", and this concept can be used for graphical analysis – draw the isotherms, and you have an illustration of the direction of heat flow.



Of course, when heat flows, we haven't yet reached a steady state, because the body through which the heat is passing will heat up in the process. And it can take a significant time for that heat to travel along a structure. This gives rise to the idea of thermal capacitance, which is an analogue of the electrical situation, where energy is needed to raise the temperature of the body, and the amount of energy that is needed is the product of its mass and specific heat, often referred to as the "thermal mass". The rate at which the temperature rises depends both on this thermal mass and on the rate of heat input, or more correctly on the rate of net heat input, as heat will also be flowing away from the source of heat.

The fact that real bodies have a thermal mass is responsible for "thermal lag", which is a phase shift in temperature between the source of heat and any point at some distance from the source. Steady-state measurements can only be made after all heat flows have been allowed sufficient time to stabilise.

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The rules that apply: Convection
▪ Conceptually very different from conduction
  ▪ heat-transport medium a fluid rather than a solid
  ▪ gross movement of the medium is involved
  ▪ energy density in the medium very much lower than with conduction
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	So far we have looked at conduction and Fourier's Law. We now move to convection, which is conceptually very different. The medium through which heat is transported is a fluid rather than a solid, and the medium is not static. In fact, gross movement of the medium is involved, with energy-carrying parts of the medium moving through the rest to discharge their energy on cooler surfaces. Heat transfer through convection is thus very, very different from conduction and the energy densities are much lower.

The rules that apply: Convection
▪ Conceptually very different from conduction
▪ Heat transferred by convection given by
$q = hA(T_{solid} - T_{fluid})$
  ▪ *A* area across which heat transfer takes place
  ▪ *q* the heat flow (units W)
  ▪ T_{solid} and T_{fluid} the surface temperatures of the solid and the interfacial temperature
  ▪ proportionality constant *h* (units $W{\cdot}m^{-2}K^{-1}$) 'convection heat transfer coefficient'
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	The heat transferred by convection is given by Newton's Law of Cooling, expressed by an equation that relates the heat flux to the area across which heat transfer takes place, the difference in temperature between the solid and the fluid medium, and a proportionality constant *h*, referred to as the convection heat transfer coefficient.

Newton's Law of Cooling
$q = hA(T_{solid} - T_{fluid})$
▪ "Newton's Law of Cooling"
  ▪ heat flux proportional to temperature difference
▪ Heat transfer coefficient
  ▪ frequently temperature-dependent
  ▪ value of *h* dependent on many different factors:
    • thermal conductivity of fluid
    • viscosity of the fluid
    • specific heat capacity of the fluid
    • type of fluid flow (whether turbulent or laminar)
    • nature of the surface (e.g. surface roughness)
    • density of the fluid (can change with altitude)
only some can be controlled
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	So we have a heat flux that is proportional to the area, to the temperature difference, and this heat transfer coefficient. So what is *h*? A good estimate to the answer is actually around 10 in most cases, surprising as that may seem, but it does depend on a number of different factors, which make calculation quite tricky. Especially as we can only control some of these!
	
	We can do nothing about the thermal conductivity of the air, or its viscosity, or its specific heat capacity. What we can do is to change how fast the air moves and whether the air is impinging on the surface or just flowing over it. *h* also depends on the nature of the surface, which gives us the opportunity to modify aspects such as the surface roughness. Finally, while we can't do anything about the fluid density, this reminds us that what happens at sea level is very different from what happens at 20,000m or so.

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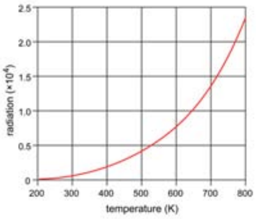
The rules that apply: Radiation

- Not a linear phenomenon
- Plot of radiated heat against surface temperature for a perfectly emitting surface



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So far we've looked at convection and conduction, with equations that are relatively linear, though some parameters are temperature-dependent. The third way in which heat is transferred is radiation and, by contrast, radiation is not a linear phenomenon. You can see this from the diagram, which is a plot against surface temperature of the heat radiated from a perfectly-emitting surface. Nothing is happening at lower temperatures, but the rate of increase is literally exponential.

The Stefan–Boltzmann law

- Most of the time bodies *exchange* radiation
- Exchange between small surface and a much larger surrounding isothermal surface
  - all the radiated power will be collected
  - none is reflected
  - net thermal energy emitted, per unit area of surface, given by

$$q = \sigma\varepsilon(T_s^4 - T_{sur}^4)$$

for most purposes radiation is relatively insignificant

  - ε is the emissivity of the radiating surface
  - σ is the Stefan-Boltzmann constant
  - T_1, T_2 absolute temperatures of each body

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Whilst not everything is a perfect emitter, everything emits radiation, the amount depending on the temperature. So most of the time heat transfer by radiation reflects the fact that the bodies exchange radiation, and the hotter body gives out more radiation than it receives from its surroundings.

Where we have a relatively small emitting surface and a much larger environment surrounding it, we can assume that all the radiated power will be collected, and that none is reflected, and derive a simplified equation for the net thermal energy emitted per unit area of surface.

The net flow of heat is given by a formula that includes the emissivity of the radiator and the Stefan–Boltzmann constant, and crucially the fourth power of the temperatures expressed in Kelvin. So radiation is something we cannot ignore at high temperatures, but for most purposes in electronics cooling it is relatively insignificant.

How excess heat can be removed

only dealt with at a surface level

- Assisting natural conduction processes:
  - local heat-sinking for suitable components
  - mounting power devices on external heat sinks
  - 'thermal vias' under hot components
  - heat sinks on underside of thermal vias
  - using thermal interface materials (TIMs) to improve heat transmission
  - adding thermally-conductive cores to laminate

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So far in this discussion we have looked at where heat comes from, and the rules that apply to its transfer. But it wouldn't be right to move to the next section without saying something about how excess heat can be removed, although we are only dealing with it at this stage at a surface level.

Broadly speaking we remove excess heat by assisting natural processes of conduction and convection. Most of these involve including more metal, making better use of thermally-conductive materials, and increasing the amount of heat removed by convection by using "extended surfaces" (which is thermal engineering speak for heat sinks).

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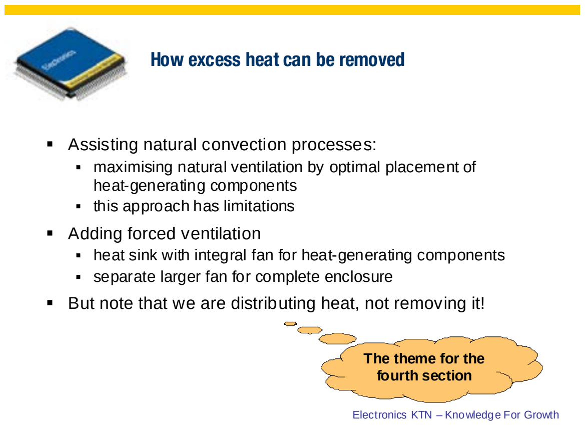
Where heat goes



We can enhance natural convection by optimising the layout of heat-generating components, but this has its limitations. More typically we will be adding forced ventilation, using heat sinks with integral fans for heat-generating components in combination with a separate larger fan for the complete enclosure. Note however that, in every case, what we're doing is not removing the heat entirely, but only improving its distribution.

Of course, in a typical thermal management situation, we will be selecting the best combination of several different approaches in order to reach an optimal solution, and this will be our theme for the fourth section.

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