Electronics Design and Manufacturing

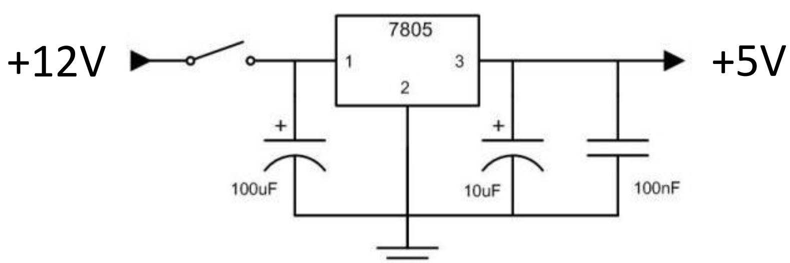
EE20194: Group Design and Professional Engineering Practice II

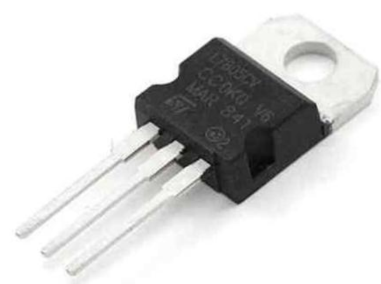
Lectures 4/6 and 5/6

Dr Robert J. Watson

Thermal design

- Assuming energy is not transformed into another form *e.g.,* light (LED) or motion (motor) *etc* - it must be dissipated as heat – it can't just disappear!
- Quick example calculation: simple voltage regulator LM7805 to convert 12V to 5V and pass 1A of current – how much power will it dissipate?





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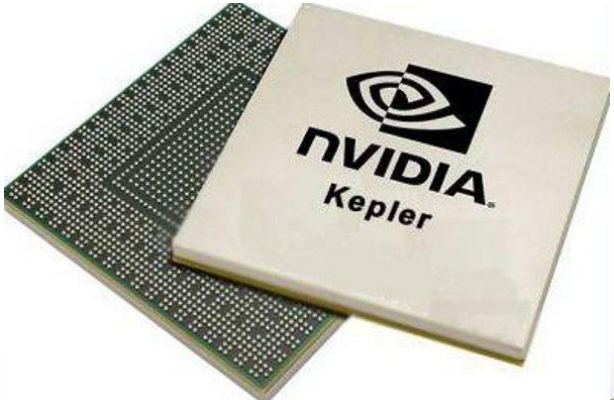
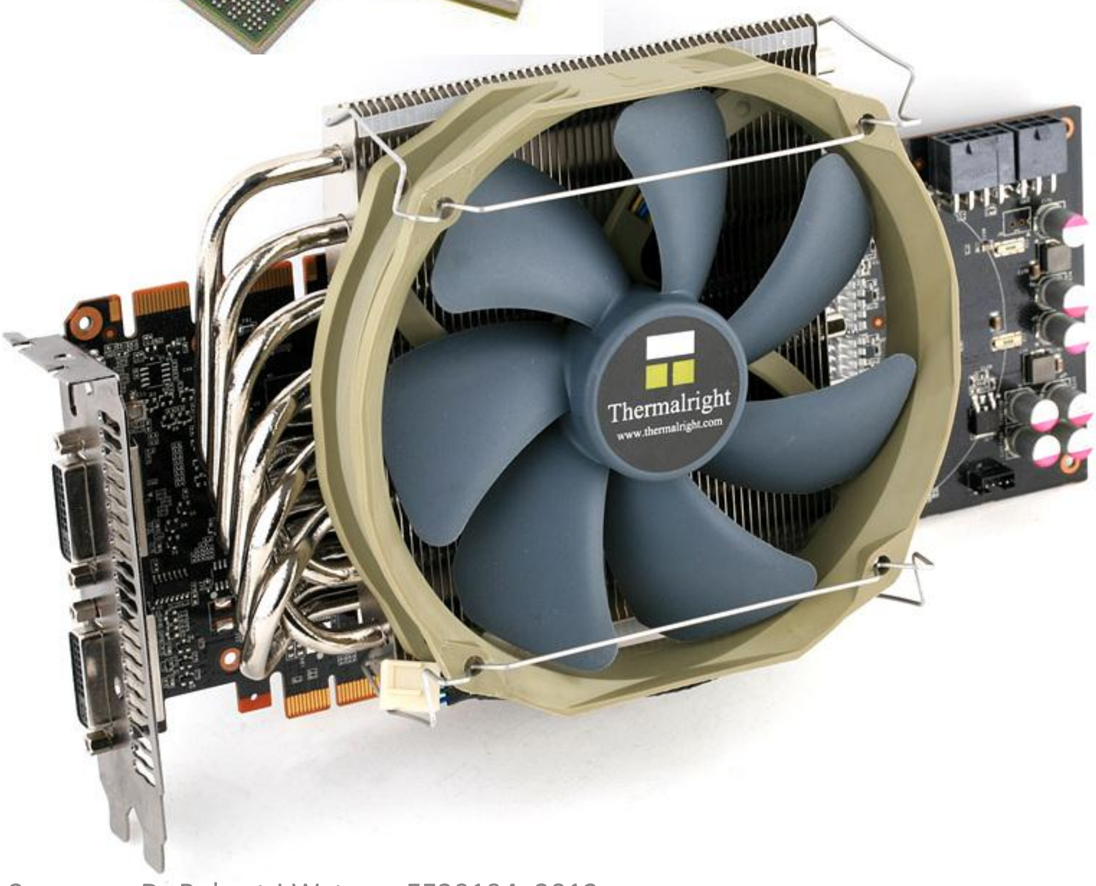
Extreme examples





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What's the problem?

- Component reliability is related to temperature
- Maximum junction temperature typically 150°C
- High junction temperatures:
  - accelerate chemical reactions
  - speed up growth of contaminants
  - thermal cycling creates micro fractures
- Rate of reactions determined by Arrhenius equation: $\lambda = Ke^{-E/kT}$ (thermally driven failure)
- Failure rate doubles for every 10°C rise in temp.

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Thermal management

- Maintain temperature at a reasonable level
  - obtain viable lifetime, reliability etc.
- Heat transfer via:
  - Conduction *e.g.,* package to heatsink
  - Convection *e.g.,* air passing over heatsink
  - Radiation *e.g.,* black anodised heatsink
- In its basic form, we can analyse problem using an electrical analogue of the thermal problem
  - which means we can use circuit theory ☺
- For complex problems need to solve heat diffusion
  - quite nasty partial differential equations ☹

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Thermal and electrical equivalence

- Heat sources = current sources
- Thermal impedance = resistors
- Thermal inertia = capacitor (often ignored)

Thermal parameter	Units	Electrical analogue	Units
Temperature difference	°C or K	Potential difference	Volts
Thermal resistance	°C/W or K/W	Resistance	Ohms
Heat flow	J/s	Current	Amps
Heat capacity	J/°C	Capacitance	Farads

- Thermal resistance of a material reflects rise in temperature (in °C or Kelvin) per Watt of power dissipated

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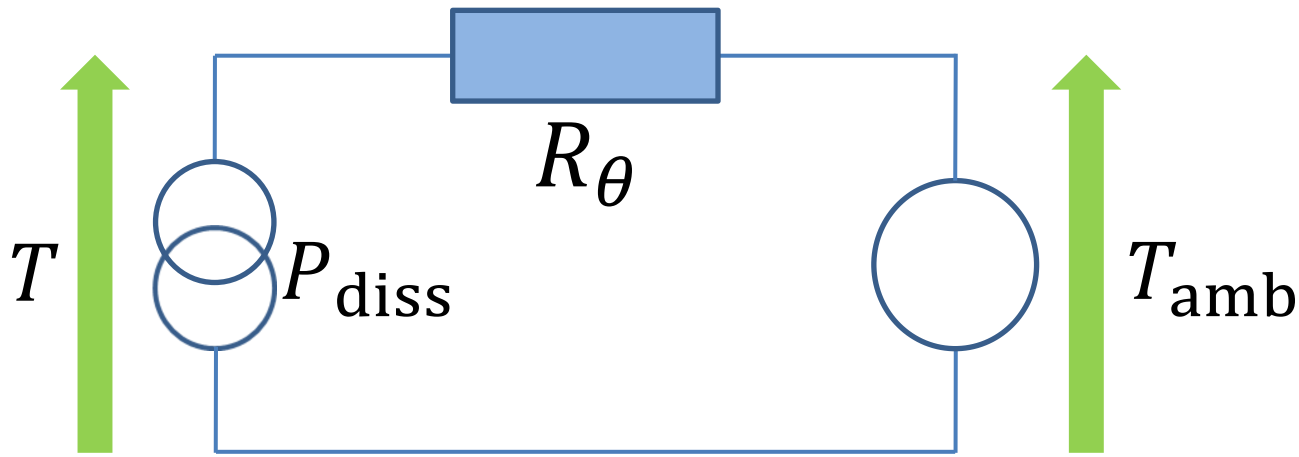
Electrical equivalent circuit

- Consider a resistor at a temperature T, dissipating a power P_{diss}. The ambient temperature is T_{amb}
- The temperature at the heat source is:

$$T = P_{\text{diss}} \times R_{\theta} + T_{\text{amb}}$$



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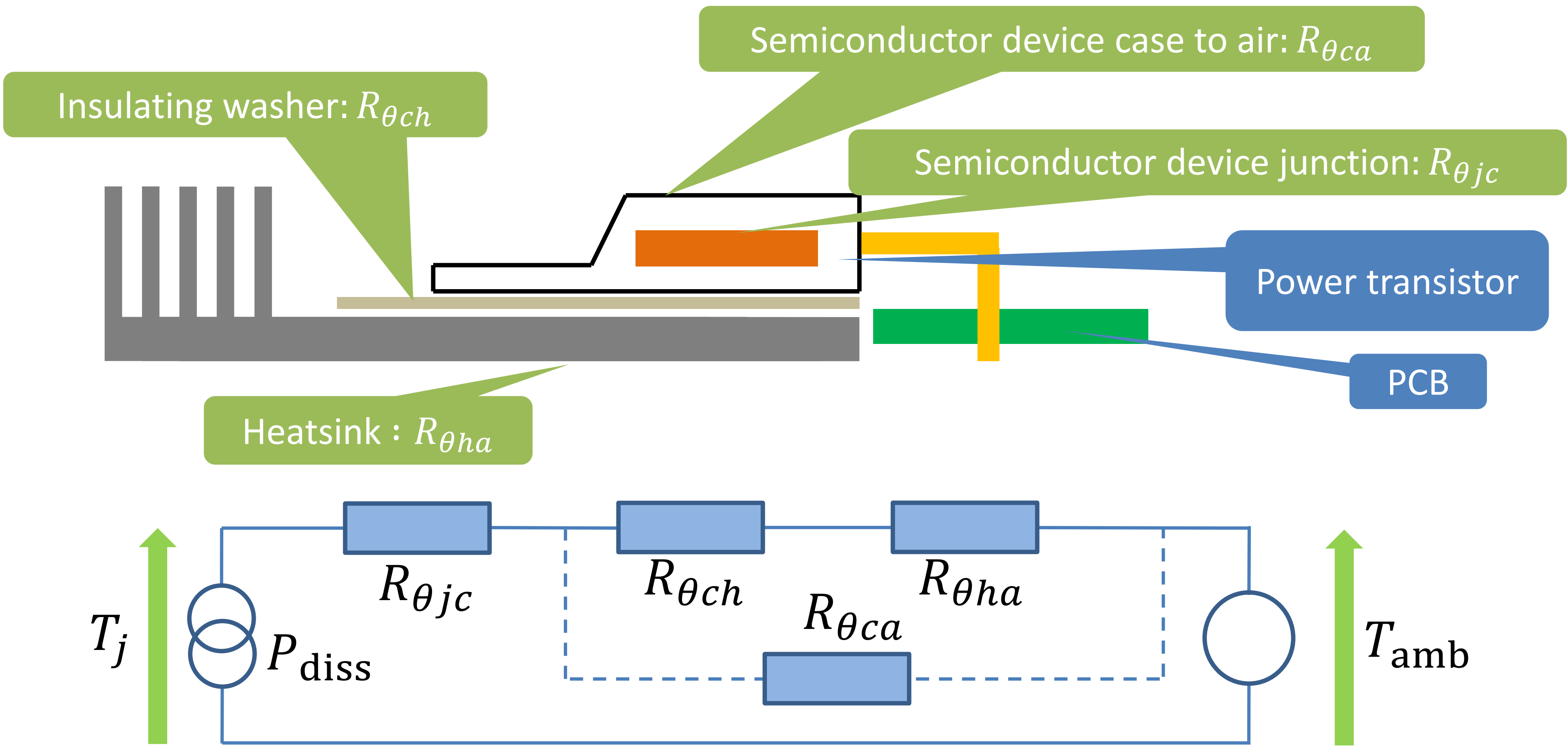
Thermal resistance example (I)

- Example: transistor on a heatsink



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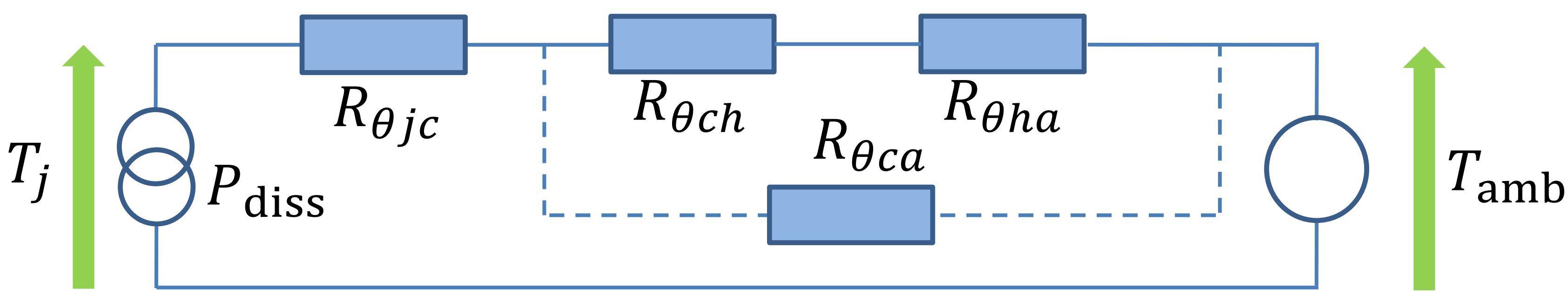
Thermal resistance example (II)

- TO-220 transistor: BD911 dissipating 9W
  - Max junction temperature: $T_{j(\max)} = 150$°C
  - Thermal resistance (junction-case): $R_{\theta jc} = 1.4$ °C/W
  - Insulating washer: $R_{\theta ch} = 2.1$°C/W
  - Heatsink SK104-38.1 (heatsink-air): $R_{\theta ha} = 11$ °C/W
  - Thermal resistance (case-air): $R_{\theta ca} \approx 60$ °C/W



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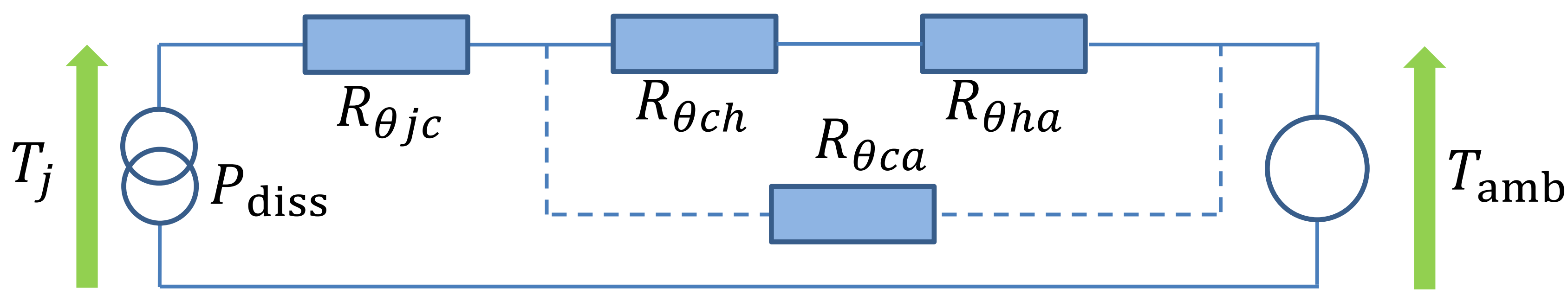
Thermal resistance example (II)

- Total thermal resistance:
  - $R_\theta = 1.4 + (2.1 + 11)||60 \approx 12.2$ °C/W
- Assuming maximum ambient: $T_{\mathrm{amb(max)}} = 40$ °C
  - If transistor dissipates 9W: $T_j = 149.8$ °C
  - This is only just OK: 149.8 °C $< T_{j(\mathrm{max})}$

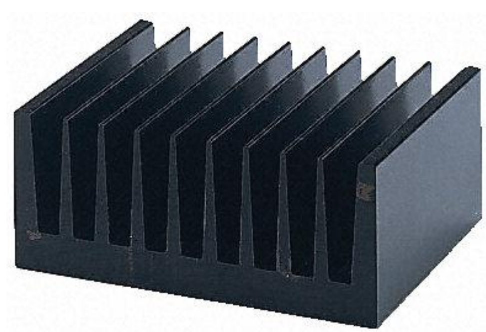


Thermal resistance example (III)

- BD911 datasheet says device can dissipate 90W!
  - How? We are already at max junction temp with 9W
  - Easy! We need a better heatsink (lower value of $R_{\theta ha}$)

$R_{\theta ha} = 11°C/W$

$R_{\theta ha} = 1°C/W$



$R_{\theta ha} = 0.1°C/W$

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Heatsinks (I)

- Strictly the ambient environment is the *sink*
  - this is usually air but could be a liquid
- What is conventionally called a heatsink is actually a *heat exchanger* (options are heat pipes, heat pumps)
- Heatsinks loose heat by convection and radiation
  - Convection efficiency: proportional to surface area
  - Radiation efficiency: depends on the surface finish
    - Matt black painted aluminium: 0.9
    - Matt black anodised aluminium : 0.8
    - Polished aluminium: 0.04

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Heatsinks (II)

- Majority of heatsinks are pressed or extruded aluminium *e.g.,*
- Enormous range of devices commercially available
  - http://www.aavidthermalloy.com/
  - http://www.fischerelektronik.de/
- Comparative bulk thermal conductivity…

Material	Thermal conductivity $\mathrm{W\,K^{-1}m^{-1}}$	Applications
Aluminium	210	Majority of heatsinks, inexpensive
Copper	380	Very expensive – heavier than Aluminium
Beryllium Oxide	300	Electrical insulator – dust is extremely toxic
Silver	430	Heavy and expensive
Diamond	30,000	Electrical insulator – very high power semis
Liquid Helium II	100,000	Cryo-cooling for Deep Space comms.

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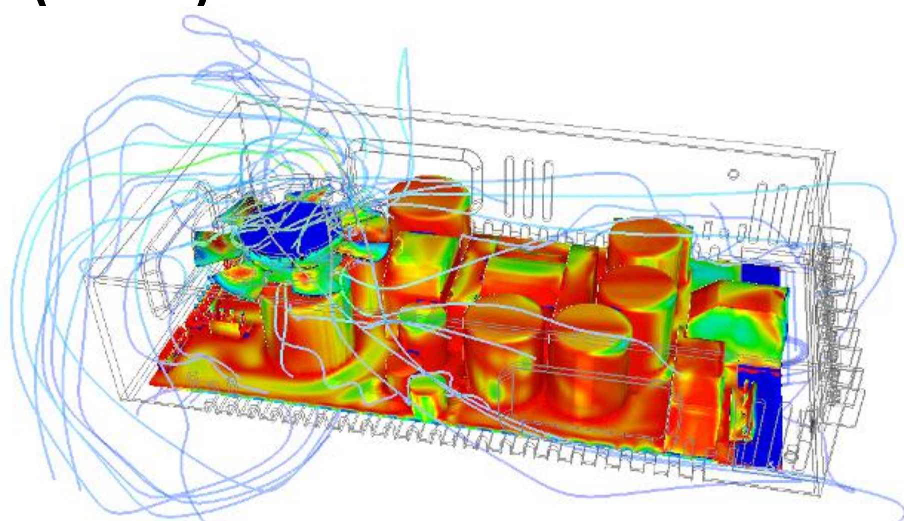
Heatsinks (III)

- Efficiency can be improved with *forced air cooling*
  – use a fan to blow air across an existing heatsink
  – radiative cooling becomes insignificant – don't need to paint/coat it black.
- Finite-element methods (CFD) often used



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Other solutions

- Quite often it’s easier to efficiently move the heat away from the device and then dump it
  - Heat exchanger (liquid-air) *e.g.,* water cooled PC. Requires a pump to circulate the fluid
  - Heat pipes (sealed tubes – transition liquid/vapour) *e.g.,* used in laptops for cooling several devices (CPU, GPU and IO device) with one heatsink
  - Heat pumps (Peltier effect) can heat AND cool *e.g.,* used to stabilise the output amplitude/wavelength of laser diodes

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Liquid cooling: Cray 1 (1976)

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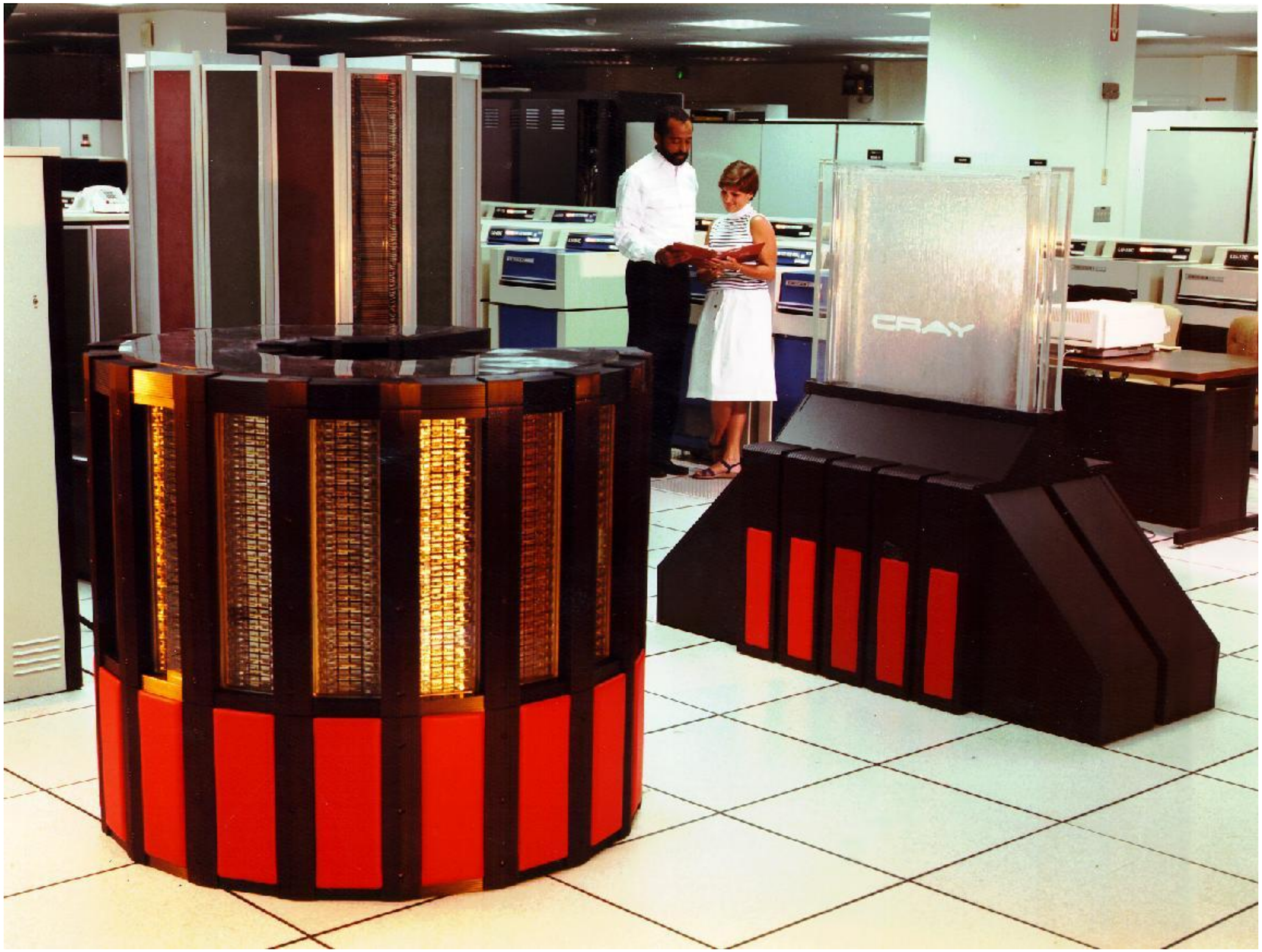
Liquid cooling: Cray 2 (1985)



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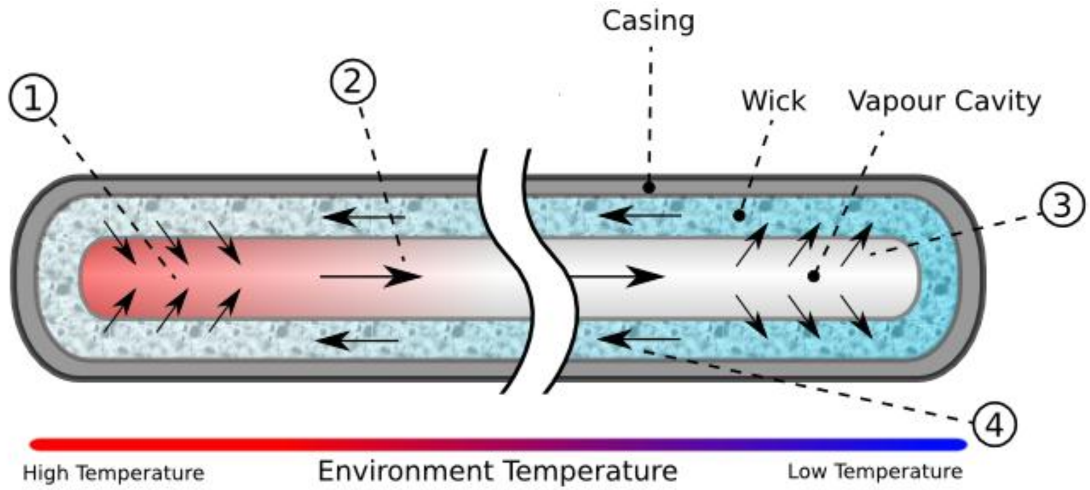
Heatpipes

- Exploit latent heat required to turn a liquid into a vapour
- Heat at the “hot” end evaporates a working fluid
- Vapour travels to the “cold” end
- Cold vapour condenses
- Fluid travels back to the “hot” end



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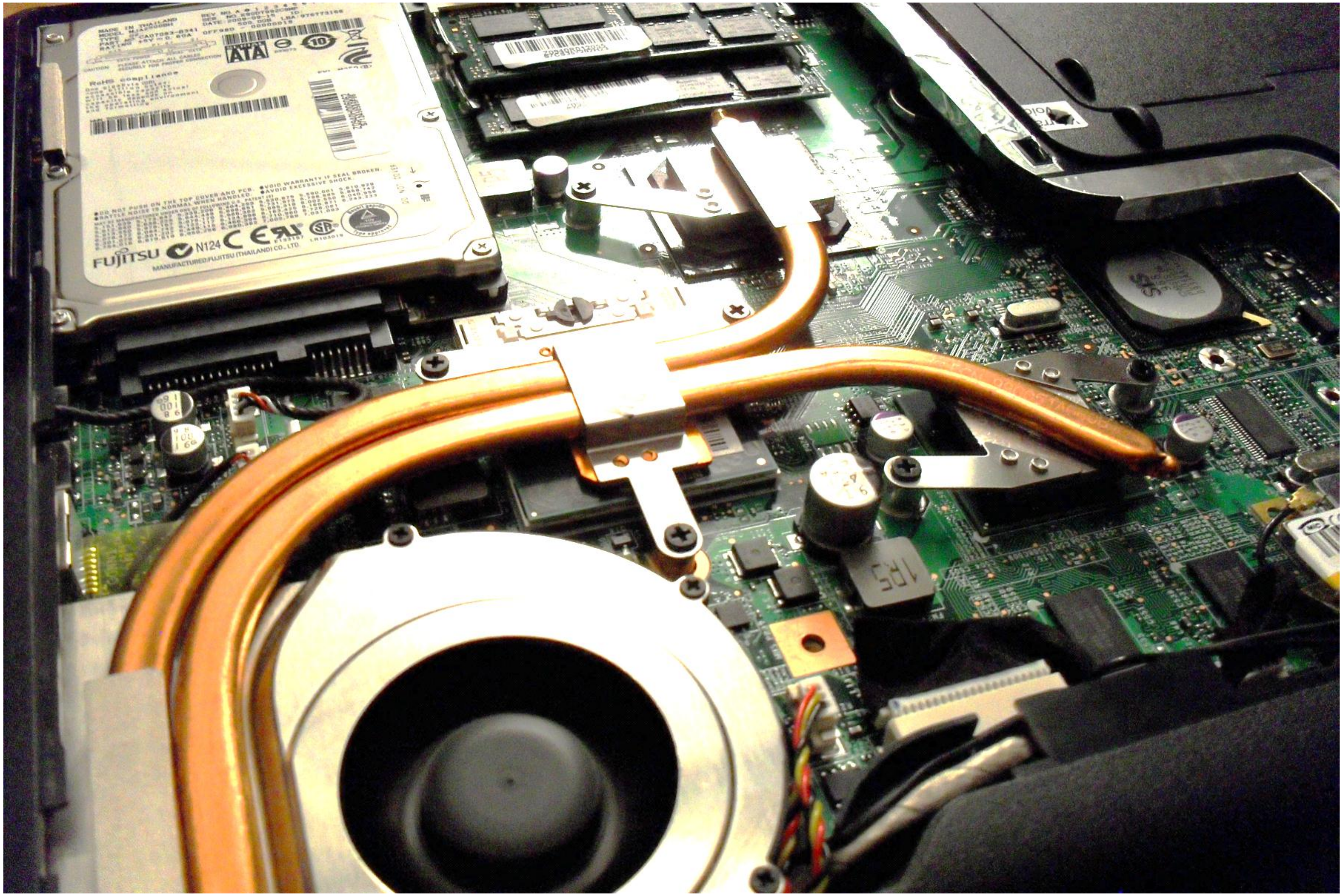
Laptop heatpipes for CPU and GPU



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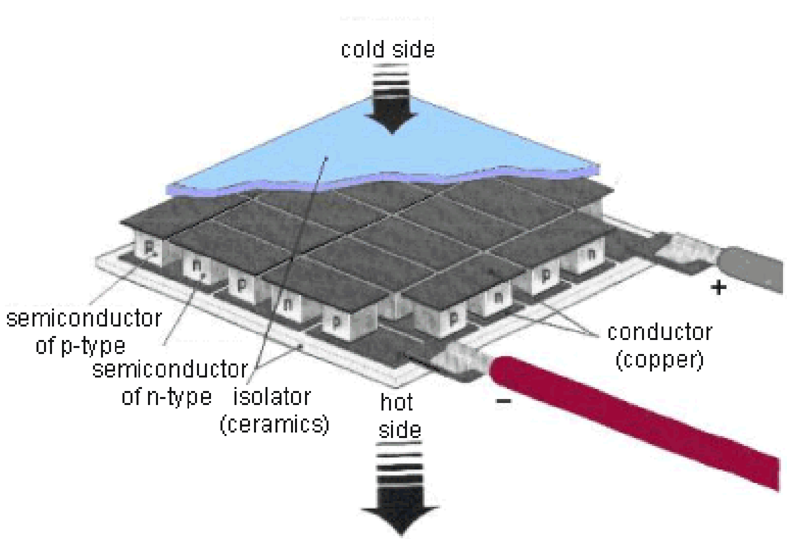
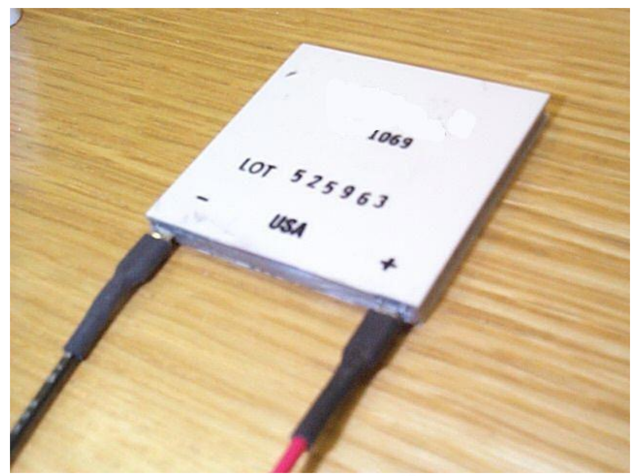
Peltier effect heat pump

- Discovered by Jean Charles Athanase Peltier (1785-1845), in 1834
- Heat pump – uses electrical energy to pump from heat from away from cold side to hot side
- Can generate electrical energy – Seebeck effect





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Summary

- Why we need to worry about heat?
- How can we calculate what size of heatsink we need?
- What other factors are important?
- What can we do if we don’t have space for a large enough heatsink?

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