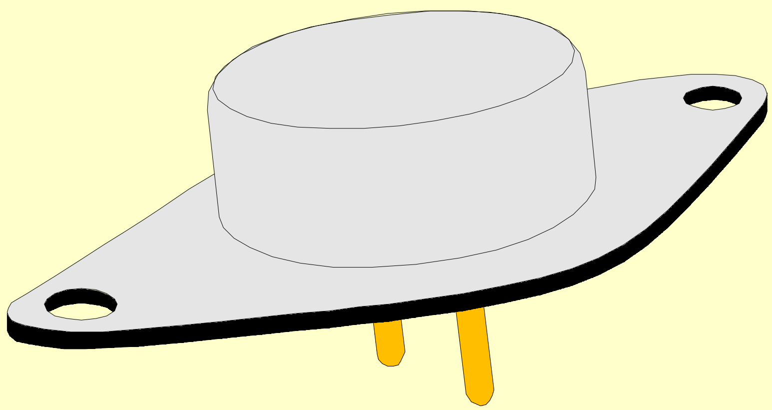
Heat Management

Heat

Our power transistors have thermal stability.
That's their heatsinks' undoubted ability.
So now let's turn up the heat
and enjoy our amplification feat.



Heat

- is generated in all operating electronic systems
- results from flow of electrons
- is energy in the form of molecular vibrations
- is measured in Joules

Heat Generation

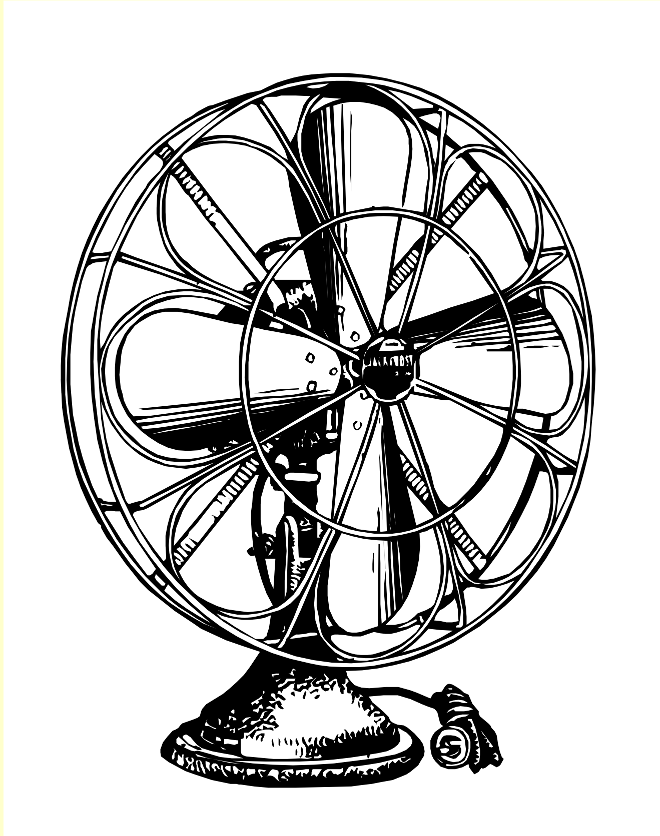
- conductor carrying electric current (P = IV)
- eddy currents in core of transformer or inductor
- currents induced in walls of wave guide by E and B fields
- dielectric of capacitor charging or discharging

Heat Transfer

- Laws of cooling
- Heat sinks and temperature calculations
- Forced Air Cooling
- Military, industrial and commercial requirements

We need to remove excess heat!

- Components are rated according to the heat they can dissipate
  - e.g. resistors rated at 1/8, 1/4. 1/2 W
- Heat must be removed from components or they will become hotter and hotter until they fail
- Cooler equipment is more reliable



ICs - a Thermal Challenge

- ICs dissipate energy internally
- Some ICs (CMOS) dissipate much less energy than other types
- The energy dissipated increases with the switching speed (dQ/dt)

conduction

- When ICs are closely packed on a PCB it is difficult to remove the heat due to this energy dissipation
- When ICs that dissipate a large amount of energy are used, liquid coolants are circulated in channels attached to one side of the ICs

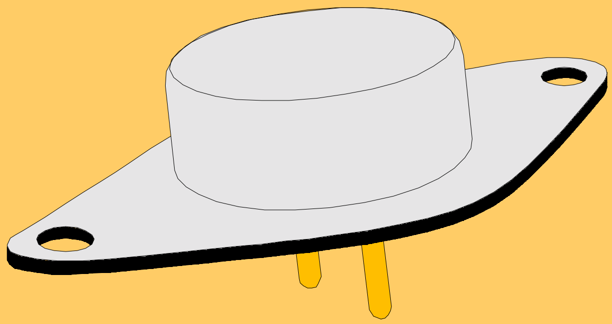
convection

Heat Transfer Mechanisms

- Conduction
- Convection
- Radiation

Heat Transfer Mechanisms

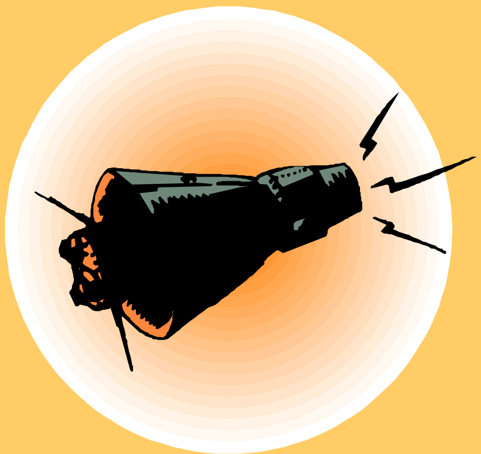
Electronic Devices



Conduction
of heat
from device to
casing & heat sink

Convection:
removal of heat
from
casing & heat sink
to surrounding air

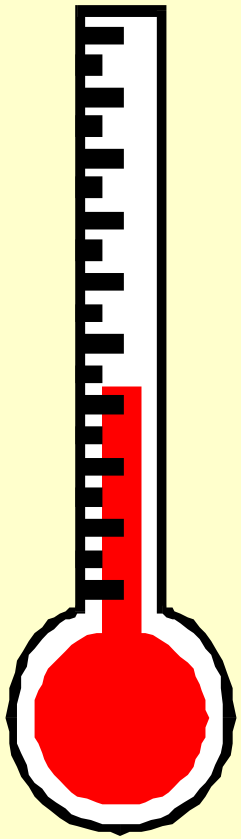
Space Travel



Radiation:
only way
heat can be lost
from craft

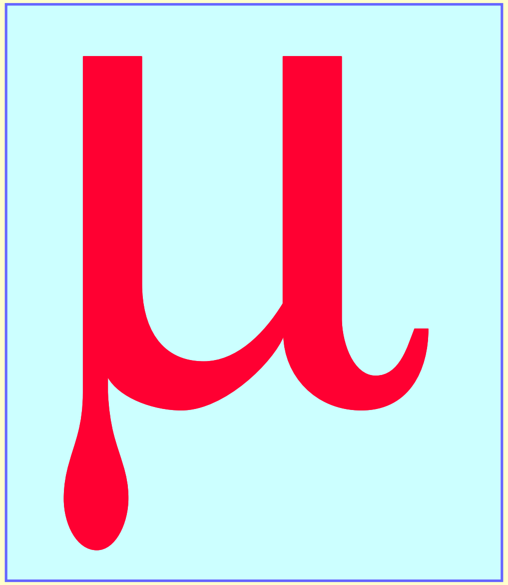
Thermal Conduction

- Important for solids such as: silicon, aluminium, copper, plastic.
- Electrical and thermal conductivity both depend on electron mobility.
  - good electrical conductors (metals) are also good thermal conductors.
  - electrical insulators are poor conductors.
- TC is the first process for removing heat from inside an electronic component.



Mobility

- **In metals the outer (free) electrons of atoms**
  - are not attached to any particular atom
  - but are free to move under influence of an applied electric field E = v/l, where V is the voltage between the ends of a wire of length l
  - The free electrons rapidly accelerate
  - but soon collide with ions of the lattice and
  - acquire an average speed - the drift velocity v_d
- **Mobility**
  - mobility = drift_velocity / electric field
  - $\mu = v_d / E$



Thermal Conduction

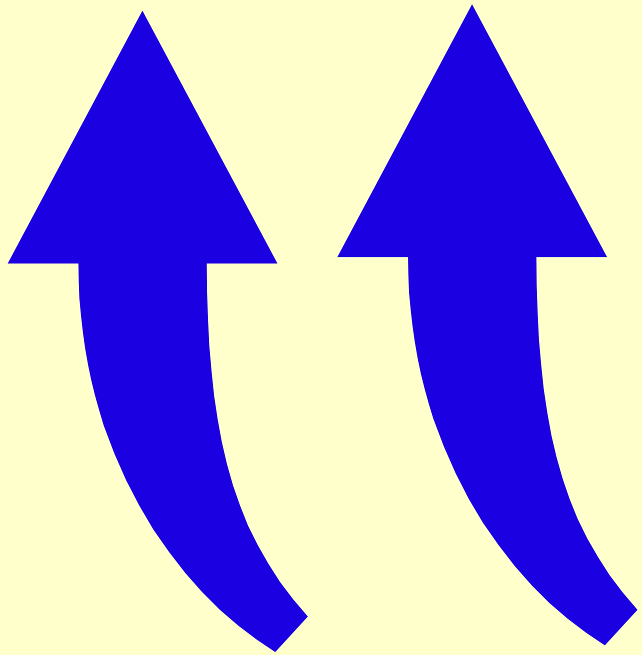
$$\frac{dQ}{dt} = -\, k\, A\, \frac{d\theta}{dx}$$

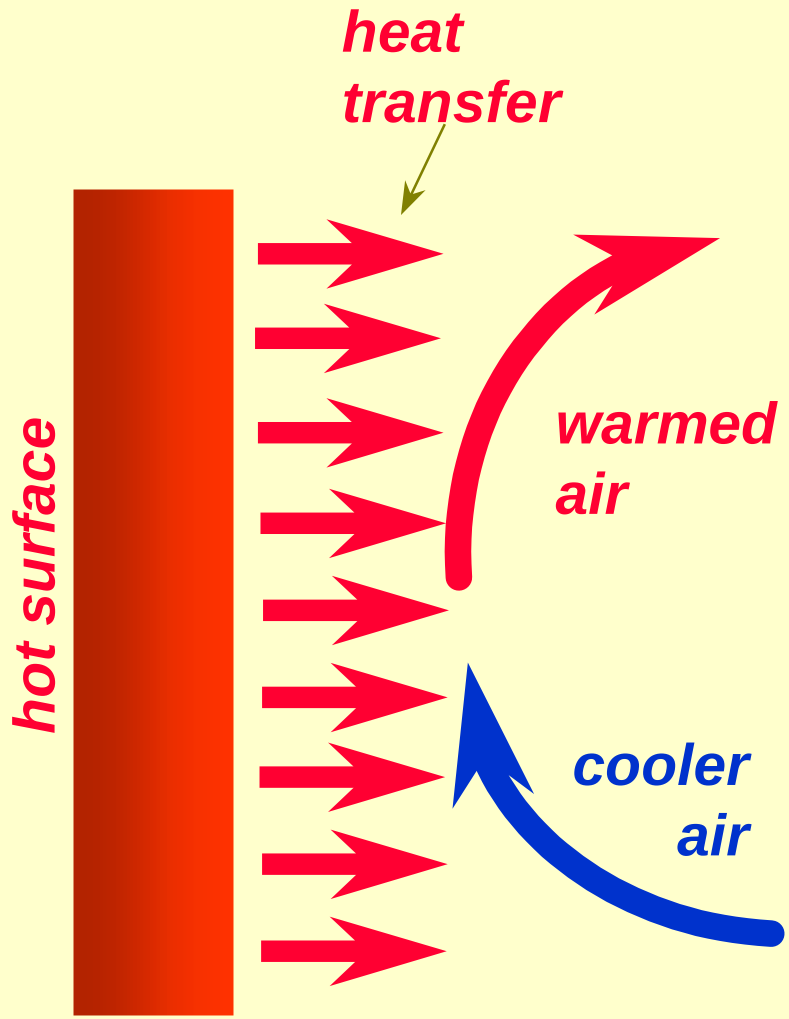
rate of heat flow (W) through X-sectional area A (m^2)

temperature gradient normal to area A ($^{O}C\ m^{-1}$)

Convection

- important heat transfer mechanism for fluids - gases and liquids
- heat transferred from most electronic systems to the surrounding air by convection





Convection

- **Cold air**
  - is heated by contact with a hot surface
- **Hot air**
  - less dense than cold air
  - hot air rises and is replaced by cold air
- **Air current**
  - is set up
  - carries the heat away

Convection is increased by:

- enlarging the hot surface
  - add fins (e.g. to heatsink)
- forcing air over the hot surface with a fan
  - forced convection

Convection

$$\frac{dQ}{dt} = -h\,A\,\Delta\theta$$

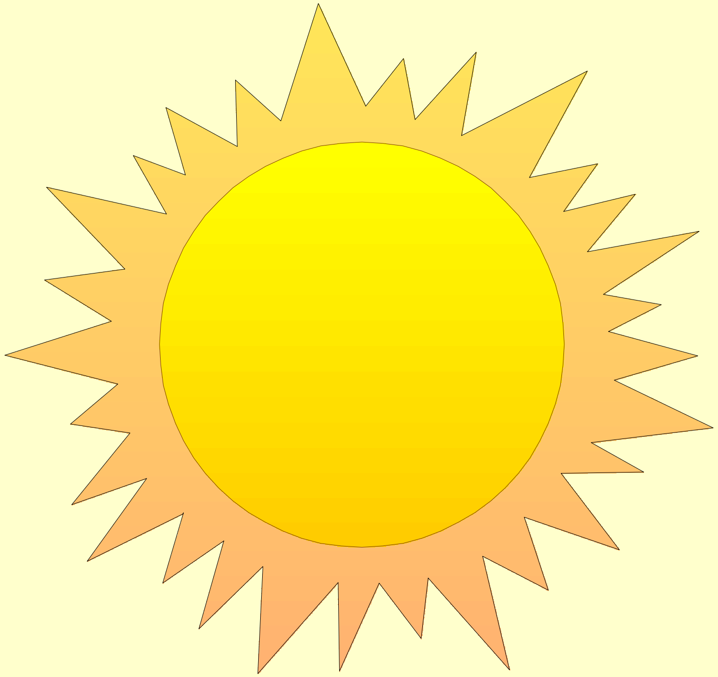
rate of heat loss (W) from an area A (m^2)

convective heat transfer coefficient ($W\,m^{-2}\,{}^0C^{-1}$)) depends on temperature

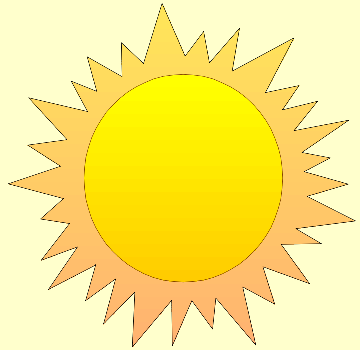
temperature difference between hot surface & surrounding fluid(^OC)

Radiation

- **heat loss by emission of electromagnetic radiation**
  - **electronic systems (e.g. -50^{0}C to 150^{0}C) energy radiated in microwave and infra-red regions**
- **radiation also works in a vacuum**
  - **only mechanism for heat loss in outer space from satellites & spacecraft**



Radiation



$$\frac{dQ}{dt} = \sigma \, \varepsilon \, A \, (\theta_S^{4} - \theta_A^{4})$$

- $\frac{dQ}{dt}$: rate of heat loss (W) from an area A (m^2)
- σ: Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
- ε: emissivity of hot surface (dimensionless, =<1)
- θ_S: temperature of emitting surface (^{0}K)
- θ_A: temperature of surroundings (^{0}K)

Thermal Resistance

- simplifies practical calculations
- can take account of
  - conduction, convection and radiation
- is approximate
- relates to limited range of temperature values
- values usually given by manufacturers to avoid calculation from first principles

Thermal Resistance

analogous to Ohm's Law

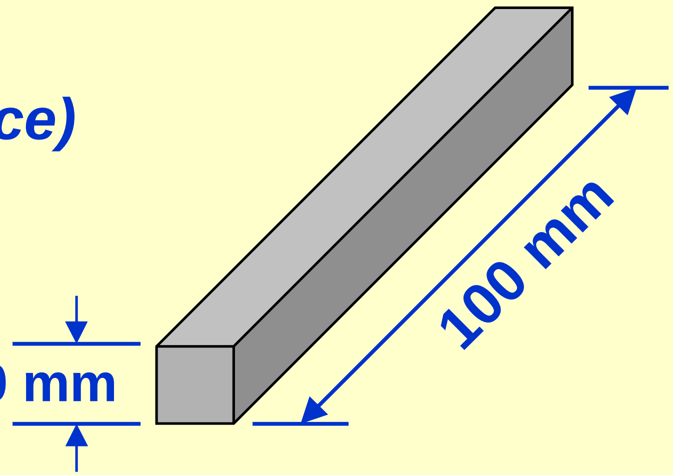
$$\Delta\Theta = \frac{dQ}{dt} R$$

temperature difference (^{O}C)
(cf . volts)

heat transfer rate (W)
(cf. current)

thermal resistance
($^{O}C\ W^{-1}$)
(cf . resistance)

Calculate the thermal resistance between the end faces of a 10mm x 10mm aluminium alloy bar of length 100mm, ignoring heat loss from the side of the bar. The thermal conductivity of the alloy is $k = 170\ \mathrm{W\ m^{-1}\ {}^{0}C^{-1}}$.



Now $\Delta\Theta = R\,(dQ/dt)$ *(thermal resistance)*

and $(dQ/dt) = -kA(d\Theta/dx)$ *(conduction)*

Hence, ignoring sign,

$$R \simeq \frac{\Delta\Theta\ dt}{dQ} \simeq \frac{\Delta x}{k\,A} \quad \text{or}$$

$$R \simeq \frac{100\ \mathrm{mm}}{170\ \mathrm{W\ m^{-1}\ {}^{0}C^{-1}} \times 10\ \mathrm{mm} \times 10\ \mathrm{mm}} \times \left[\frac{1000\ \mathrm{mm}}{1\ \mathrm{m}}\right]$$

“unity bracket”

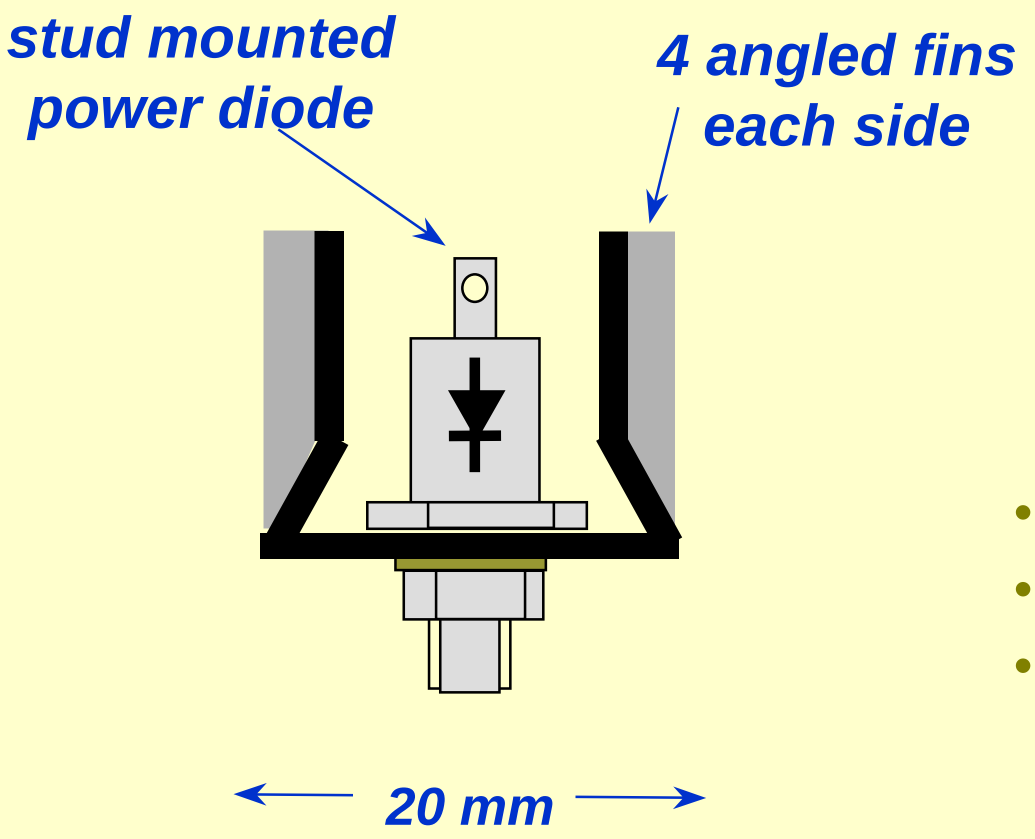
$$R \simeq 5.9\ \mathrm{{}^{0}C\ W^{-1}}$$

Heatsinks

- used to
  - conduct heat from power semiconductors & resistors
  - dissipate this heat to the surroundings
- heat dissipation to the surrounding air by
  - convection
    - *main mechanism*
    - *clip-on heat dissipators up to 2W*
    - *fan-assisted removal possible (high W)*
  - radiation
    - *blackened surface to enhance radiation heat loss*
    - *blackened surface adds very little extra cost*

Heatsinks

- *effectiveness increases with area*
- *emissivity increases with darkness*
- *usually made from Al alloy (high thermal conductivity)*



Heatsink

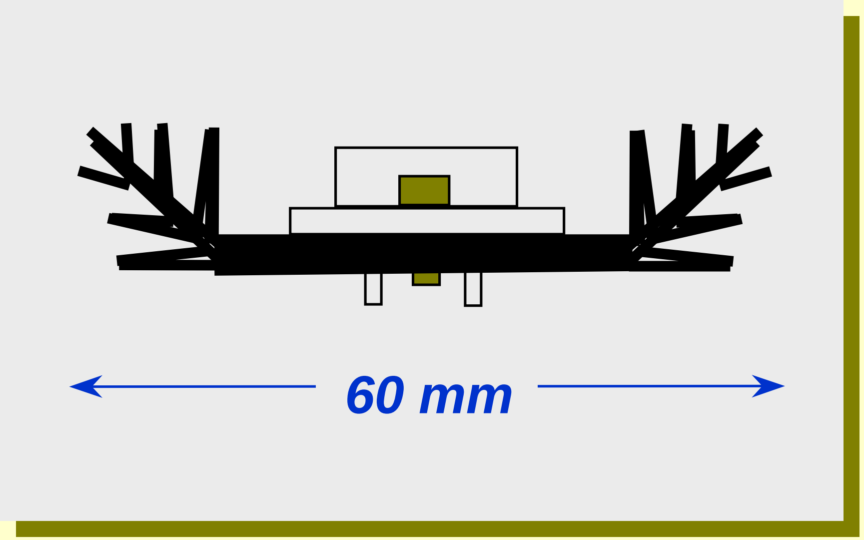
- thermal resistance 20 $^{0}C\ W^{-1}$
- used for power diodes
- aluminium alloy

→ *16 mm* ←

Heatsink

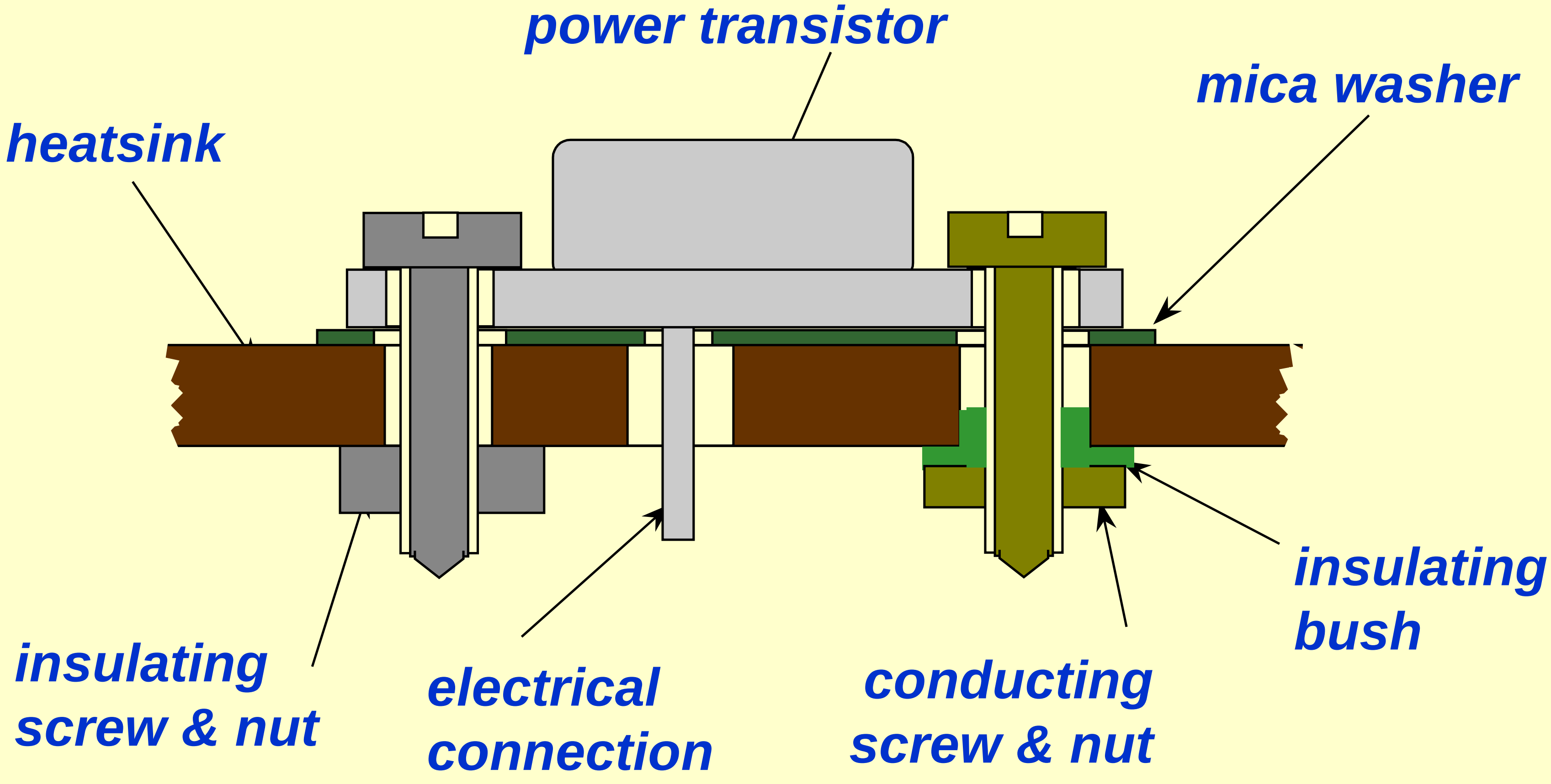
- thermal resistance 30-50 $^{0}C\ W^{-1}$ depending on length
- used for small transistors
- clip-on
- aluminium alloy

Heatsink



- thermal resistance 2-5 $^{0}C\ W^{-1}$ depending on length
- used for power transistors & voltage regulators
- aluminium alloy

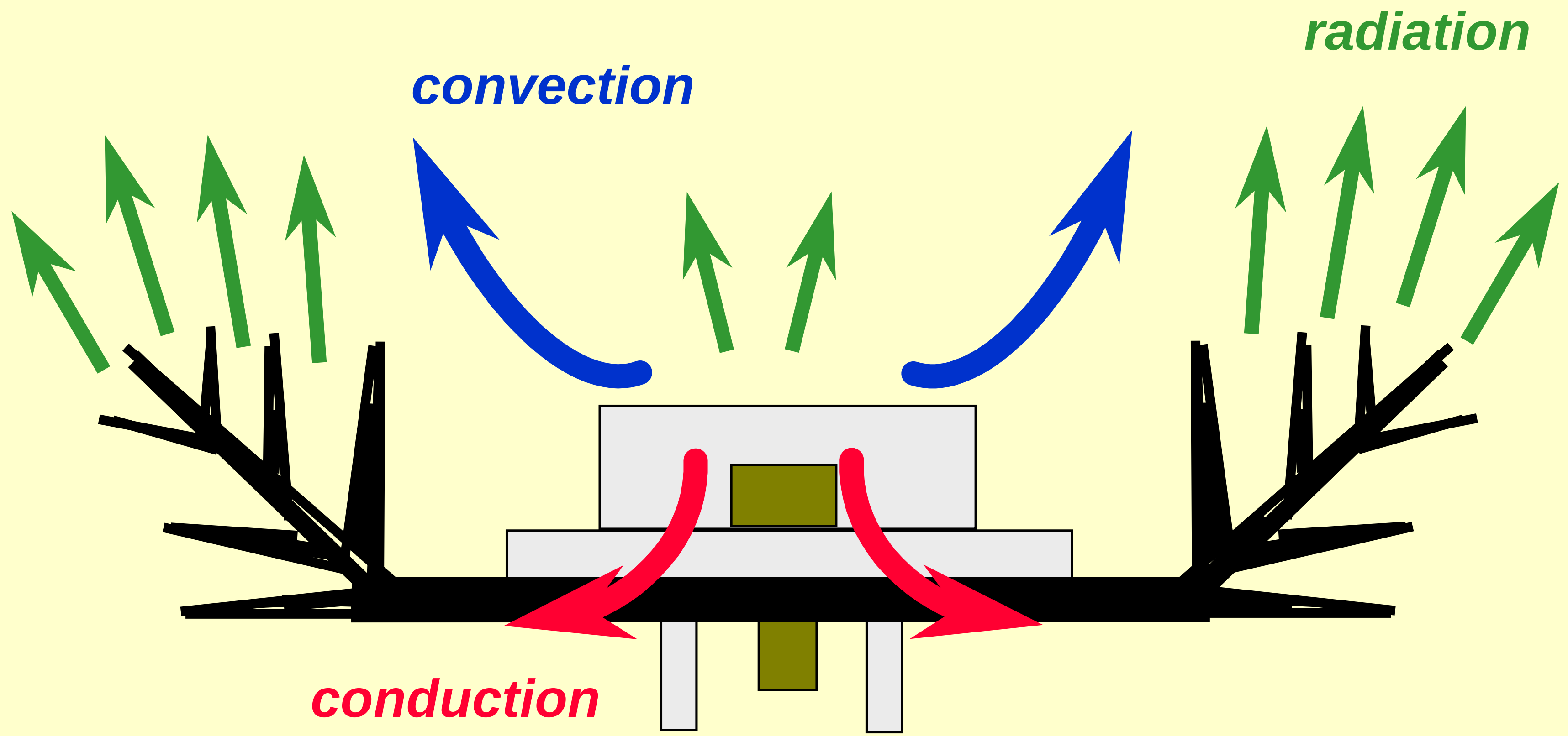
Power Transistor Mounting



Power Transistor Mounting

- **if transistor is to be electrically isolated from heatsink, use:**
  - ***thin mica washer***
  - ***use heat conducting compound (eg. silicone grease) on both sides of mica washer to fill any voids between metal and mica***
  - ***insulating screws and nuts (e.g. nylon) or***
  - ***metal screws with insulating bush***

Conduction, Convection, Radiation



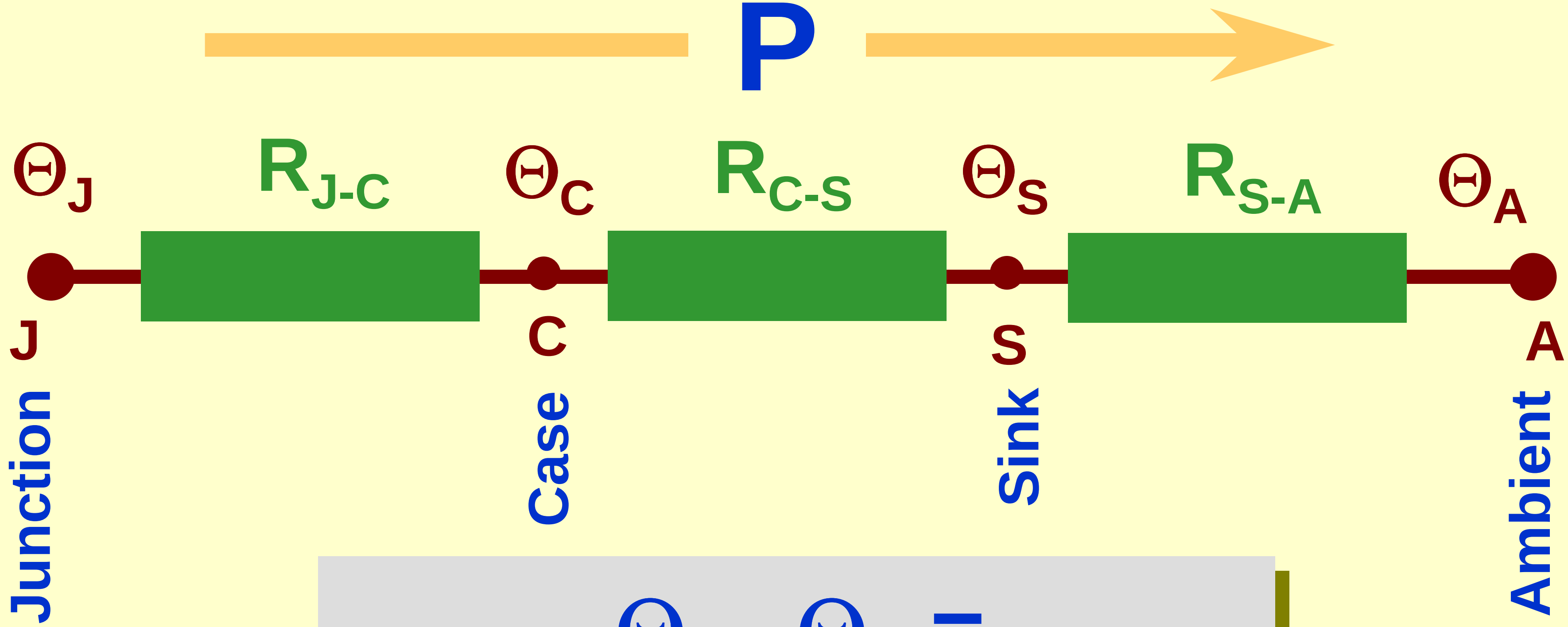
Heatsink Calculations

- The thermal path for a single power device on a heatsink can be analysed as a series of thermal resistances.

$$\Theta_J - \Theta_A = P(R_{J\text{-}C} + R_{C\text{-}S} + R_{S\text{-}A})$$

P = power flow from the device to ambient (W)
Θ = temperature (^{0}C)
R = thermal resistance (^{0}C/W)
J = junction (e.g. PN junction of power device)
C = case of device
S = sink (heatsink)
A = ambient

Heatsink Calculations



$$\Theta_J - \Theta_A =$$
$$P(R_{J\text{-}C} + R_{C\text{-}S} + R_{S\text{-}A})$$

Heatsink Example 1

- Given that
  - device dissipates 5W
  - ambient temperature = 25°C
  - device thermal resistance = 3.2°C/W
  - case to heatsink thermal resistance = 0.5°C/W
  - maximum allowable junction temperature = 125°C ,
- what thermal resistance can the heatsink have?

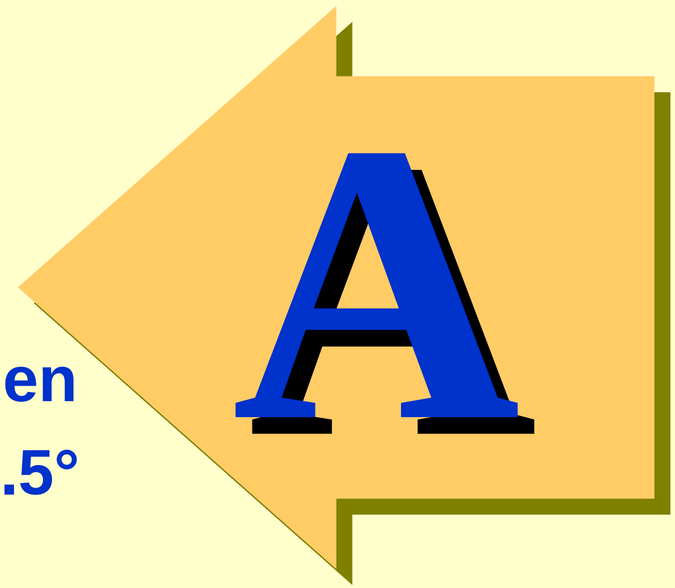
- If a 15°C/W heatsink is used, what:
  - is the junction temperature for 25^{0}C ambient, or
  - can the ambient rise to for a junction temperature of 125^{0}C?

Heatsink Example 1

$\Theta_J - \Theta_A = P(R_{J\text{-}C} + R_{C\text{-}S} + R_{S\text{-}A})$

$125 - 25 = 5(3.2 + 0.5 + R_{S\text{-}A})$

$R_{S\text{-}A} \quad = 16.3\ °C/W$



Suppose a 15°C/W heatsink is used, then

$\Theta_J - \Theta_A = 5(3.2 + 0.5 + 15) = 5 \times 18.7 = 93.5°$

Hence:

- $\Theta_J = 93.5 + 25.0 = 118.5°C$ or
- ambient can go up to 125 - 93.5°C = 31.5 °C without exceeding Θ_J

Heatsink Example 2

- A silicon transistor has thermal resistances from junction to case and case to ambient of 10 and 30 ^{O}C/W. The ambient temperature is at 30^{O}C and the junction temperature must not exceed 150^{O}C.
- What is the maximum permitted power dissipation?
- If a heatsink with a thermal resistance of 7^{O}C/W is fitted, the thermal resistance between case and heatsink can be ignored. What is then the maximum allowable heat dissipation?
- Using this heatsink, what is the junction temperature when the power dissipated is 5W?

Heatsink Example 2

(a) $\Theta_J - \Theta_A = P(R_{J\text{-}C} + R_{C\text{-}A})$

$150 - 30 = P_{MAX}\,(10 + 30)$ or $P_{MAX} = 3$ W

(b) $\Theta_J - \Theta_A = P(R_{J\text{-}C} + R_{C\text{-}A})$

$150 - 30 = P_{MAX}\,(10 + 7)$ or $P_{MAX} = 7$ W

(c) $\Theta_J - \Theta_A = P(R_{J\text{-}C} + R_{C\text{-}A})$

$\Theta_J - 30 = 5\,(10 + 7)$ or $\Theta_J = 115\ ^{O}C$

Can we reduce Thermal Resistances?

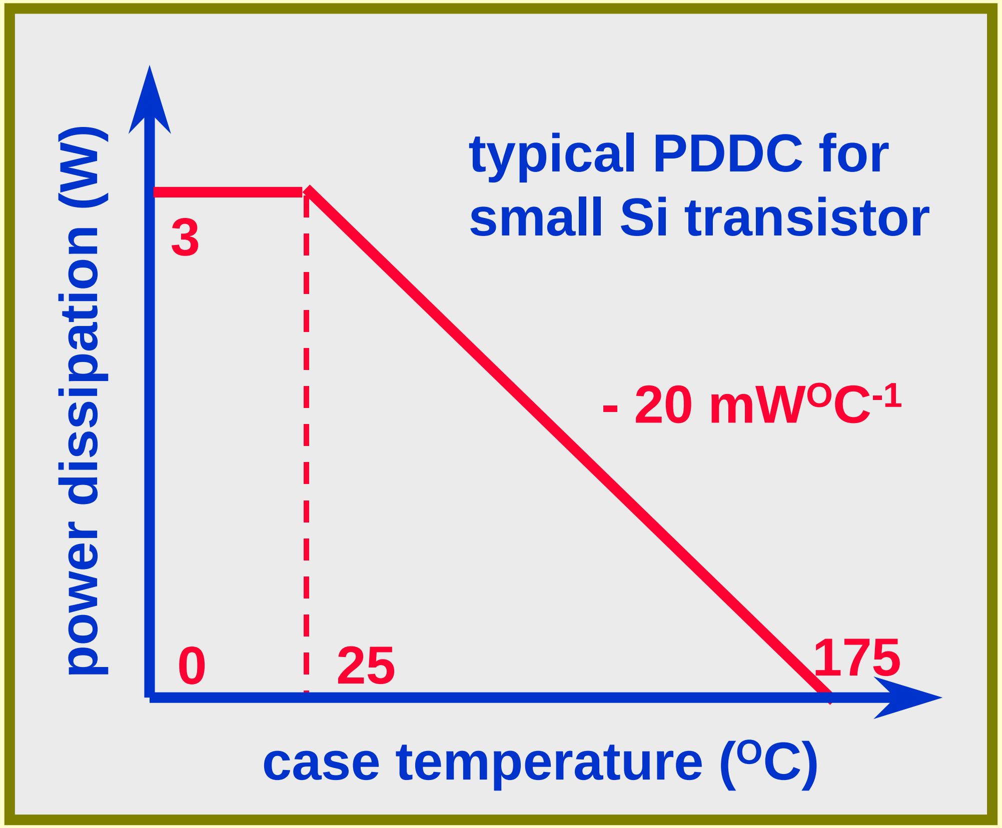
- **$R_{J\text{-}C}$ - junction and case**
  - determined by way device is made
  - nothing can be done to reduce $R_{J\text{-}C}$
- **$R_{C\text{-}S}$ - case and heatsink**
  - Remove small air gap of high thermal resistance by using thermally con-ducting paste.

??

Power Dissipation Derating "Curve"

- **PDDC often given by manufacturer instead of $R_{J\text{-}C}$.**
- **in this example, if**
  - **J = junction**
  - **C = case**
  - **$R_{J\text{-}C}$ = thermal resistance junction to case**
  - **P = power dissipation**
  - **Θ_J = junction temperature**
  - **Θ_C = case temperature**
- **$R_{J\text{-}C} = (\Theta_J - \Theta_C) / P$**

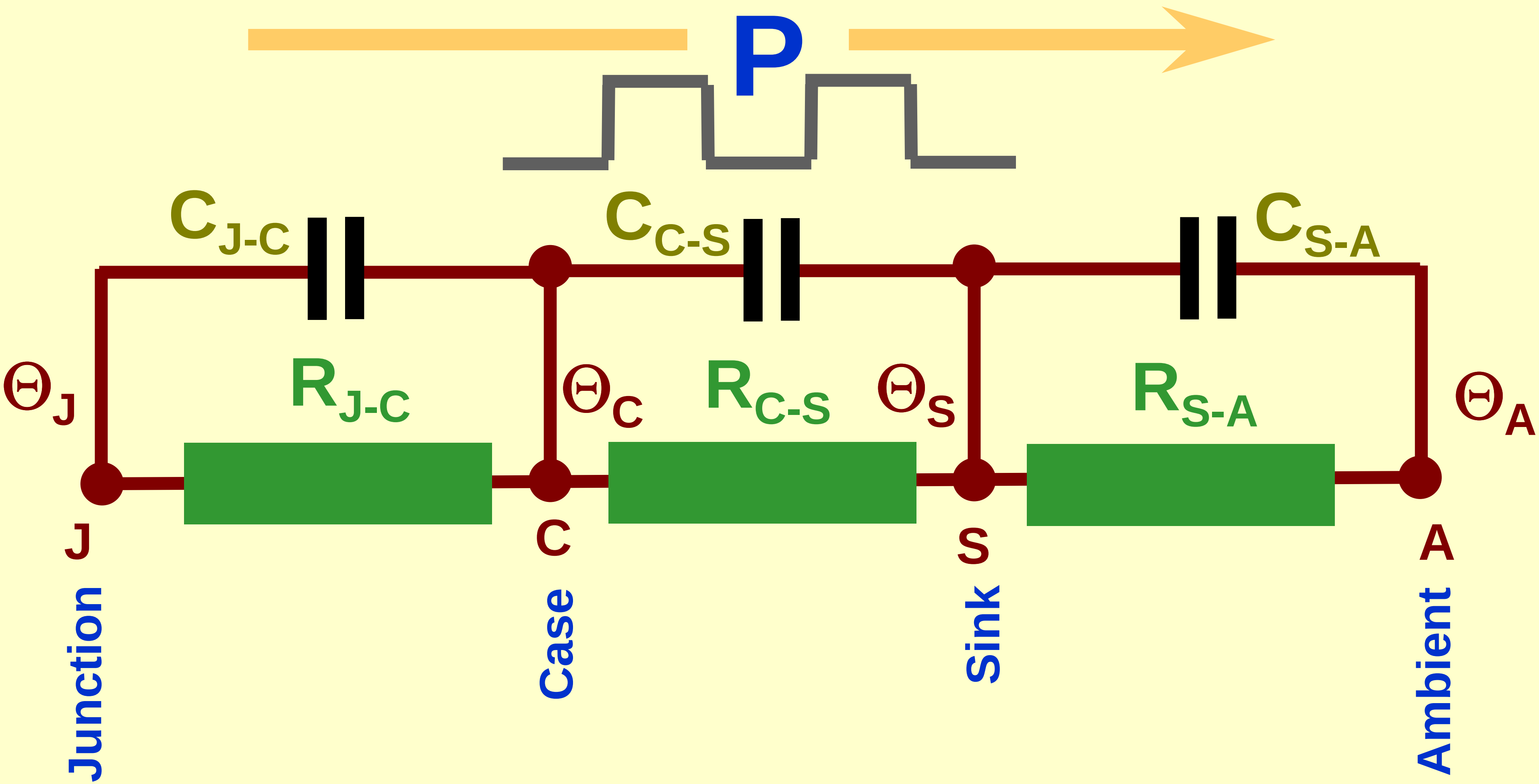
  $= (175\text{-}25) / 3 = 50^{O}C / W$



Transient Heat Calculations

- When power dissipation fluctuates (e.g. in power amplifiers) heatsinks can be smaller.
- The heatsink and device have a thermal capacities (thermal masses) (C_{J-C} and C_{S-A}) so heating is not instantaneous when the power increases.
- The thermal mass (C_{C-S}) of the heatsink itself can be ignored as a conservative assumption.

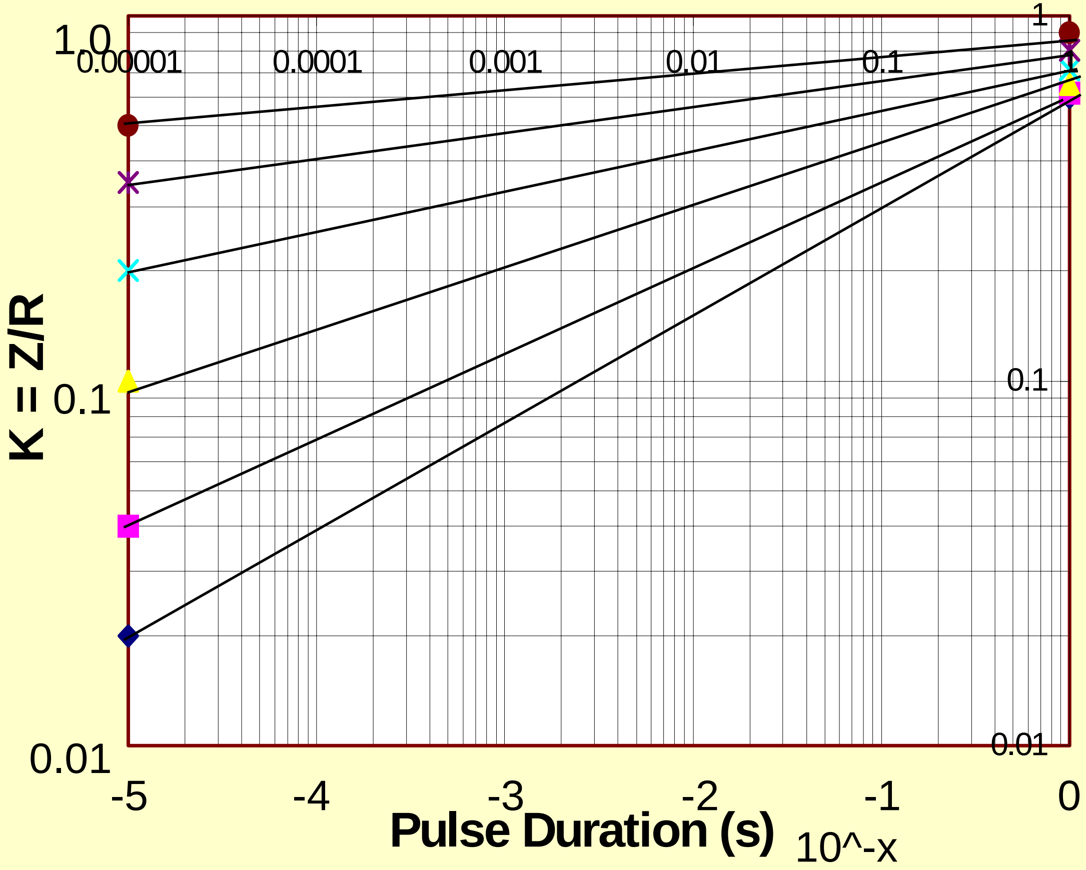
Transient Heat Calculations



Transient Heat Calculations

- Manufacturers give data
- z = transient thermal impedance
- R = steady state thermal resistance
- *k = z /R*
- k allows for the thermal mass of the transistor.
- δ is the DUTY CYCLE
- = ratio of
  - on time t_p to
  - period *T* of waveform
- graph: top to bottom, δ =
- 0.5, 0.4, 0.3, 0.1, 0.05, 0.01

Thermal Impedance Curves

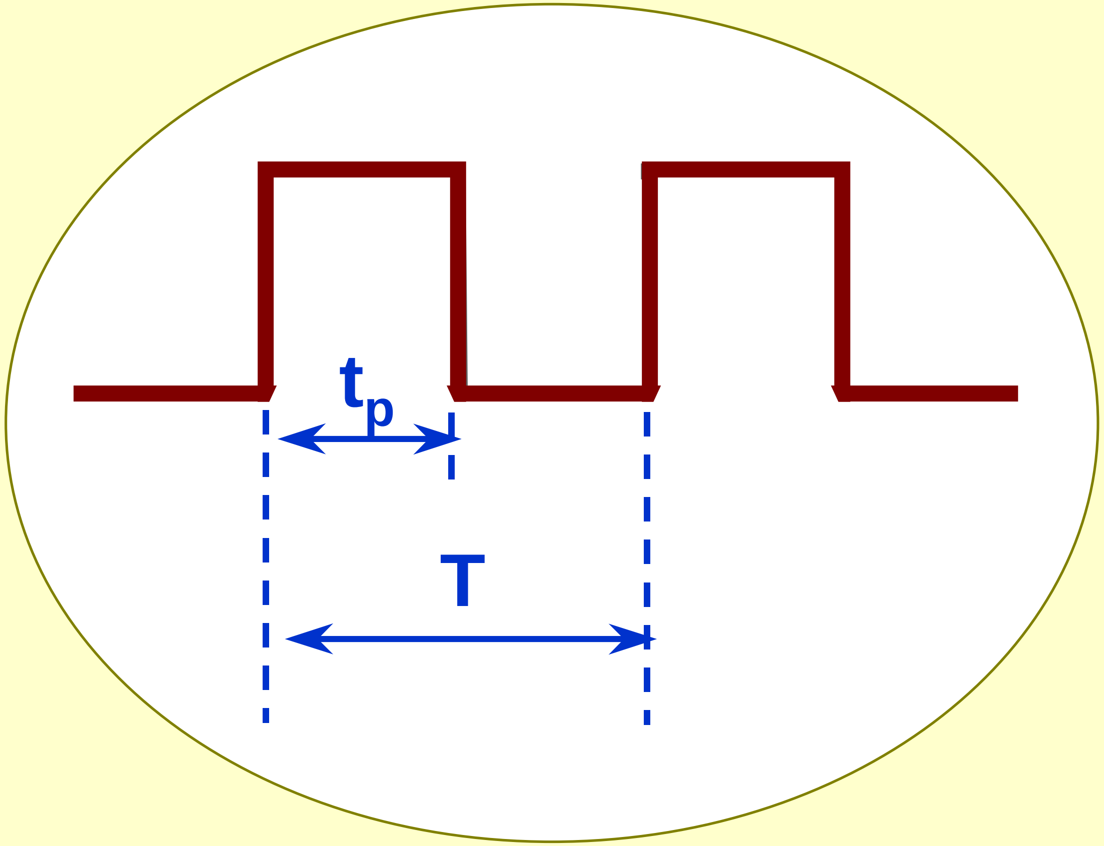


Duty Cycle

t_p = on time

T = period

$\delta = t_p/T$



Transient Heat Calculations

Pulsed Power Dissipation

$$\Theta_J - \Theta_A = P_{max}(kR_{J\text{-}C} + \delta\, R_{C\text{-}S} + \delta\, R_{S\text{-}A})$$

k takes account of $C_{J\text{-}C}$
δ assumes no $C_{C\text{-}S}$ or $C_{S\text{-}A}$

non-rectangular pulses have to be reduced to equivalent rectangular pulses

A power transistor switches a resistive load with a 10% duty cycle, a waveform of period 5ms and 40W power dissipation when in the conduction mode. The junction to case thermal resistance is 1°C/W and the mica washer gives 0.2°C/W.

If the ambient temperature = 40°C and the maximum junction temperature is 150°C, what heatsink is required? Assume the previous curves apply.

Compare with case where 40W power is continuous.

on time = $0.1 \times 5X10^{-3}$ s = $5x10^{-4}$ s, also from chart $k = 0.2$

$$\therefore \quad \Theta_J - \Theta_A = P_{max}(kR_{J\text{-}C} + \delta R_{C\text{-}S} + \delta R_{S\text{-}A})$$

$$150 - 40 = 40(0.2x1 + 0.1x0.2 + 0.1xR_{S\text{-}A})$$

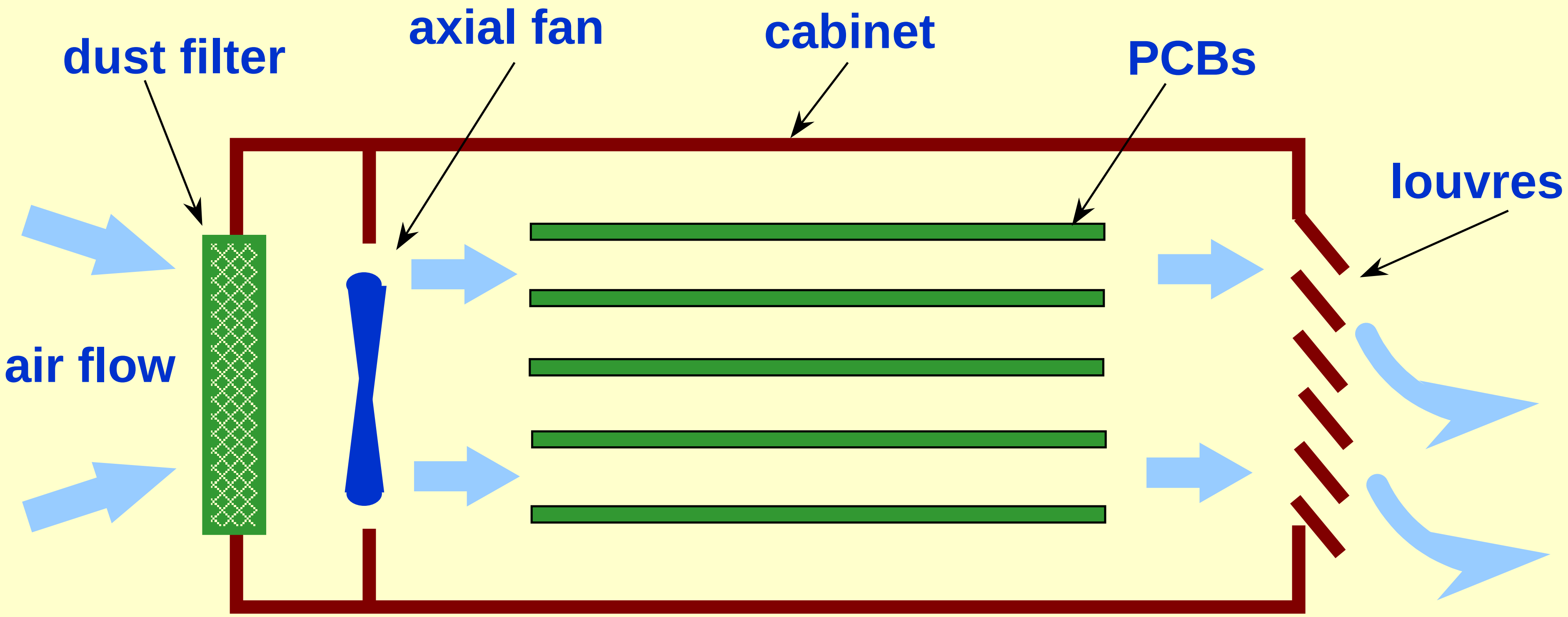
$$R_{S\text{-}A} = 25.3°C/W$$

if power is continuous,

$$150 - 40 = 40(1 + 0.2 + R_{S\text{-}A})$$

$$R_{S\text{-}A} = 1.55°C/W$$

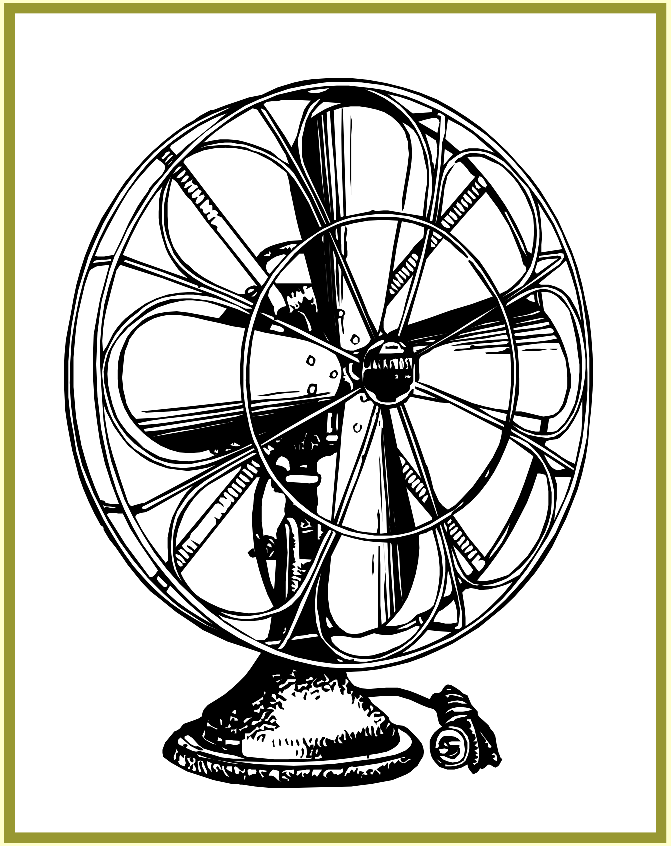
Force Cooling PCBs



Force Cooling PCBs

- The airflow depends on the resistance to flow due to filters, PCBs, grills.

- A 100mm fan can give 100m^3/hour airflow



Calculating Required Air Flow

$$P = \frac{dV}{dt} \rho \, c \, \theta$$

rate of heat removal (W)

volume flow rate ($m^3 \, s^{-1}$)

density ($kg \, m^{-3}$)

specific heat capacity of air ($J \, kg^{-1} \, {}^{O}C^{-1}$)

temperature above ambient (${}^{O}C^{1}$)

Air Flow Example

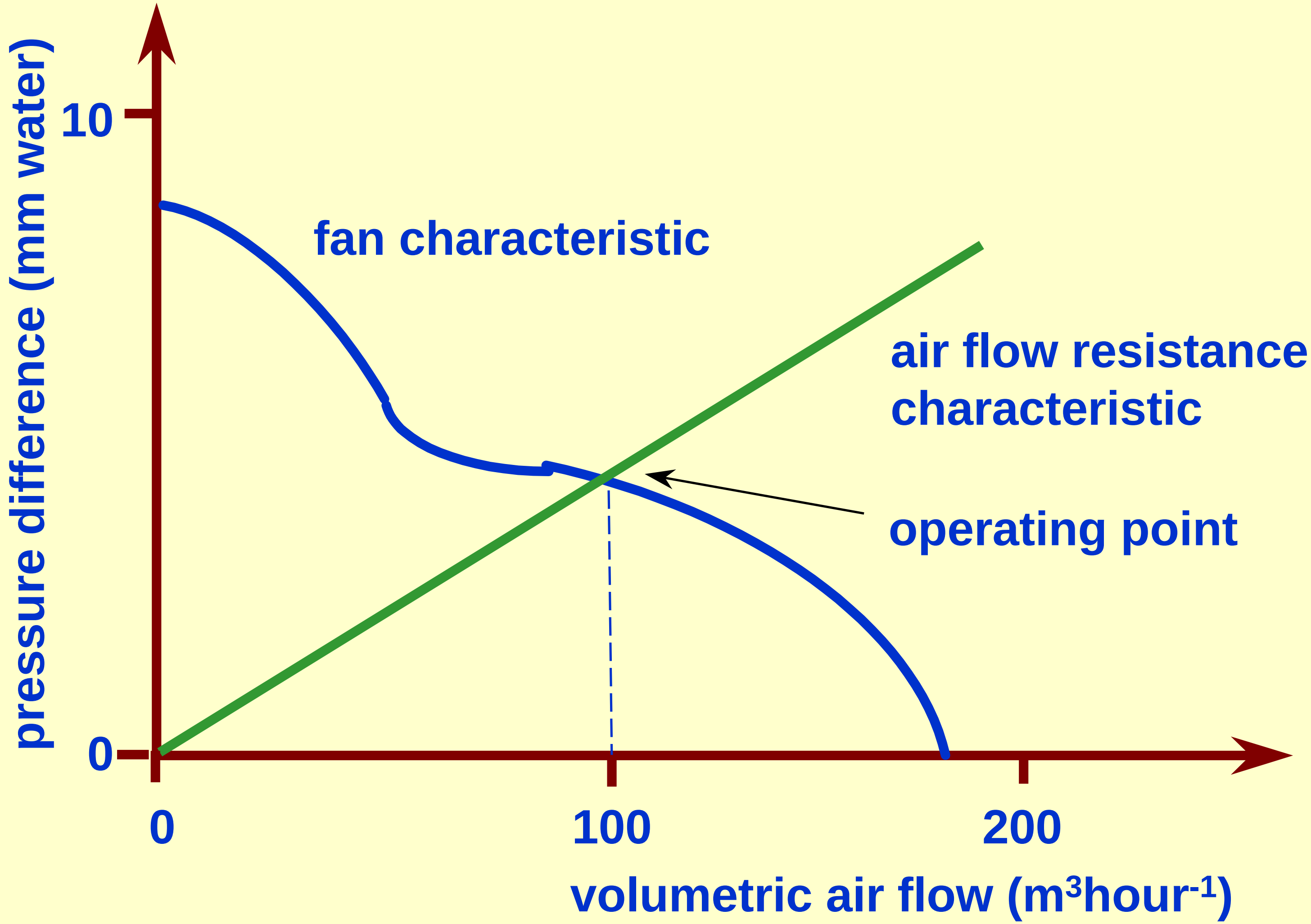
- **A cabinet contains electronics that dissipate 150 W. The temperature inside the cabinet should not exceed $50^{O}C$ with an air inlet temperature of $30^{O}C$. At $30^{O}C$ air has a specific heat capacity of $1 KJ/(Kg^{O}C)$ and (at normal atmospheric pressure) a density of 1.3 Kg/m3**
- **Find the minimum airflow rate needed.**

$$P = \bar{V} \rho \, c \, \Theta$$

$$150\ W = \bar{V} \times 1.3\ Kg\ m^{-3} \times 1000\ J\ Kg^{-1}\ {}^{O}C^{-1} \times (50 - 30)\ {}^{O}C$$

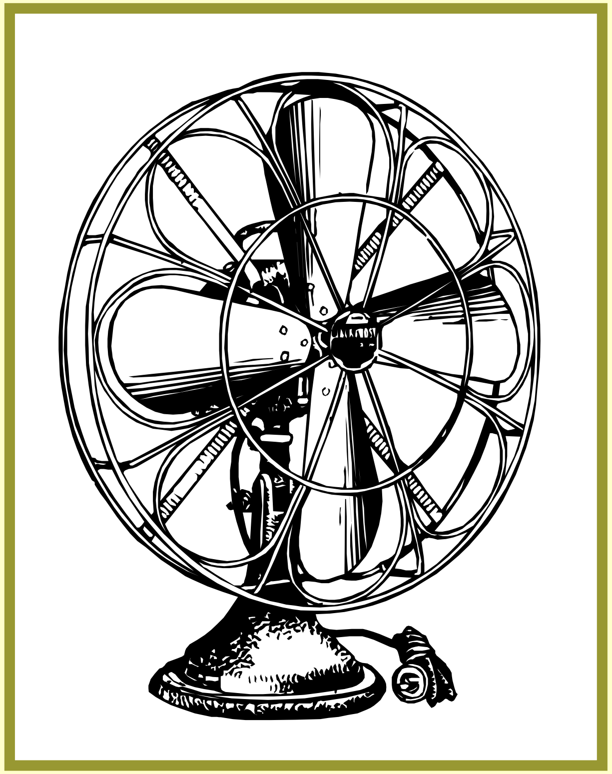
$$\text{or } \bar{V} = 21\ m^{3}h^{-1}$$

Determining Air Flow Rate



Cooling Methods

- **Heatsinks**
  - use Ohm's Law analogy for calculation
- **Forced Air Cooling**
  - fan and dust filter
- **Heat Ladder**
  - in multilayer PCBs
  - usually metal
  - bonded to PCB between rows of ICs
- **Liquid Cooling**
  - usually water
  - high speed computers
  - components close together



Specifications

type	*applications*	*range (deg C)*
commercial	laboratory office home	+5 to +40
industrial	process plant factory floor	0 to +70
military	weapons systems military vehicles	-55 to + 125

To Conclude

- **Electric Current generates heat**
- **There are 3 processes:**
  - **conduction, convection, radiation**
- **Practical heat calculations are analogous to Ohm's Law**
- **Heatsinks provide cooling**
- **Forced Airflow enhances cooling**
- **Three specifications:**
  - **commercial, industrial and military**


EDA