Thermal Management

Fundamentals of Thermal Technologies

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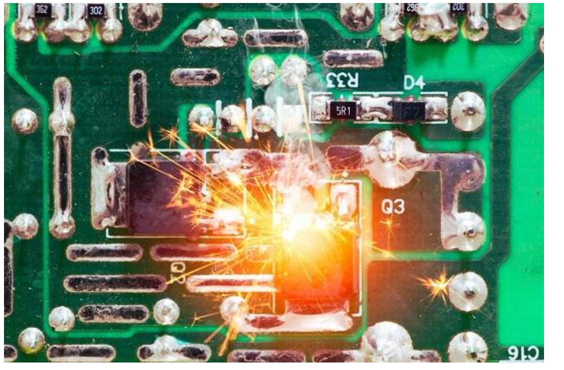
Why thermal management?

Thermal Management

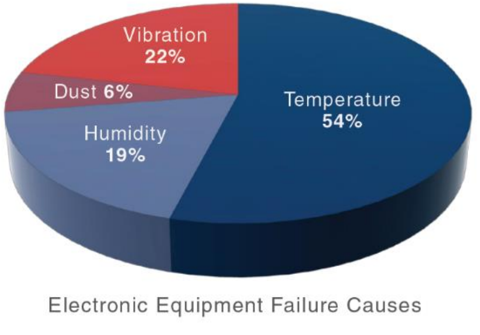
- Heat generated during operation of electronic components
  - Joule heating Q= I^2Rt



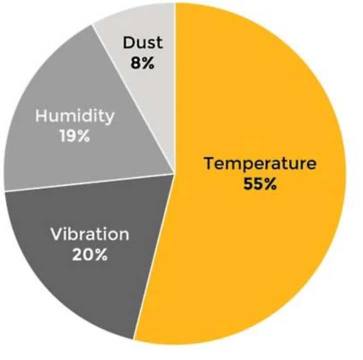
Source: Sierra Circuits

- Functioning of ICs restricted by temperature limits
  - Material constraints

- Performance limited by Thermal Design Power (TDP)



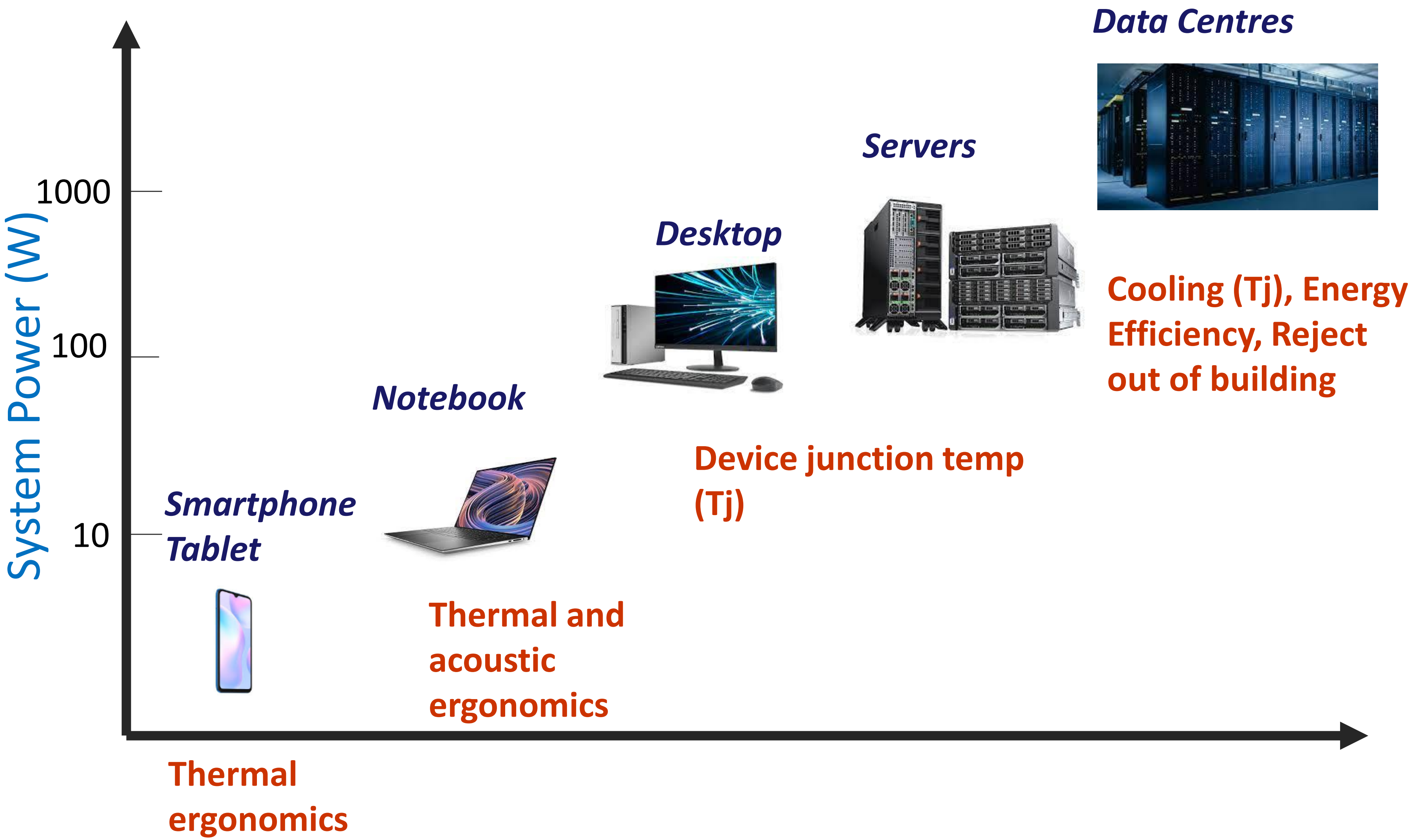
Source: https://www.vortec.com/



Source: Steinberg, "Vibration Analysis of Electronic Equipment" Wiley, 2000

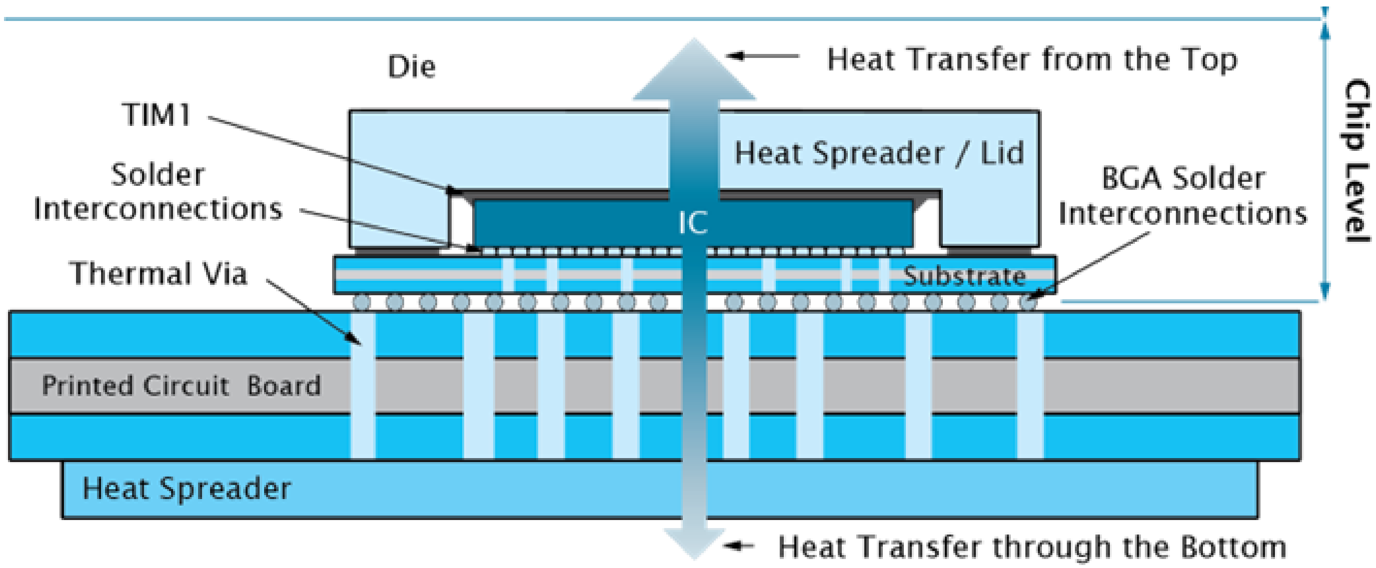
Thermal Challenge Spectrum

Thermal Management



Anatomy of a Package

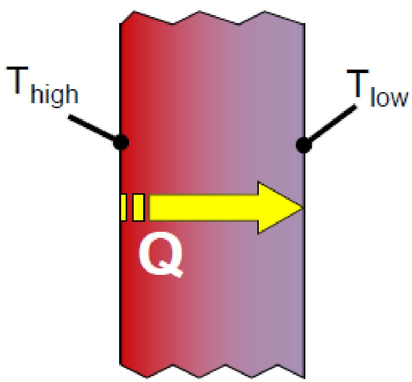
Thermal Management

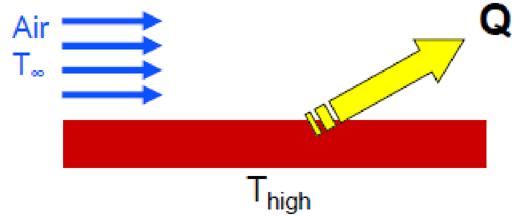


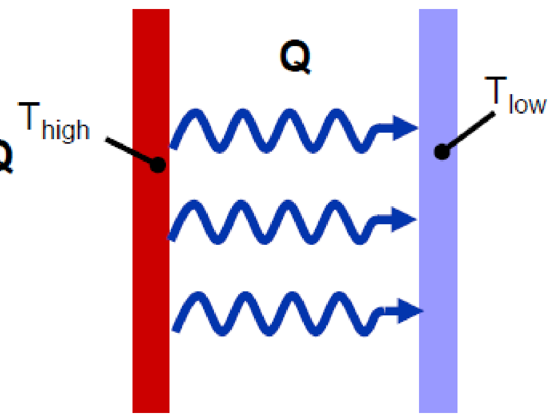
Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

What is Heat Transfer?

- Heat transfer is energy in transit due to a temperature difference
- Temperature gradient has to exist - heat flow will be in a direction so as to equalize the temperature at various points.
- 3 Modes: Conduction, Convection, & Radiation





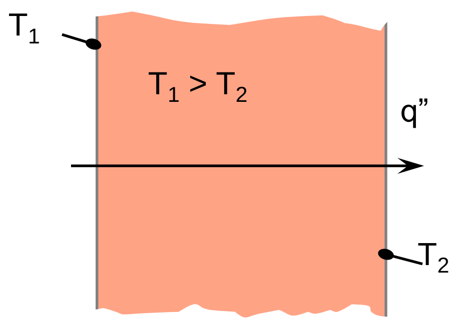


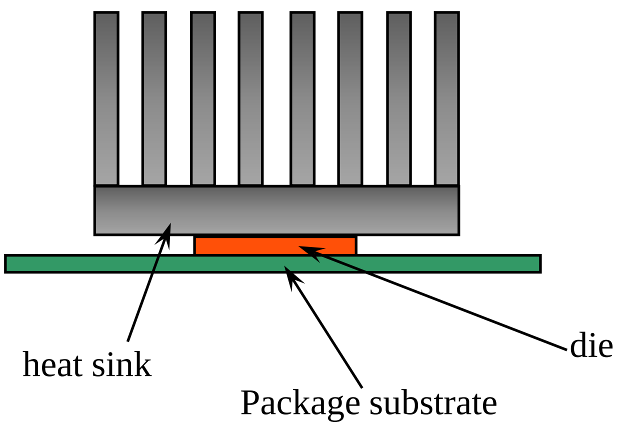
$$Q = -kA\frac{T_{high} - T_{low}}{L} = kA\frac{\Delta T}{L}$$

$$Q = hA\Delta T$$

$$Q = \varepsilon A\sigma(T_{high}^4 - T_{low}^4)$$

Concept of Heat Flux (q”)





Another important quantity is the HEAT FLUX, which is the <u>rate of heat transfer per unit area</u>.

Consider the silicon die in a IC Package below:

Power dissipated by the die = q [Watts]

Area of the die = A [cm^2]

Heat Flux: $q'' = \frac{q}{A} [W/cm^2]$

Consider a CPU die :

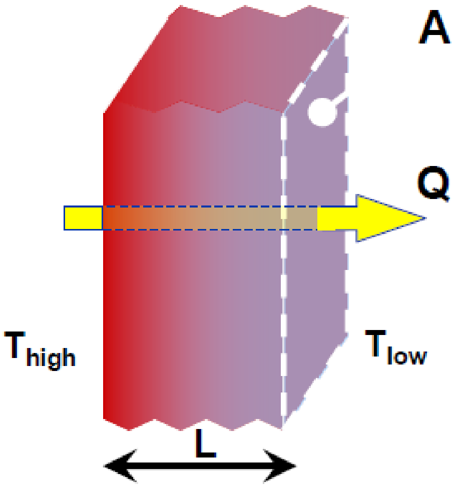
Power: $q = 25\ W$

Area: $A = 0.8\ cm^2$

Therefore, the heat flux through the die is:

$q'' = 31.25\ W/cm^2$

Thermal Resistance - Conduction



$$q = -kA\frac{T_2 - T_1}{L} = kA\frac{\Delta T}{L}$$

$$q = \frac{kA}{L}\Delta T = \frac{\Delta T}{(\text{Thermal Resistance})}$$

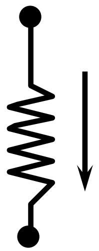
$$\text{Thermal Resistance} = \frac{L}{kA}$$

- Thermal resistance is a method used to represent thermal systems
- Thermal resistance is analogous to electrical resistance
  - Electrical resistance associated with transport of electricity
  - Thermal resistance associated with transport of heat

Thermal Resistance and Ohm's Law

Electrical Resistance

Voltage A



Electrical Resistance $= \frac{L}{\sigma A}$

Current

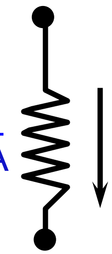
Voltage B

$$R = \frac{\text{Voltage A - Voltage B}}{\text{Current}}$$

Units: Ohm

Thermal Resistance

Temperature A



Conduction Thermal Resistance $= \frac{L}{kA}$

Power Dissipation

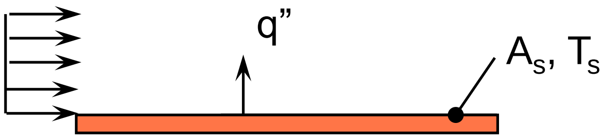
Temperature B

$$\theta_{AB} = \frac{\text{Temp A - Temp B}}{\text{Power Dissipation}}$$

Units: °C/Watt

Convection – Newton's Law of Cooling

- Energy transfer between a surface and a fluid moving over the surface.



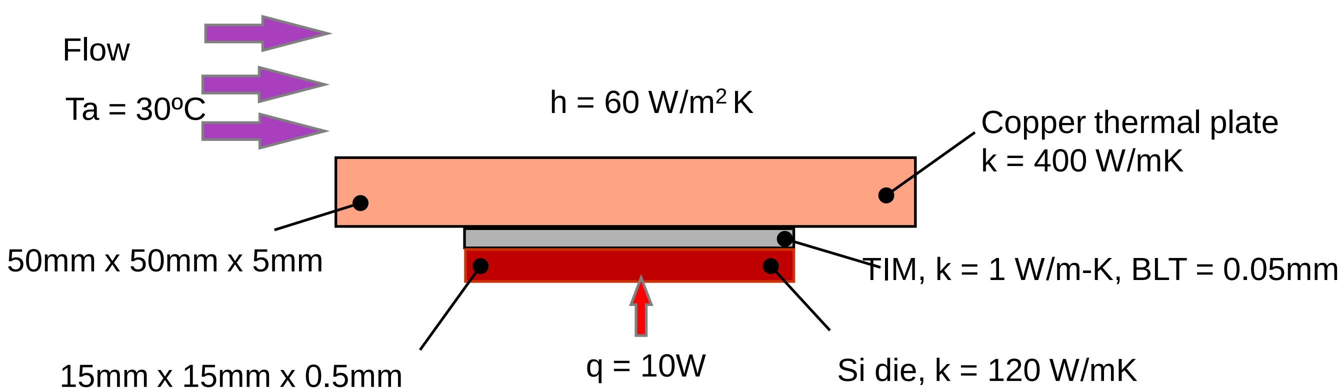
- **The heat flux is defined as** $$q'' = h(T_s - T_\infty)$$
- **The total heat flow is defined as** $$q = \bar{h} A_s (T_s - T_\infty)$$
- **Convective heat transfer coefficient *h***
  - Boundary conditions
  - Surface geometry
  - Fluid and fluid motion

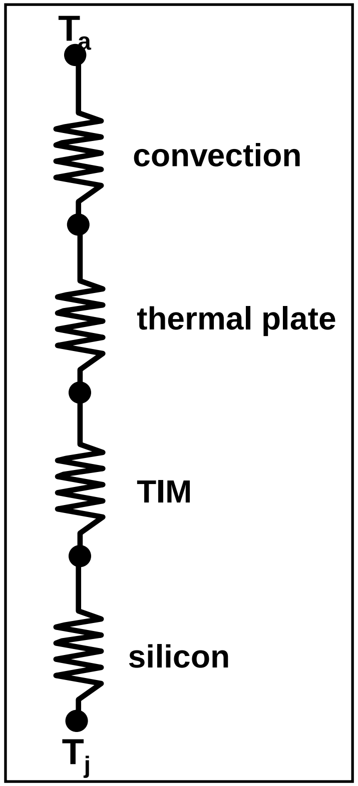
Challenge lies in determination of *h*

Example Problem

Consider the following package configuration with a silicon die attached to a thermal plate with a TIM. The die is dissipating power and the heat is lost from the thermal plate surface.

What is the die temperature (Tj)?



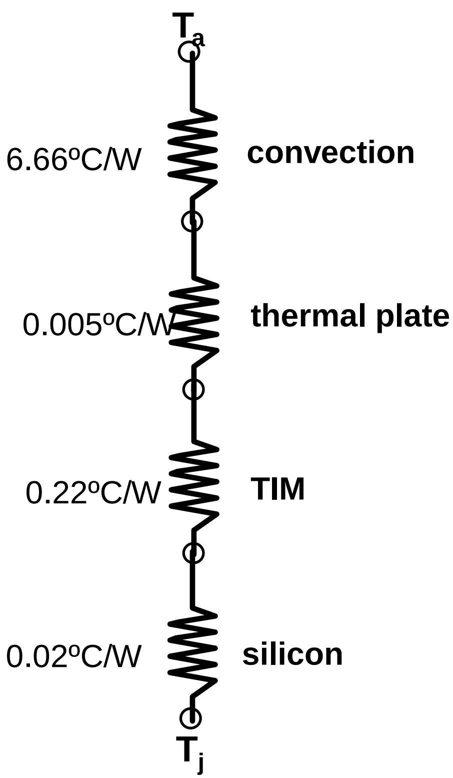


$$\theta_{conv} = \frac{1}{hA_s} = \frac{1}{(60)(50)(50)(10^{-6})} = 6.66^{o}C/W$$

$$\theta_{plate} = \frac{L}{kA} = \frac{0.005}{(400)(50)(50)(10^{-6})} = 0.005^{o}C/W$$

$$\theta_{TIM} = \frac{L}{kA} = \frac{0.05x10^{-3}}{(1)(15)(15)(10^{-6})} = 0.22^{o}C/W$$

$$\theta_{silicon} = \frac{L}{kA} = \frac{0.5x10^{-3}}{(120)(15)(15)(10^{-6})} = 0.02^{o}C/W$$



$$\theta_{ja} = \frac{T_j - T_a}{P}$$

$$T_j = T_a + \theta_{ja} P$$

$$\theta_{ja} = \Sigma\theta = 6.90^o C/W$$

$$T_j = 30^o C + (6.90^o C/W)(10W)$$

T_j = 99ºC

Commonly Used Nomenclature

θ_{XY} = X to Y thermal resistance

- X and Y could be
  - A: ambient
  - B: PCB board
  - C: case
  - J: junction
  - L: lead
  - P: thermal plate
  - S: heat sink

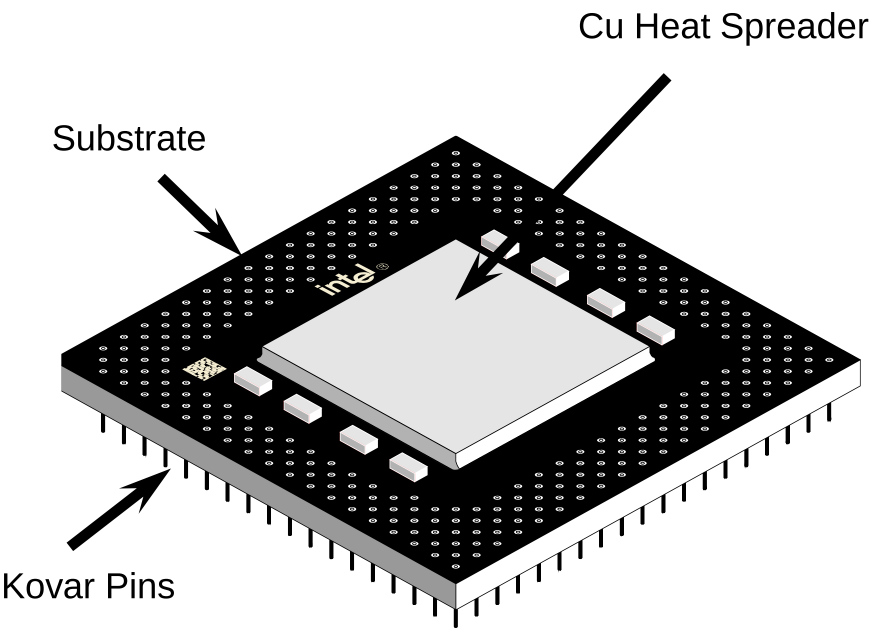
θ_{JC}

θ_{JA}

Thermal Management

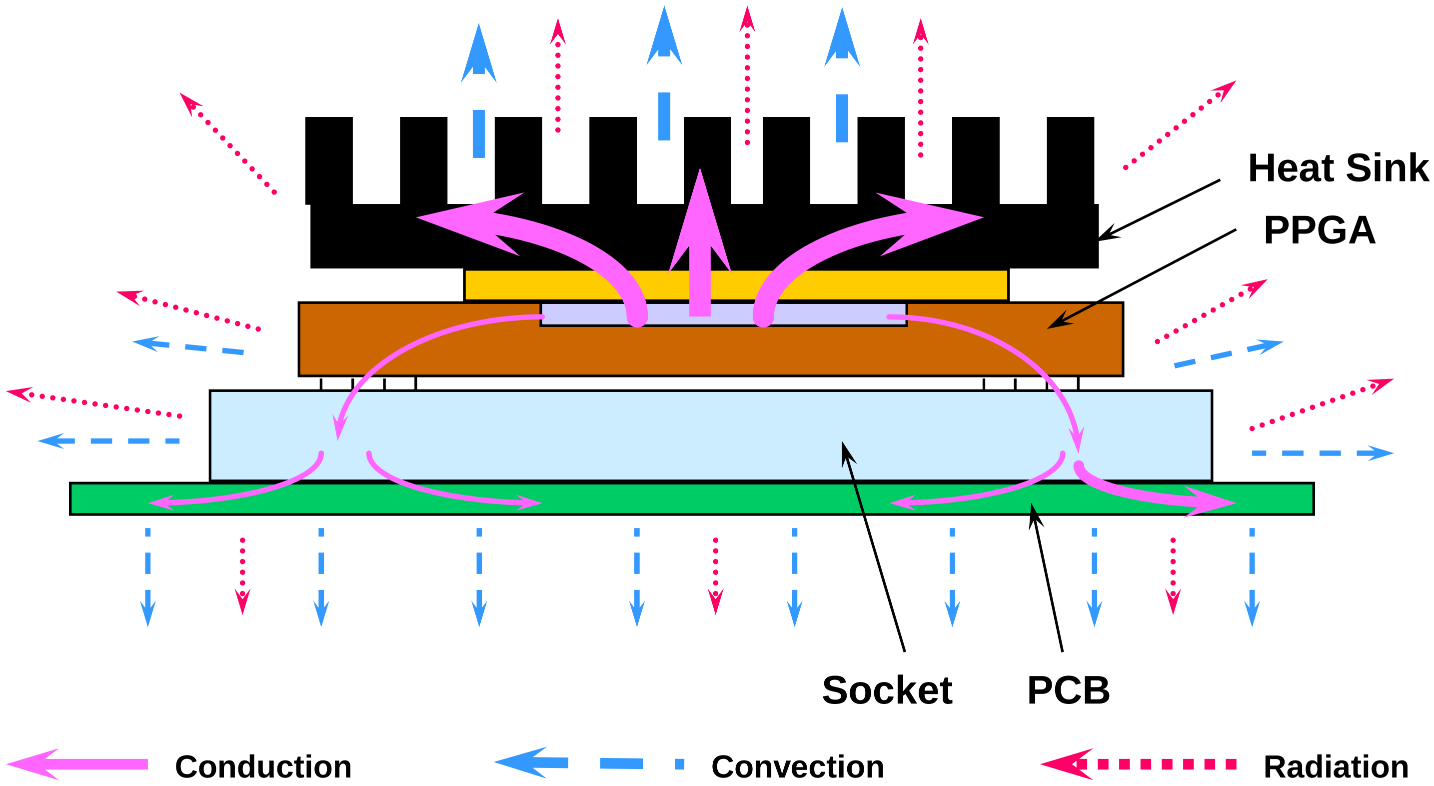
Understanding Heat Transfer Paths

- Consider the PGA package

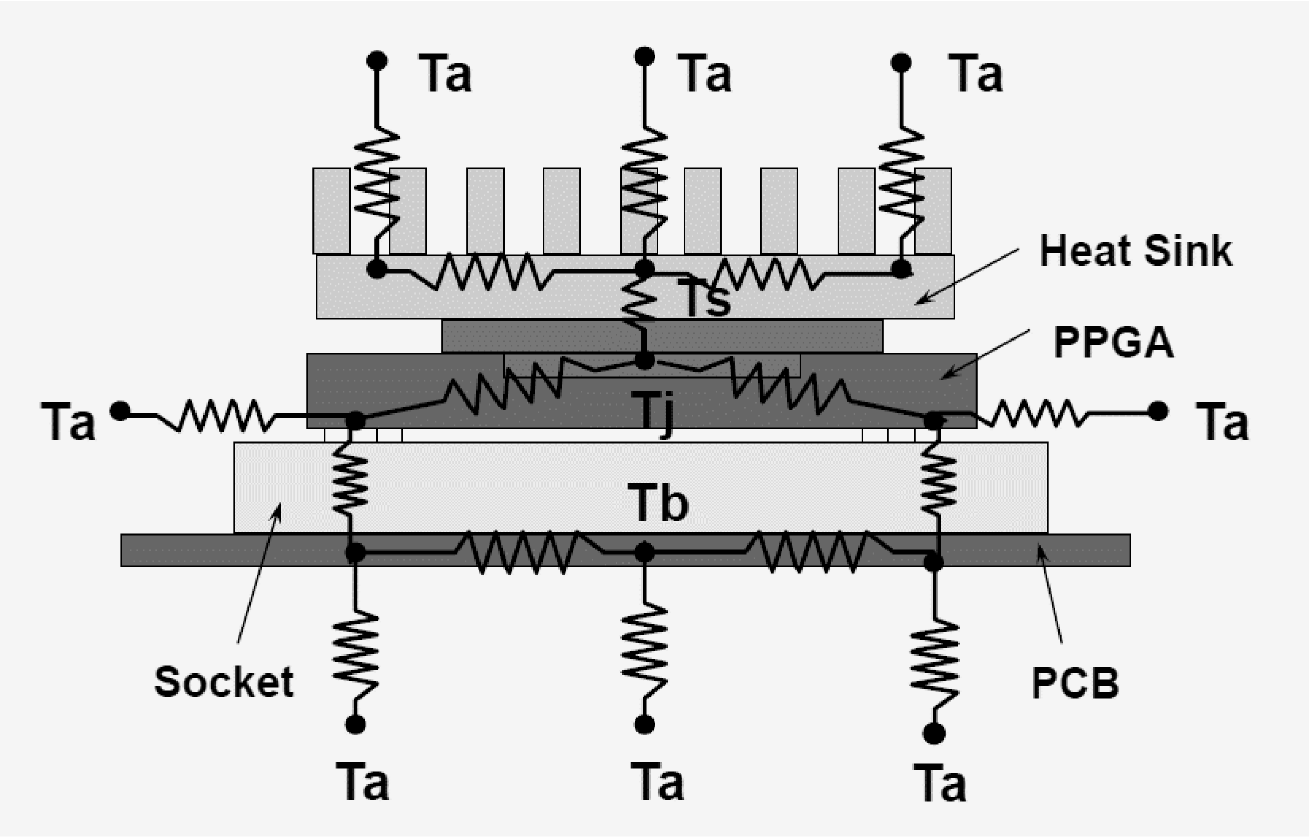


Acknowledgments: Intel Corporation

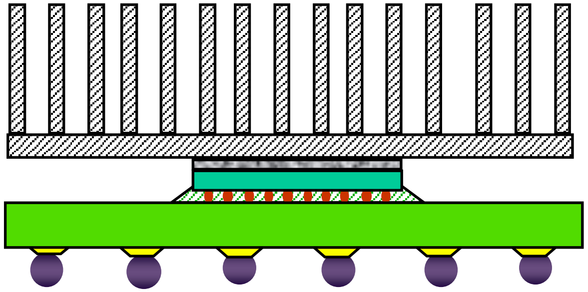
Heat Transfer Paths: PGA Example

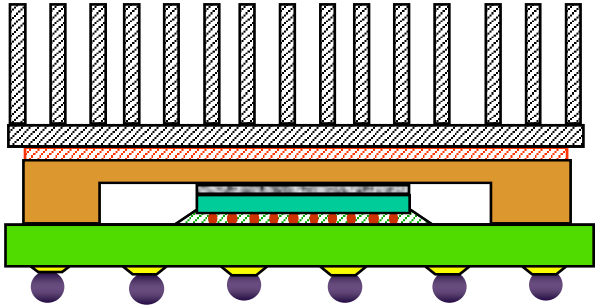


Thermal Resistance Network: PGA Example



Thermal Architectures





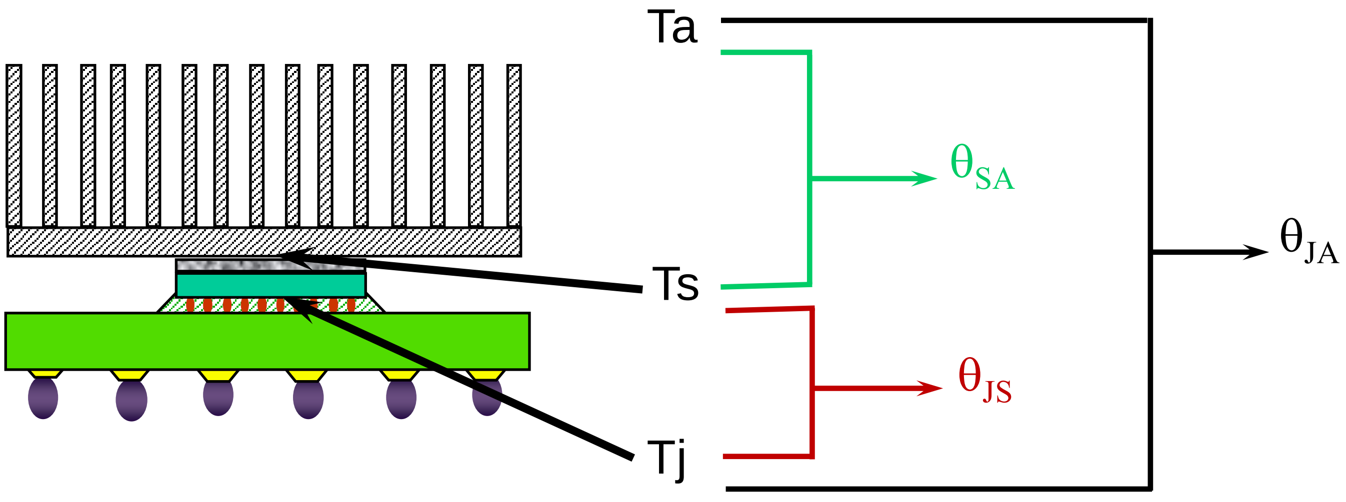
ARCHITECTURE I – Bare Die attach

- Heat sink interfaces with CPU
- Useful for mobile applications

ARCHITECTURE II – Integrated Heat Spreader

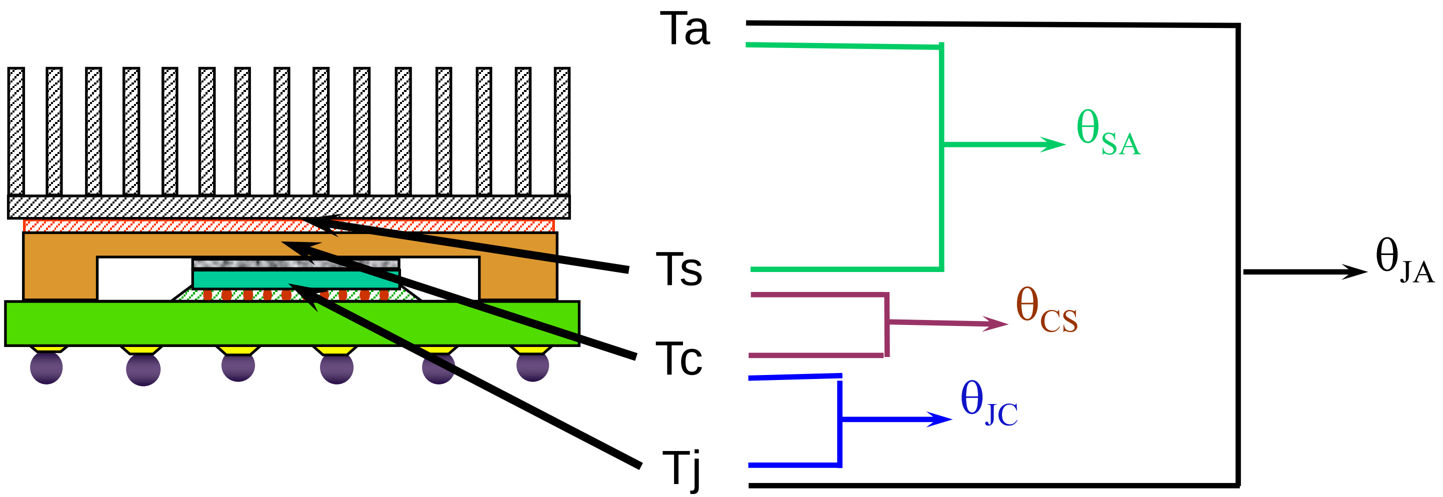
- Heat sink interfaces with IHS
- Two interfaces

Thermal Resistance: *Bare Die attach*



$$\theta_{JA} = \theta_{JS} + \theta_{SA}$$

Thermal Resistance: *Package with IHS example*

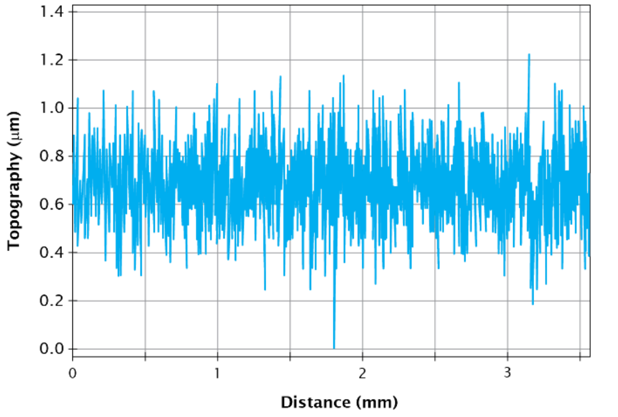


$$\theta_{JS} = \theta_{JC} + \theta_{CS}$$

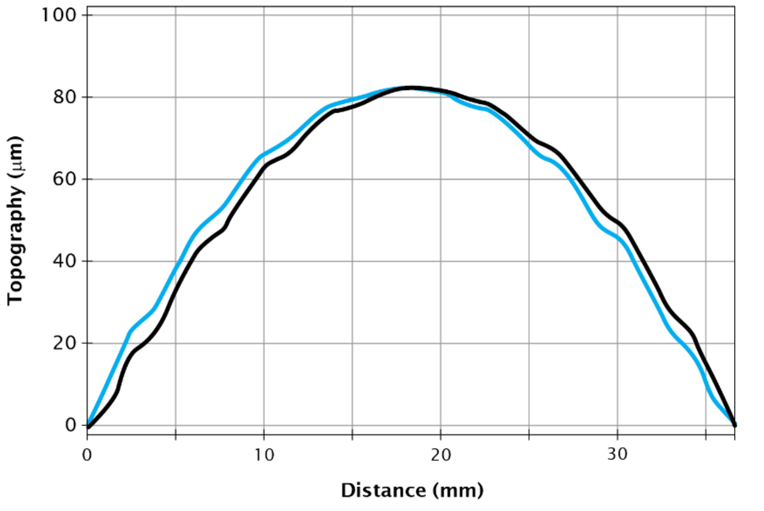
$$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA}$$

Thermal Interface Material (TIM)

- Required to reduce thermal contact resistance
  - Replace air gaps with a more conductive material
- Common types
  - Grease
  - Gel
  - Phase Change Material (PCM)
  - Solder based



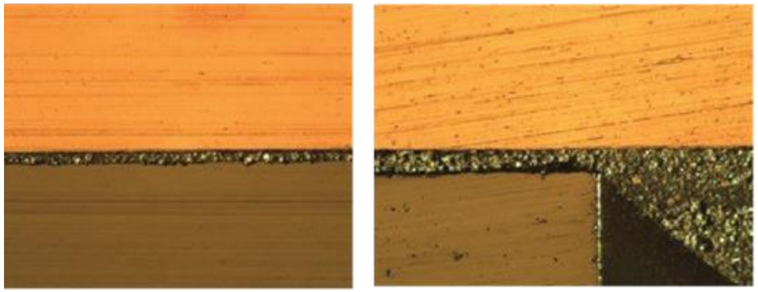
Copper surface



Chip flatness

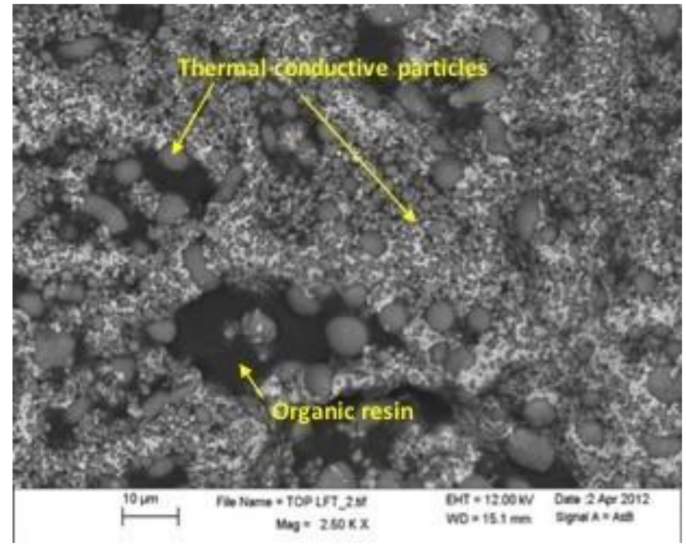
Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

Bondline thickness (BLT)



(a) (b)

Variation of BLT from (a)chip centre to (b) corner



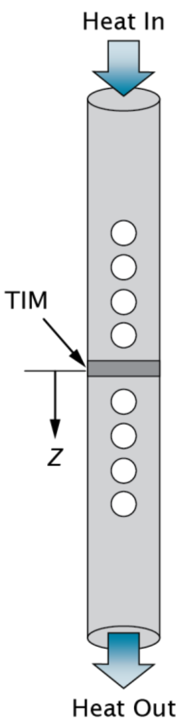
Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

- ❑ Polymeric materials laden with conductive (metallic) filler particles
  - ➢ Increase effective thermal conductivity (k)

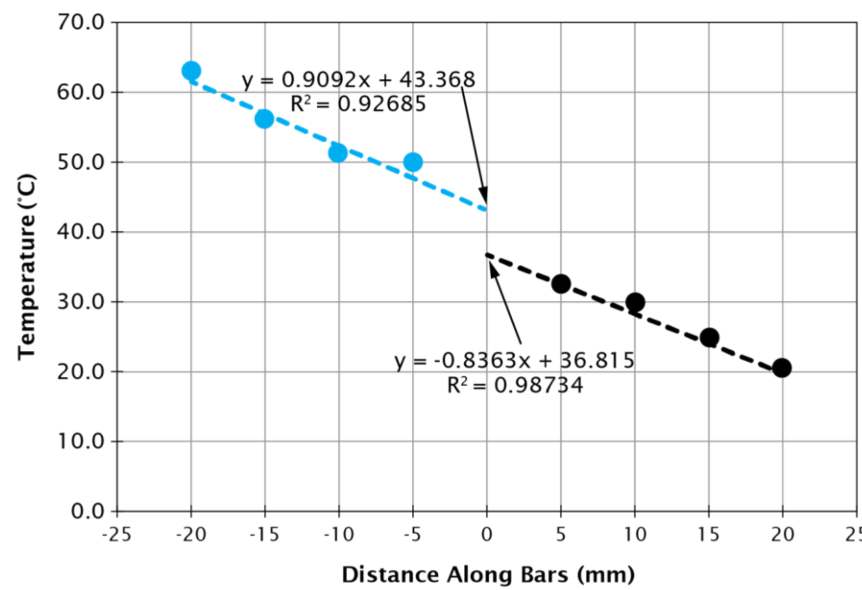
- ❑ Contact resistance contributed by
  - ➢ Bulk thermal conduction
  - ➢ Scattering at interfaces

Determination of TIM resistance

Cut bar tester



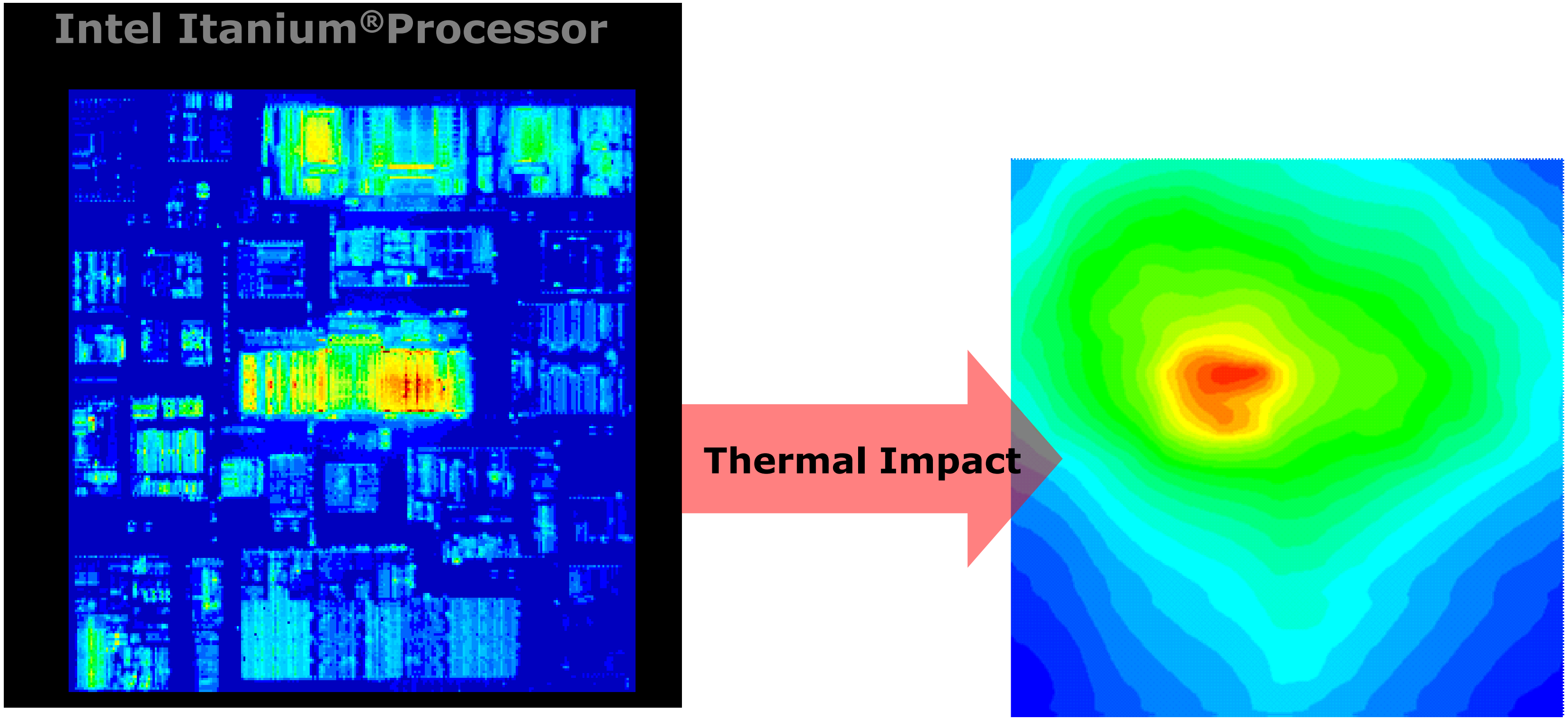
	z(mm)	*T*(C)
1	-20	62.9
2	-15	55.7
3	-10	50.9
4	-5	49.4
5	5	32.1
6	10	29.2
7	15	24.5
8	20	19.7



Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

Can you use this tester to measure thermal conductivity of a solid?

Heat Spreader

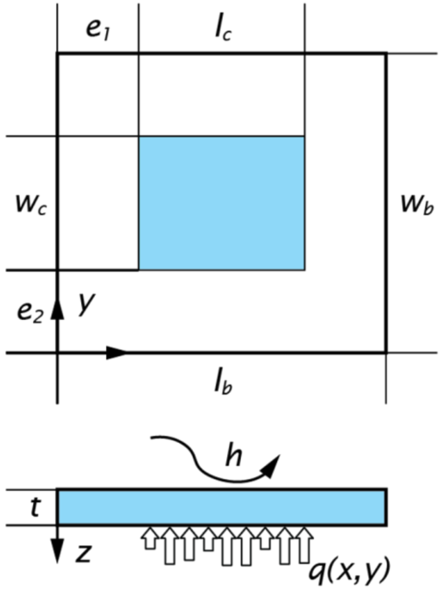


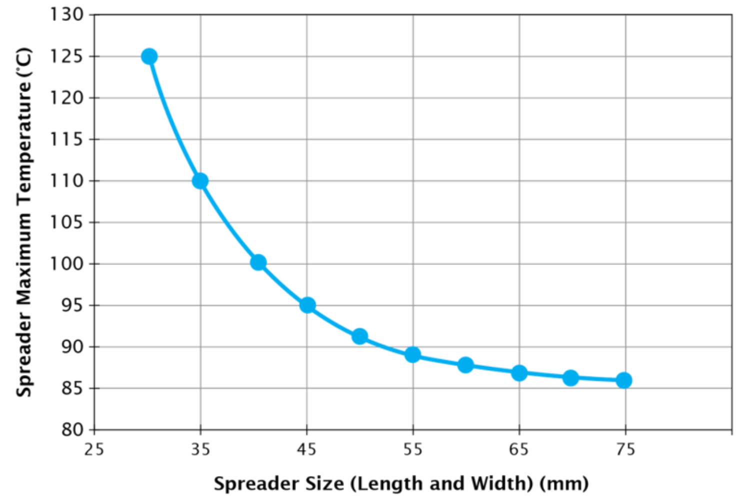
On-Die Power Map **On-Die Temperature Map**

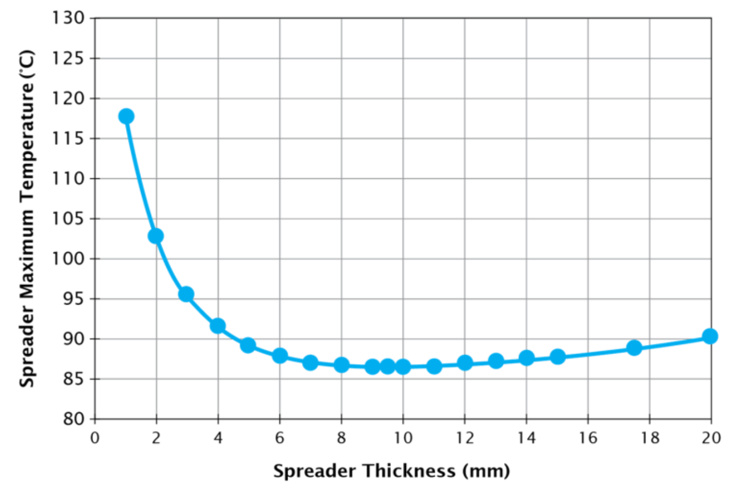
Acknowledgments: Intel Corporation

Heat spreaders help in uniformity of temperature

Illustrative example







- Trade-off
  - Addition of spreading resistance
  - Extended surface area for heat dissipation
- Presence of an optimal spreader thickness

Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

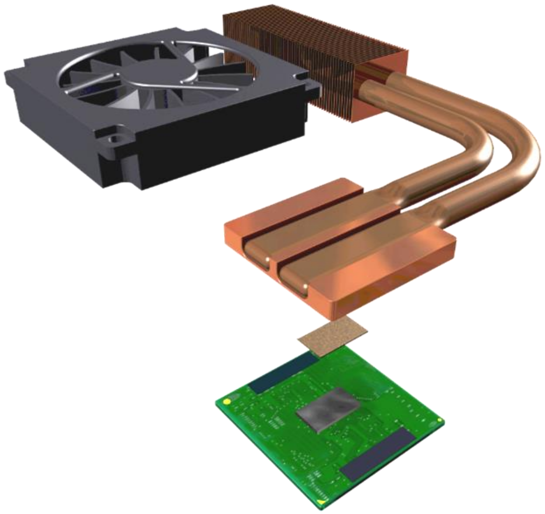
Thermal Management Solutions

Thermal Management

Desktop Systems

https://www.boydcorp.com

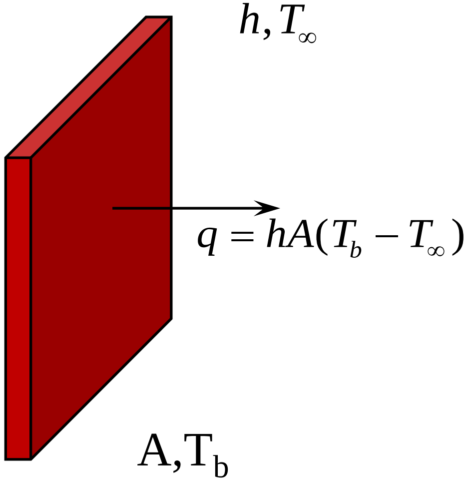
Notebook Systems

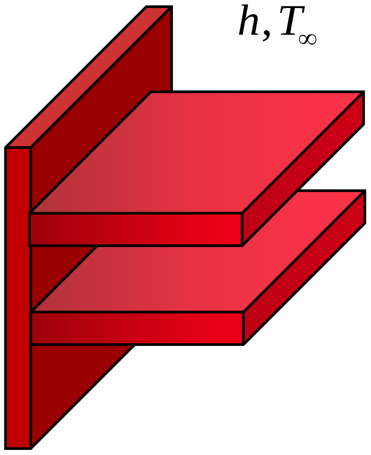


Acknowledgments: Intel Corporation

Fin Heat Transfer

Thermal Management





$$A_{tot} = A_b + \eta N_f A_{fin}$$

Fins increase surface area thus reducing 1/hA

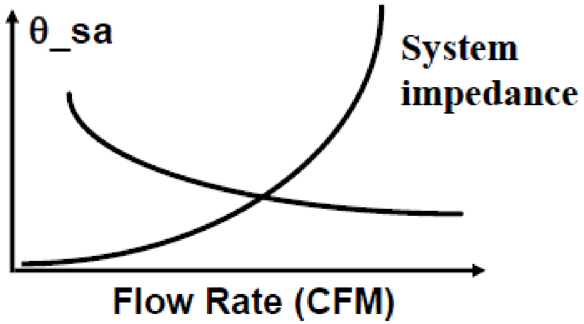
Heat Sink Characterization

Thermal Management

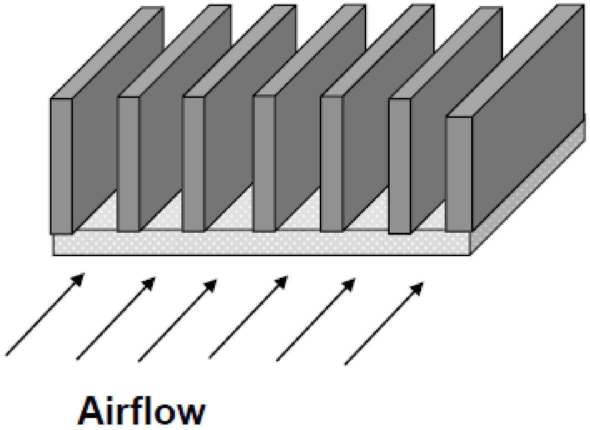
Wind tunnel tests – measure thermal resistance and system impedance

$$\theta_{sa} = \frac{T_s - T_a}{Q} = f(CFM)$$

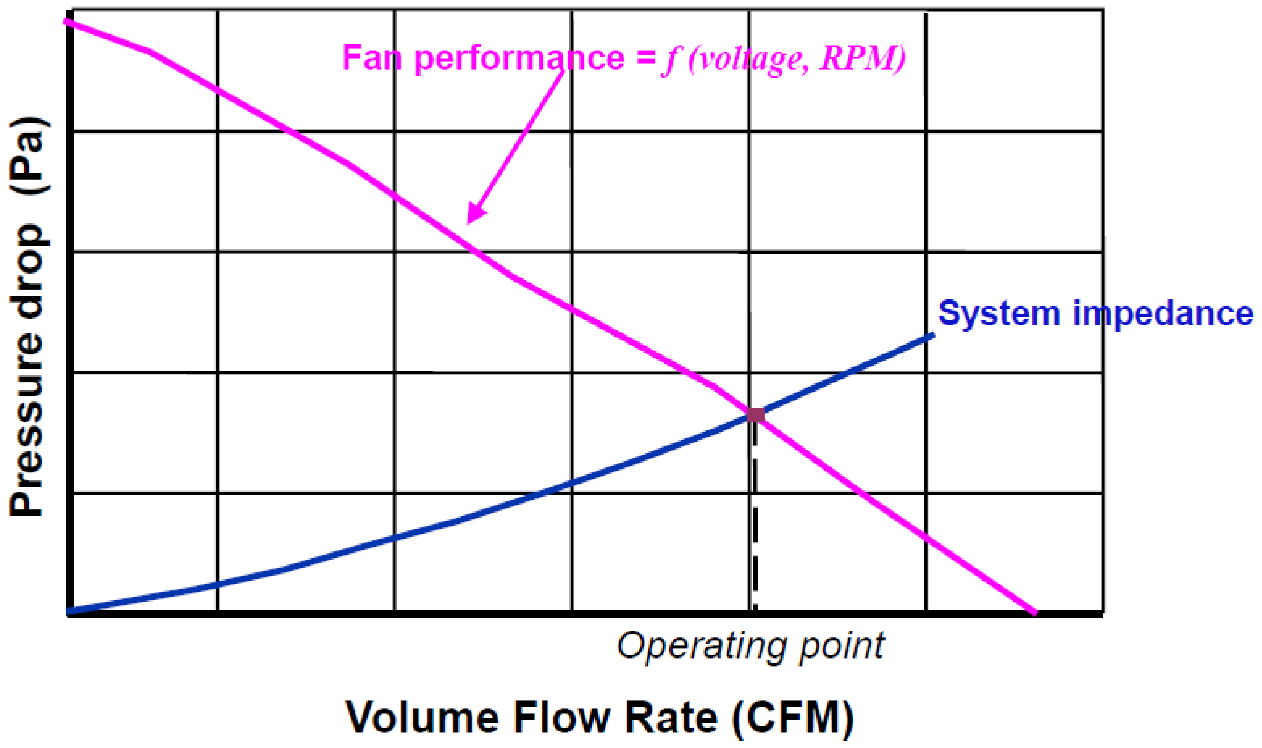
Ts: Heat sink base temperature
Ta: Approaching air temperature
Q: Power supplied to the heat sink



At what flow rate will my system operate?



Heat Sink Characterization (cont.)



Heat sink thermal resistance corresponds to the operating point flow rate

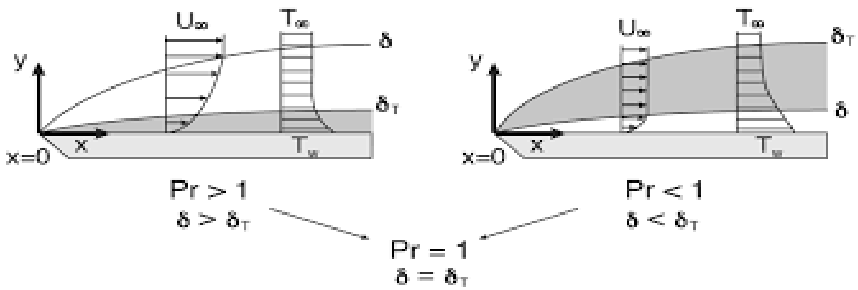
Heat Transfer calculations - correlations

- Flow over Flat Plate

$$\overline{Nu_L} = 0.664 {Re_L}^{1/2} Pr^{1/3}$$ -> Laminar Flow

$$\overline{Nu_L} = 0.0296 {Re_L}^{4/5} Pr^{1/3}$$ -> Turbulent Flow

$$\overline{Nu_L} = \left(0.037 Re_L^{4/5} - 871\right) Pr^{1/3}$$ -> Laminar fo



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- Flat plate with Unheated length

$$Nu_x = \frac{Nu_x\big|_{\xi=0}}{\left[1-\left(\xi/x\right)^a\right]^b}$$

$$Nu_x\big|_{\xi=0} = C\ \mathrm{Re}_x^m\ \mathrm{Pr}^{1/3}$$

	Laminar		Turbulent	
	Isothermal	Isoflux	Isothermal	Isoflux
a	3/4	3/4	9/10	9/10
b	1/3	1/3	1/9	1/9
C	0.332	0.453	0.0296	0.0308
m	1/2	1/2	4/5	4/5

Heat Transfer calculations - correlations

- Flow over Cylinder: Churchill and Bernstein Correlation

$$\overline{Nu}_D = 0.3 + \frac{0.62\,\mathrm{Re}_D^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+(0.4/\mathrm{Pr})^{2/3}\right]^{1/4}}\left[1+\left(\frac{\mathrm{Re}_D}{282{,}000}\right)^{5/8}\right]^{4/5}$$

- Sphere

$$\overline{Nu}_D = 2 + \left(0.4\,\mathrm{Re}_D^{1/2} + 0.06\,\mathrm{Re}_D^{2/3}\right)\mathrm{Pr}^{0.4}\left(\mu/\mu_s\right)^{1/4}$$

- Isothermal Array of Cylinders

$$\overline{Nu}_D = C_2\left[C\ \mathrm{Re}_{D,\max}^{m}\ \mathrm{Pr}^{0.36}\left(\mathrm{Pr}/\mathrm{Pr}_s\right)^{1/4}\right]$$

  - *C*, *m* and C_2 can be found in look-up tables

Forced Convection – Internal Flow

- Circular pipe – Laminar Flow

$\overline{Nu_D} = 3.66$ -> Isothermal wall

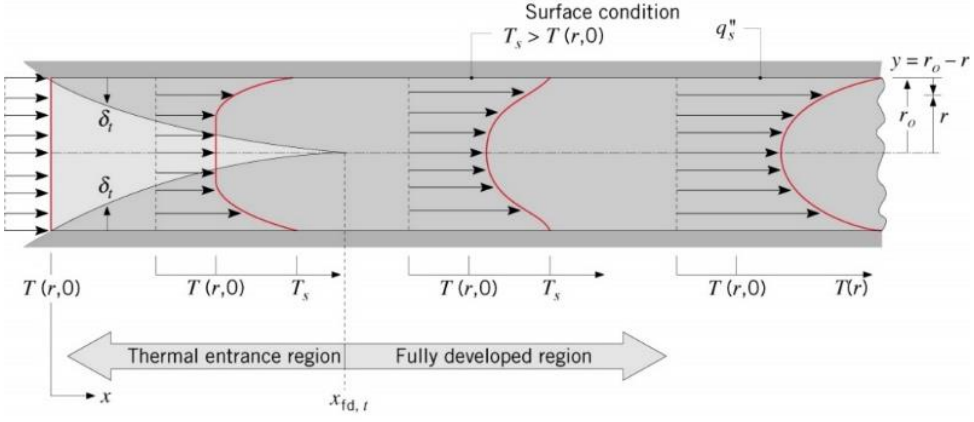
$\overline{Nu_D} = 4.36$ -> Isoflux wall

- Circular pipe – Turbulent Flow

Dittus-Boelter correlation for smooth walls (*$Re_D > 10,000$*)

$\overline{Nu_D} = 0.023{Re_L}^{4/5}Pr^n$ *[n=0.3 for heated wall; n=0.4 for cold wall]*

- Non-circular tubes
  - Use hydraulic diameter



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Pressure drop calculations

Thermal Management

- Fully Developed flow through a channel – pressure gradient along the flow direction (x)

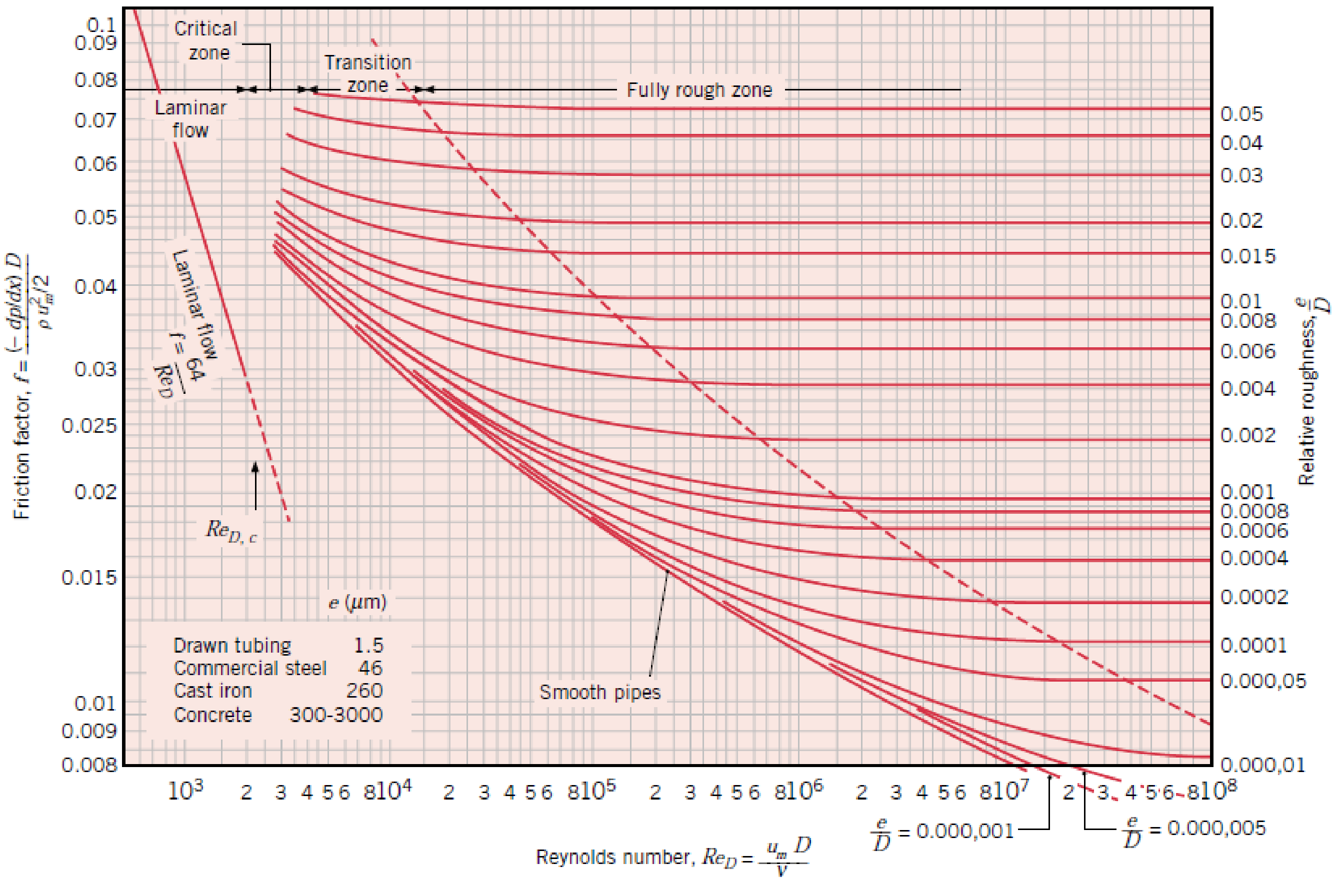
$$\frac{dP}{dx} = \frac{f}{D}\frac{\rho v^2}{2}$$

f is the friction factor

$f = 64/Re_D$ for laminar flow ($Re_D < 2000$)

f -> read from Moody chart for turbulent flow ($Re_D > 2000$)

Moody Chart for friction factor (*f*)



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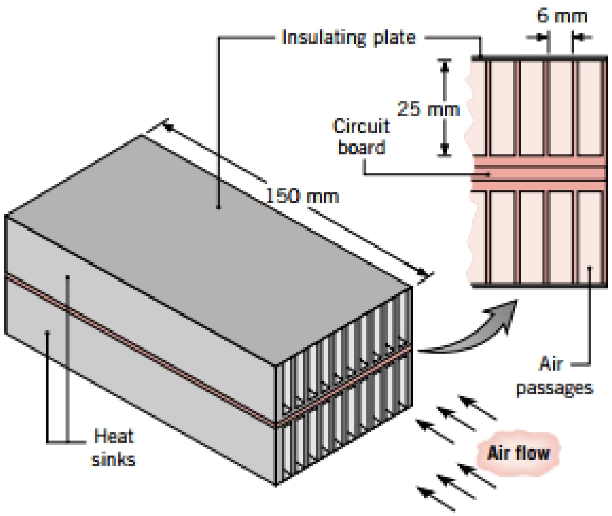
Problem -1

Thermal Management

An electronic circuit board dissipating 50 W is sandwiched between two ducted forced air cooled heat sinks. The sinks are 150-mm in length have 20 air passages of 6-mm x 25-mm. Atmospheric air at a volumetric flow rate of 0.06 m^3/s and 300-K is drawn through the sinks by a blower. Estimate the operating temperature of the board and pressure drop across the heat sinks.

Assuming air properties to be $\nu = 2 \times 10^{-5}\ m^2/s$, $Pr = 0.7$, $k = 0.03\ W/m\text{-}K$; $C_p = 1.78\ kJ/kg\text{-}K$,



Natural Convection

❑ Vertical Flat Plate

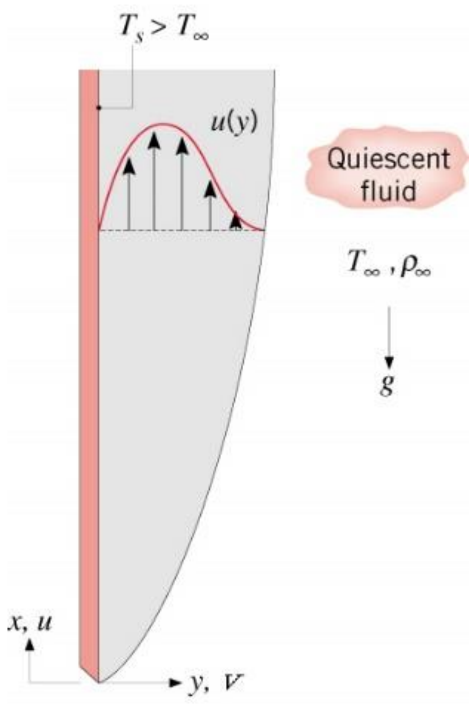
- Empirical Heat Transfer Correlations

$$\overline{Nu}_L = 0.68 + \frac{0.670\ Ra_L^{1/4}}{\left[1+\left(0.492/\Pr\right)^{9/16}\right]^{4/9}}$$

➢ Laminar Flow $\left(Ra_L < 10^9\right)$:

$$\overline{Nu}_L = \left\{0.825 + \frac{0.387\ Ra_L^{1/6}}{\left[1+\left(0.492/\Pr\right)^{9/16}\right]^{4/9}}\right\}^2$$

➢ Turbulent Flow $10^9 < Ra_L < 10^{12}$



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Natural Convection

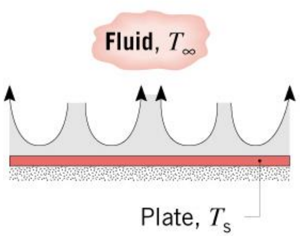
Thermal Management

- Horizontal flat plate

Facing up

$$\overline{Nu}_L = 0.54\, Ra_L^{1/4} \qquad \left(10^4 < Ra_L < 10^7\right)$$

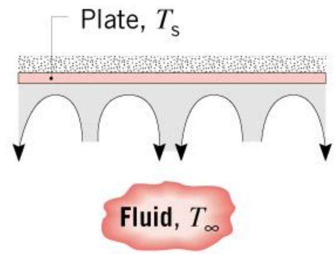
$$\overline{Nu}_L = 0.15\, Ra_L^{1/3} \qquad \left(10^7 < Ra_L < 10^{11}\right)$$



$T_s > T_\infty$

Facing down

$$\overline{Nu}_L = 0.27\, Ra_L^{1/4} \qquad \left(10^5 < Ra_L < 10^{10}\right)$$



$T_s < T_\infty$

Incropera and Dewitt, 6th Edition

Natural Convection through vertical channels

Thermal Management

- Correlations of Bar Cohen and Rohsenow for different boundary conditions

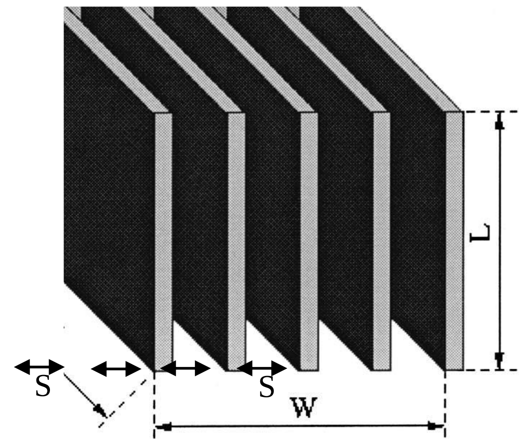
Isothermal plates:

$$\overline{Nu}_S = \left[\frac{C_1}{(Ra_S\, S/L)^2} + \frac{C_2}{(Ra_S\, S/L)^{1/2}} \right]^{-1/2}$$

Isoflux plates:

$$Nu_{S,L} = \left[\frac{C_1}{Ra_S^*\, S/L} + \frac{C_2}{(Ra_S^*\, S/L)^{2/5}} \right]^{-1/2}$$

$$Nu_{S,L} = \left(\frac{q_s''}{T_{s,L} - T_\infty} \right) \frac{S}{k} \qquad Ra_S^* = \frac{g\beta q_s'' S^4}{k\alpha\nu}$$

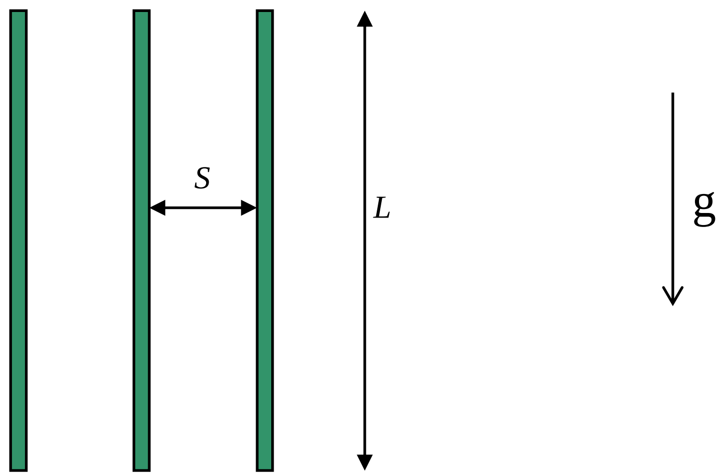


Incropera and Dewitt, 6th Edition

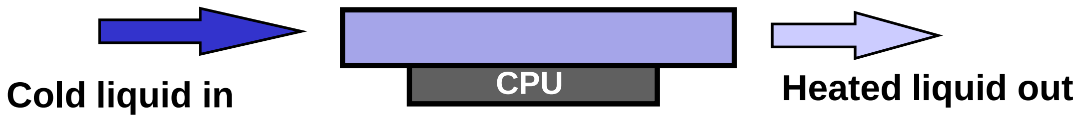
Surface Condition	C_1	C_2	S_{opt}	S_{max}/S_{opt}
Symmetric isothermal plates ($T_{s,1} = T_{s,2}$)	576	2.87	$2.71(Ra_S/S^3L)^{-1/4}$	1.71
Symmetric isoflux plates ($q''_{s,1} = q''_{s,2}$)	48	2.51	$2.12(Ra_S^*/S^4L)^{-1/5}$	4.77
Isothermal/adiabatic plates ($T_{s,1}$, $q''_{s,2} = 0$)	144	2.87	$2.15(Ra_S/S^3L)^{-1/4}$	1.71
Isoflux/adiabatic plates ($q''_{s,1} = q''_{s,2} = 0$)	24	2.51	$1.69(Ra_S^*/S^4L)^{-1/5}$	4.77

Problem -2

A vertical array of printed circuit boards is immersed in quiescent ambient air at 17ºC. Although the components on the board protrude from their substrates on the circuit boards, it is reasonable, as a first approximation, to assume them as flat plates with uniform surface heat flux. Consider boards of length and width L = W = 0.4m and spacing S = 25mm. If the maximum allowable temperature of the board is 77ºC, what is the maximum allowable power dissipation per board?

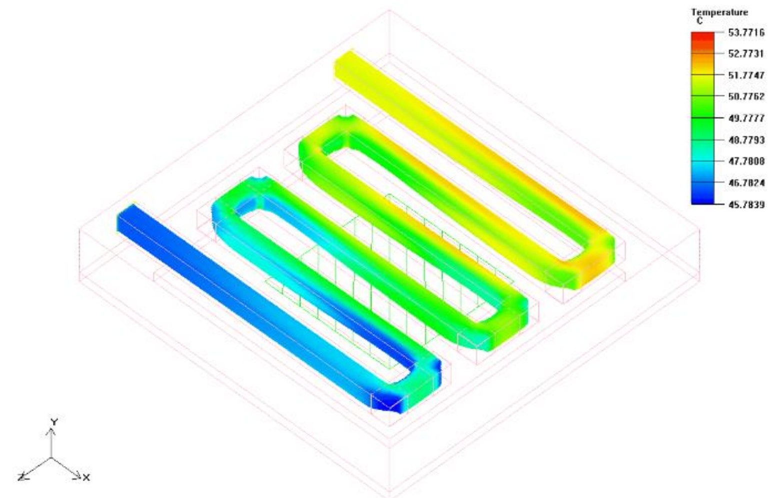


Liquid Cooled Cold Plates



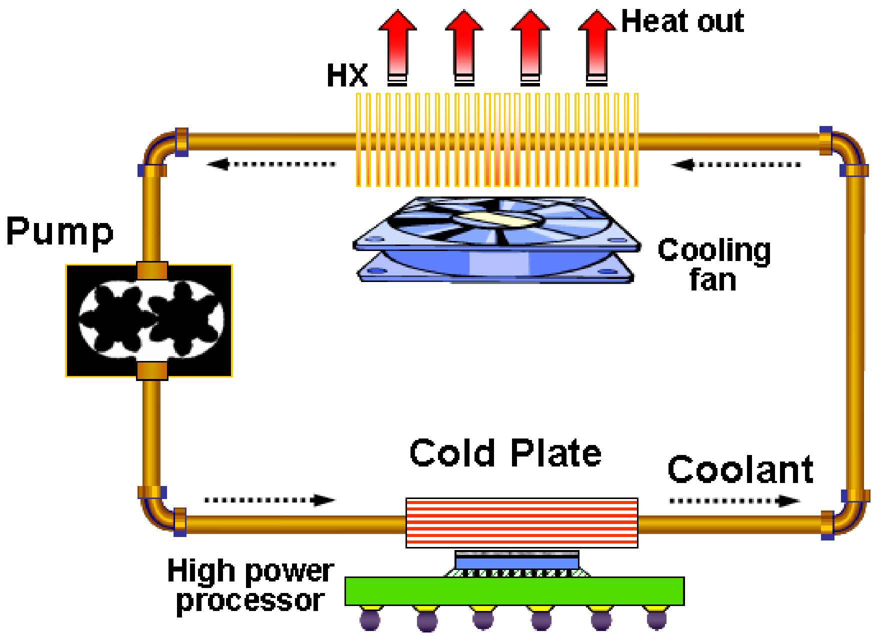
$$q = \dot{m} C_p (T_{out} - T_{in})$$

Source: https://www.lytron.com/Cold-Plates



Acknowledgment: Intel

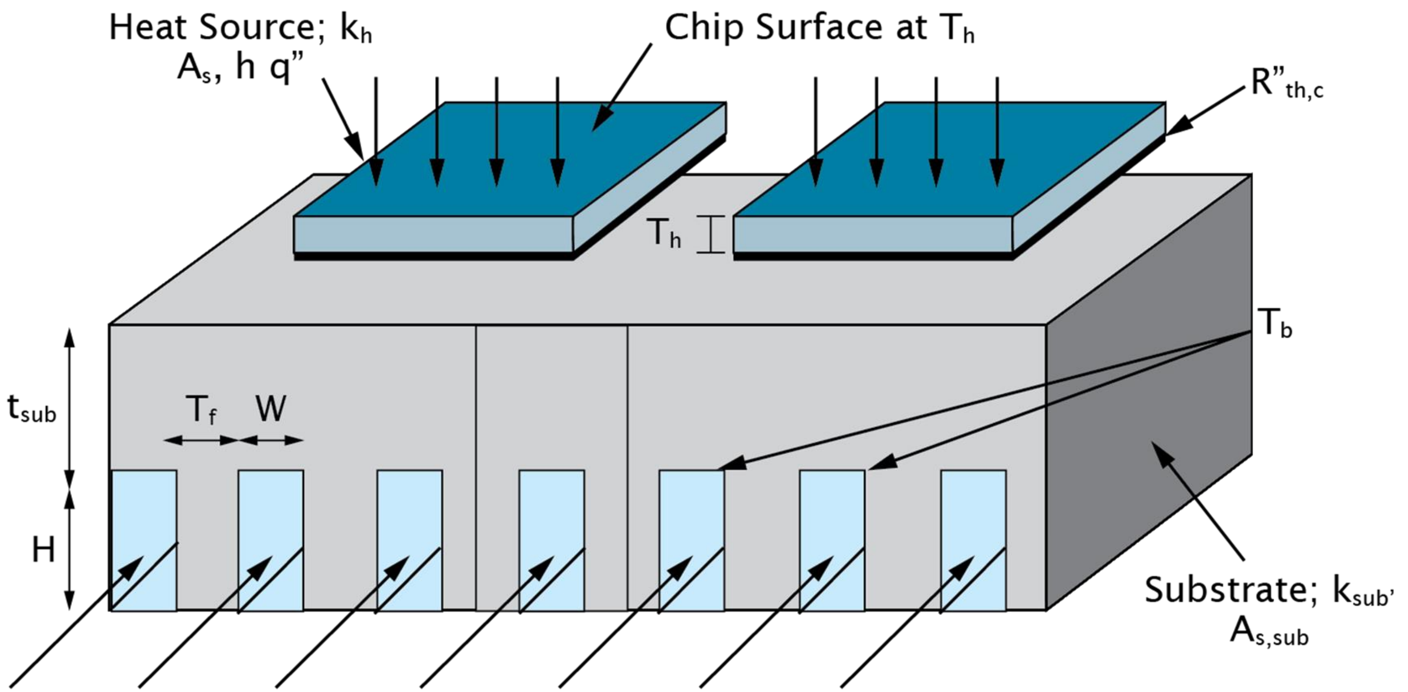
Pumped Liquid Cooling solution



Prasher et al, 2006

Finally, EVERY thermal solution is AIR COOLED

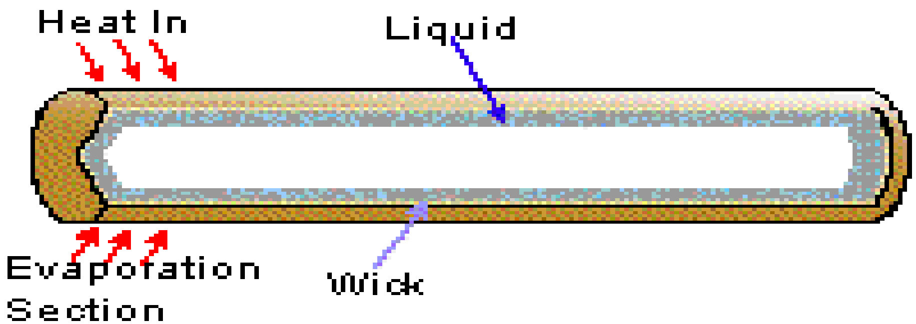
Microchannel Cold Plate

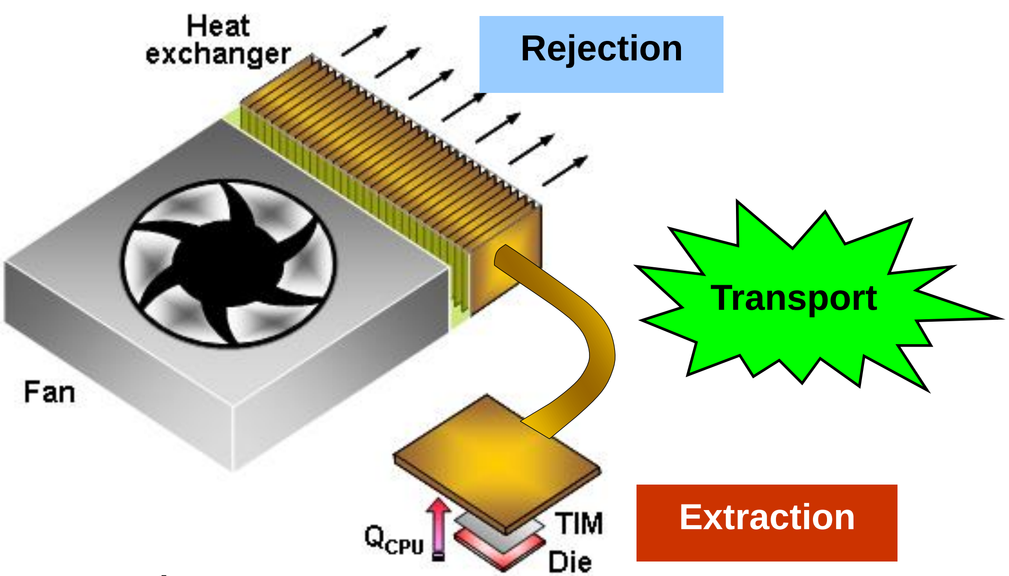


Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

- ❑ As hydraulic diameter (D_h) reduces, heat transfer coefficient h increases
- ❑ Penalty in terms of pressure drop or pumping power

Heat pipe



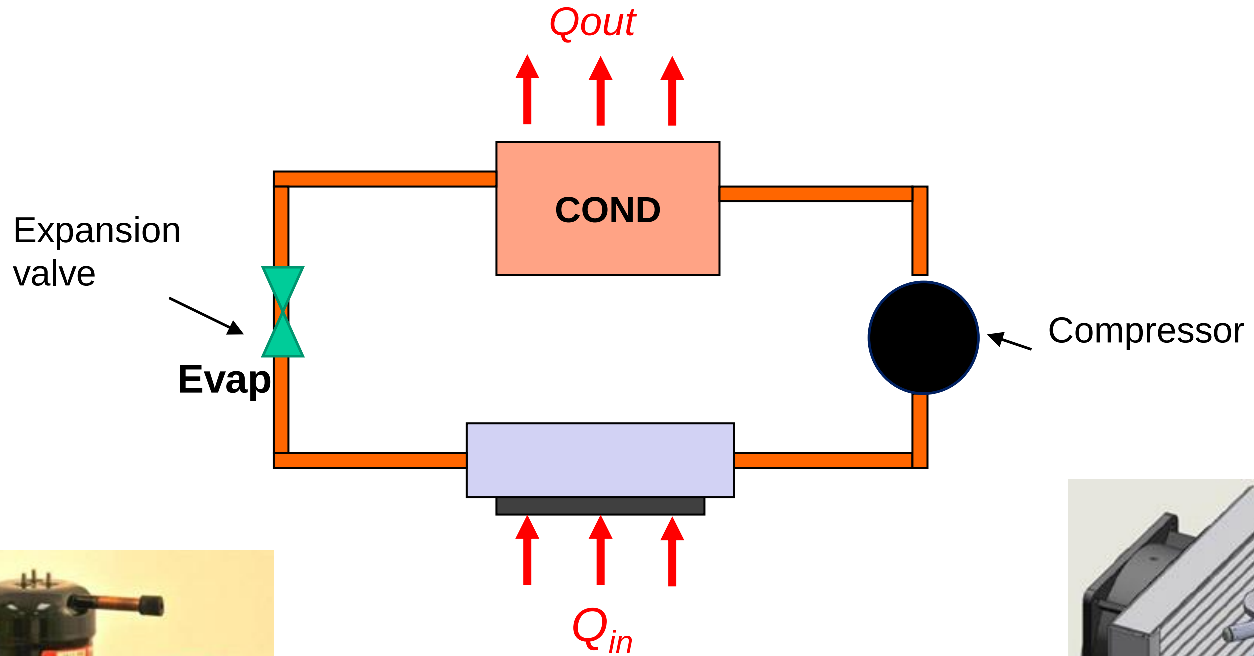


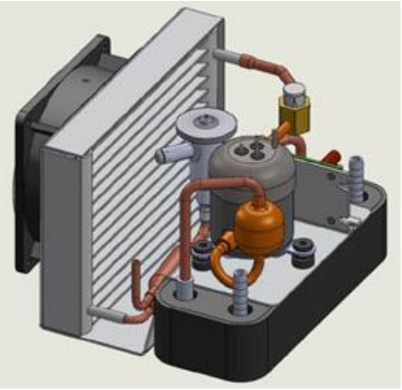
Mongia et al. 2007

- Very high thermal conductivity
  - *Effective axial k ~10,000 W/m-K*
- Means of transporting heat from an “inconvenient” location to a “convenient” location

Refrigeration Cooling Techniques

- Heat Flow across adverse temperature gradient
- Needs external energy to drive compressor

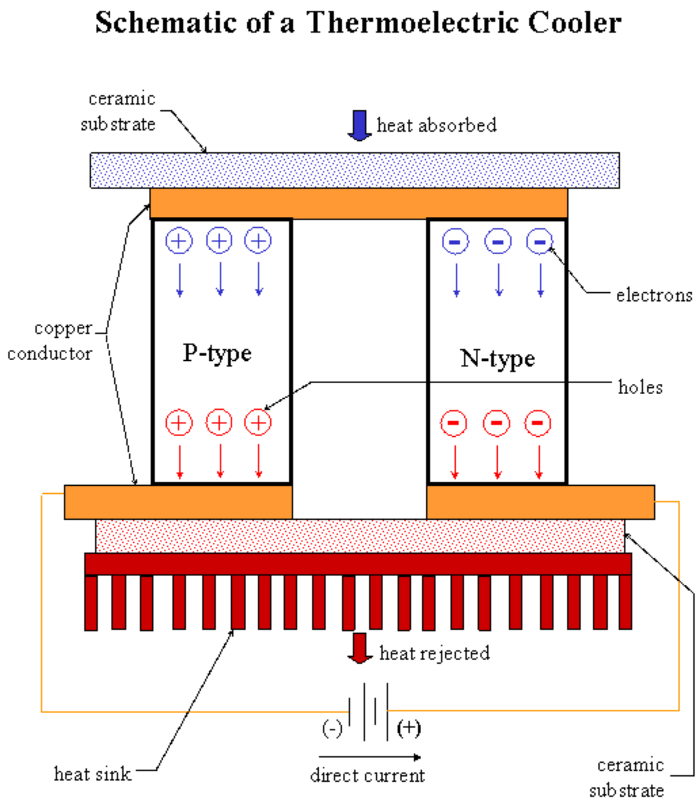




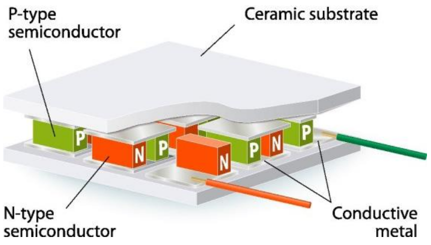
Source: Aspen Compressors

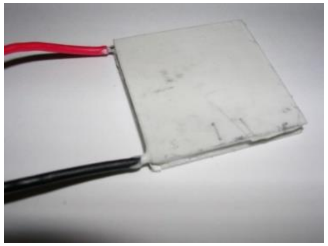
Thermoelectric Refrigeration

Thermal Management



www.santarosa.edu/~yataiiya/E45/PROJECTS/peltier.ppt



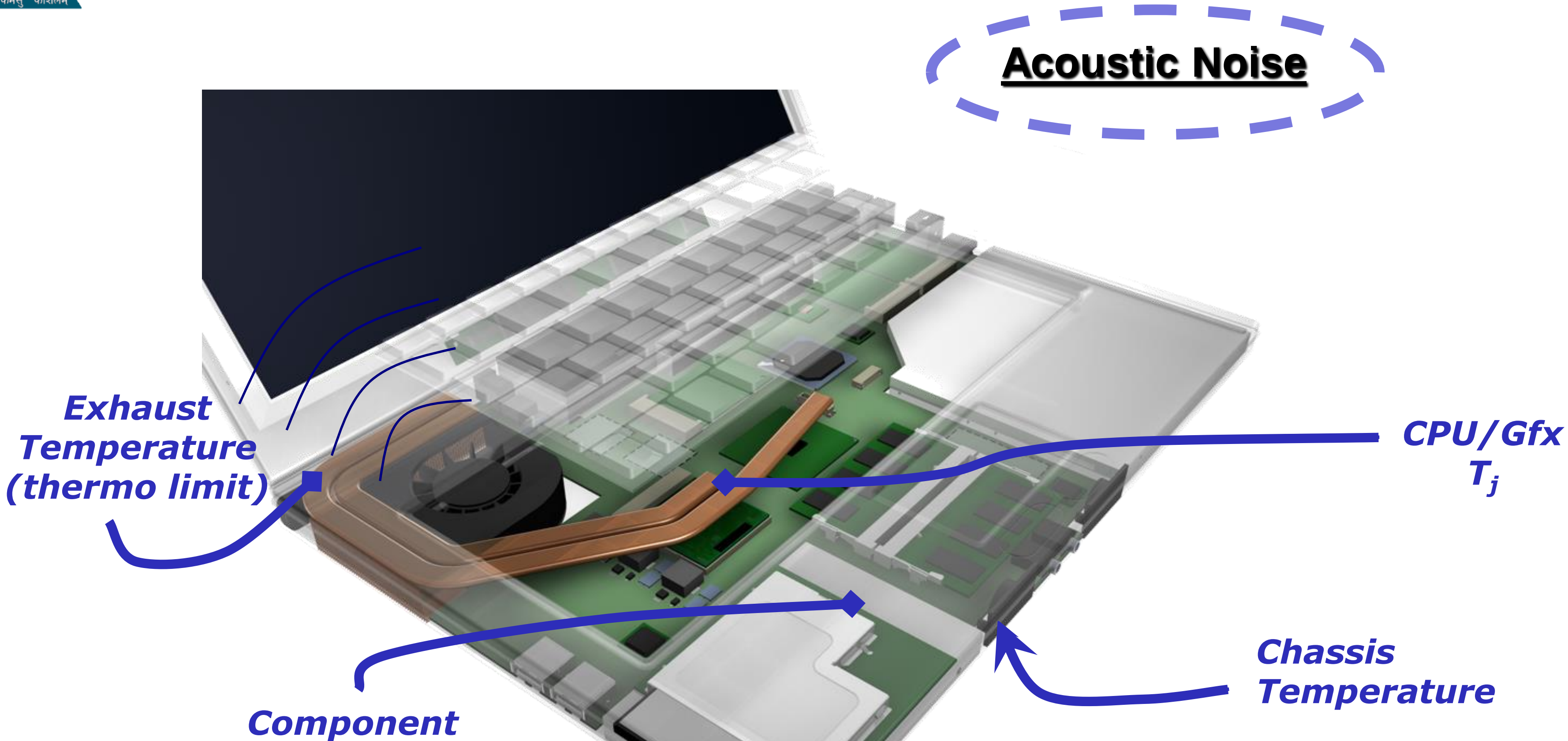


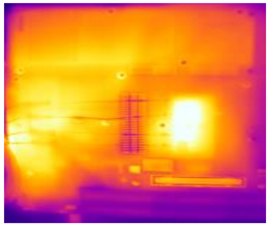
http://cleantechnica.com/2014/06/13/

- Solid State device
- No moving parts
- Inexpensive and reliable
- Low efficiency and COP

System Level Thermal Design - Laptop

Thermal Management

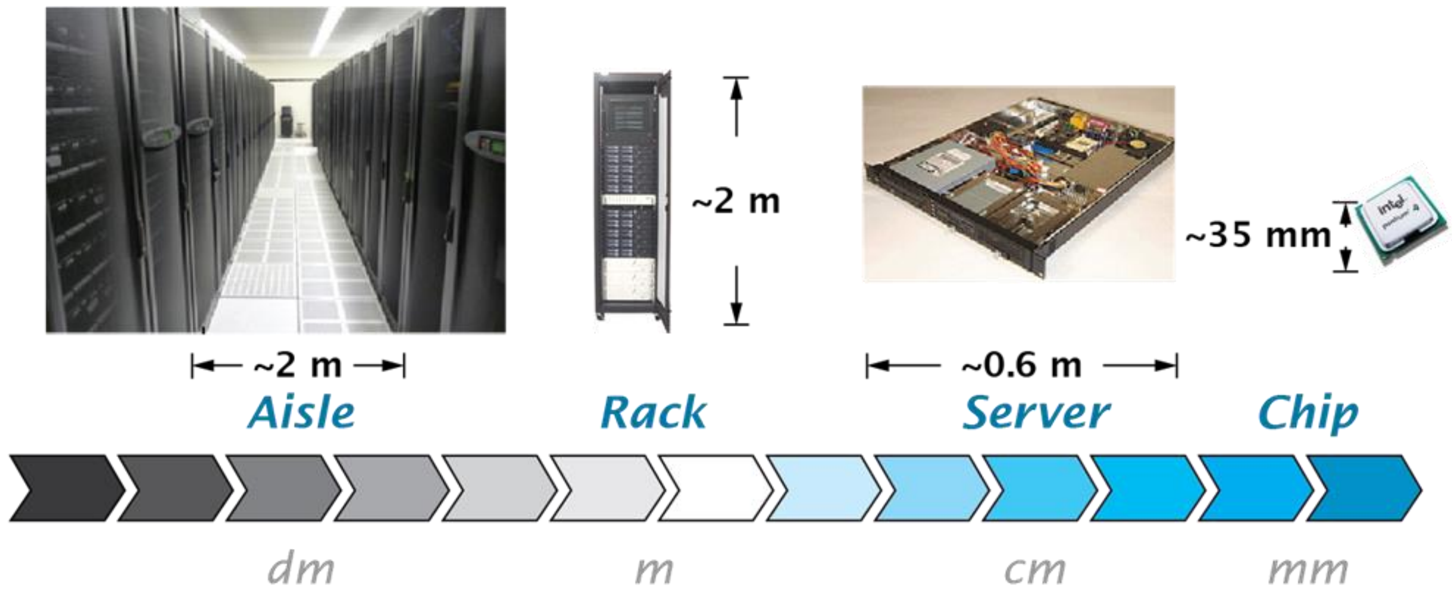


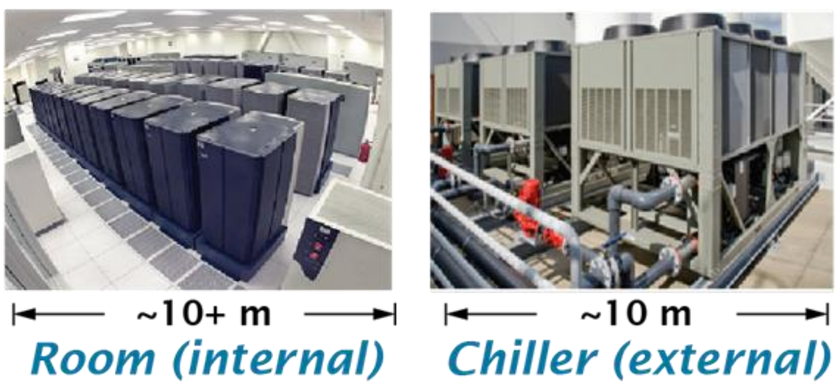


Mongia et al. (2007)

Multiple challenges at chip and system levels

Server Room and Data Centre





- O(10^5) length scales from server to ambient heat rejection
- Similar variation from on-chip interconnects to chip scale
- Multi-scale time dependence also important

Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

Air cooled server room

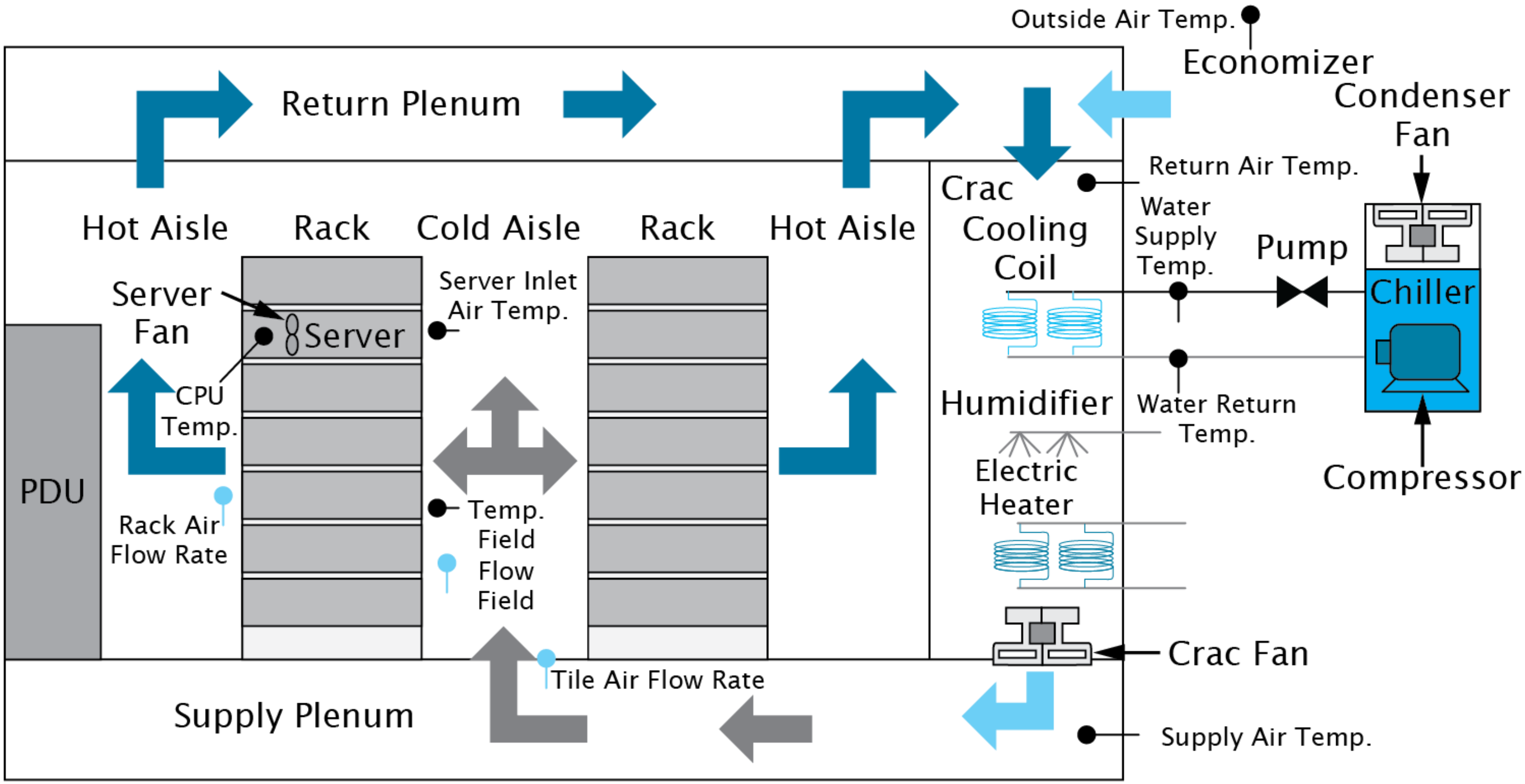
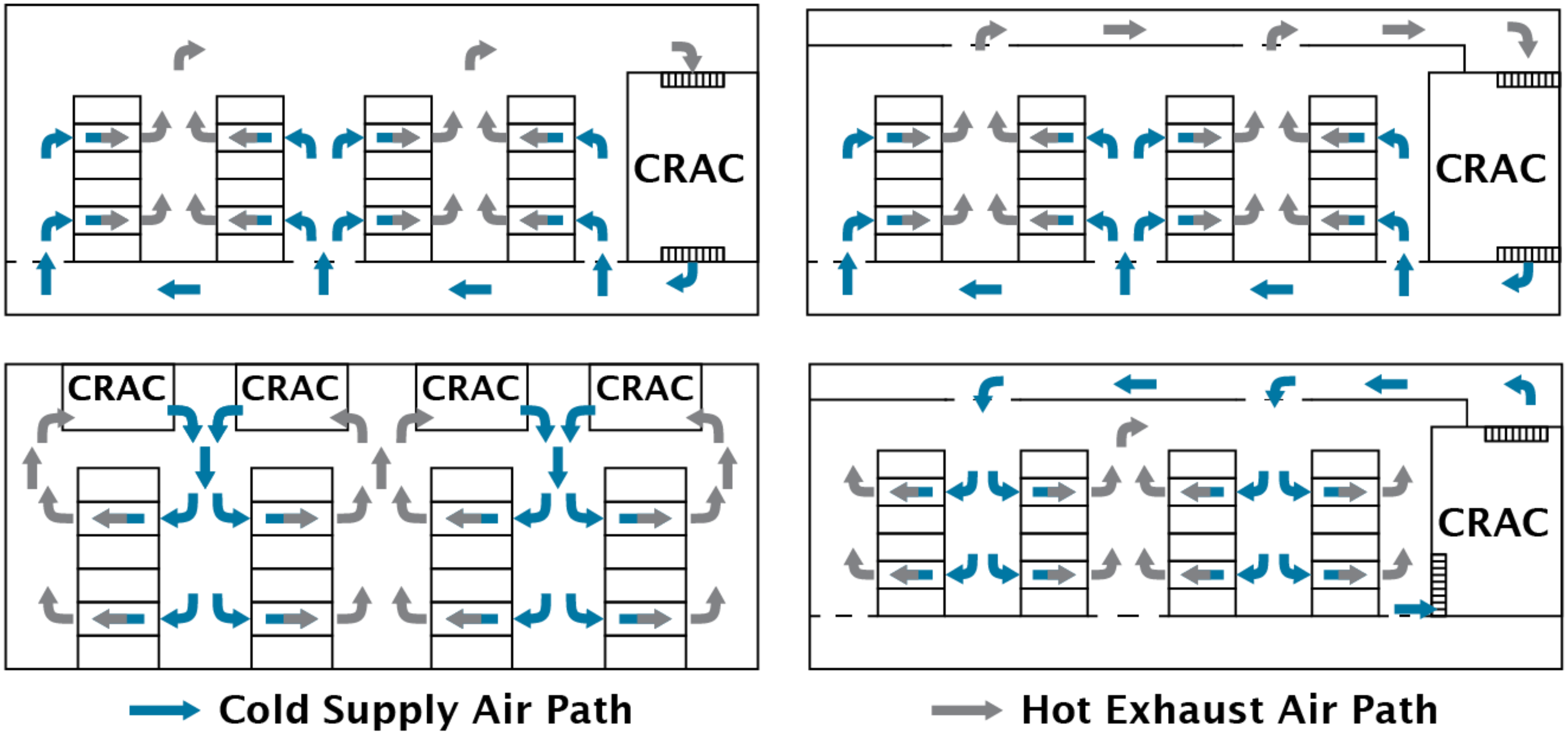


Fig 3.29 - Raised floor air-cooled

Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

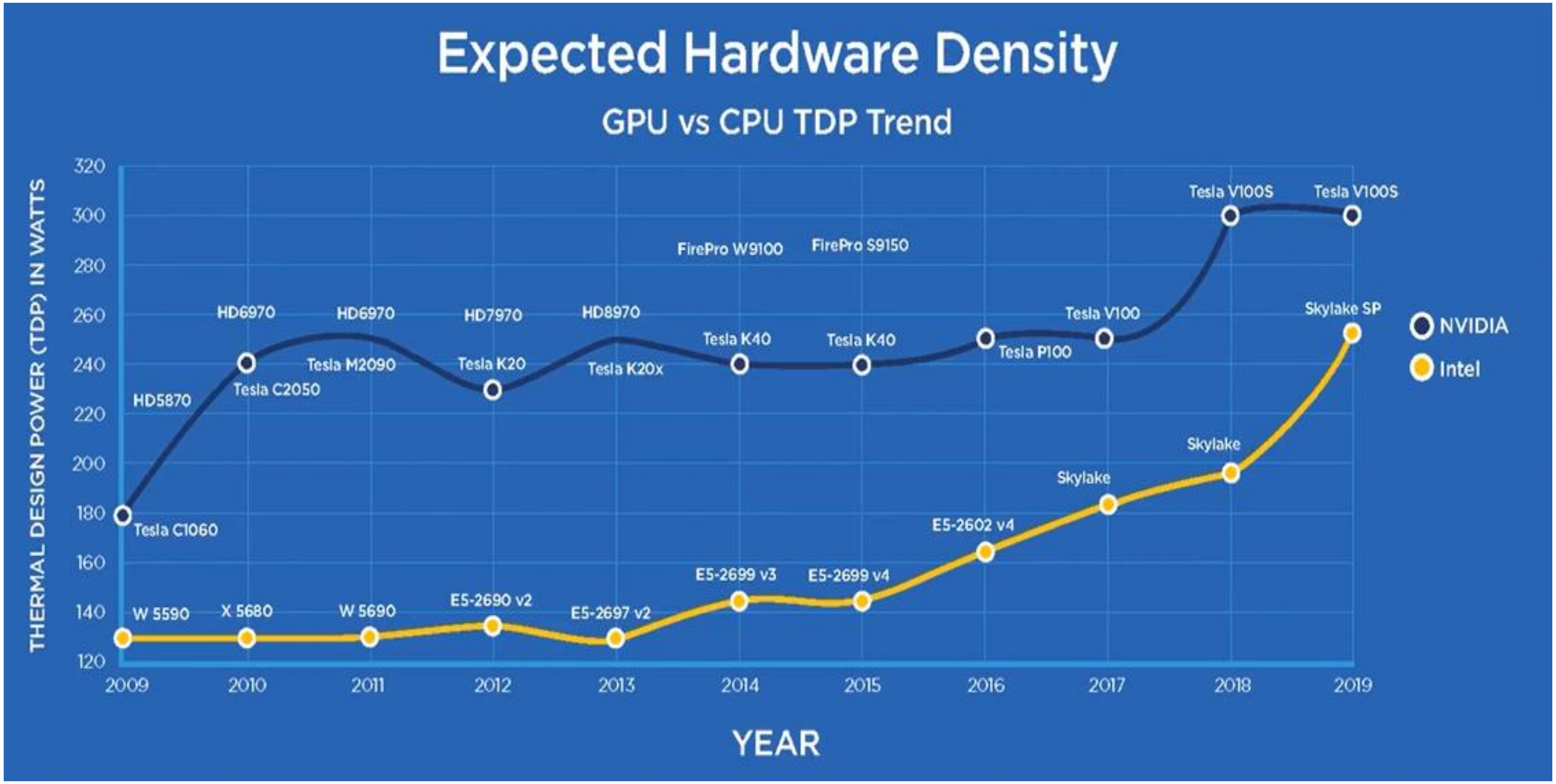
Various patterns



Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

“Hardware is Heating up!” …

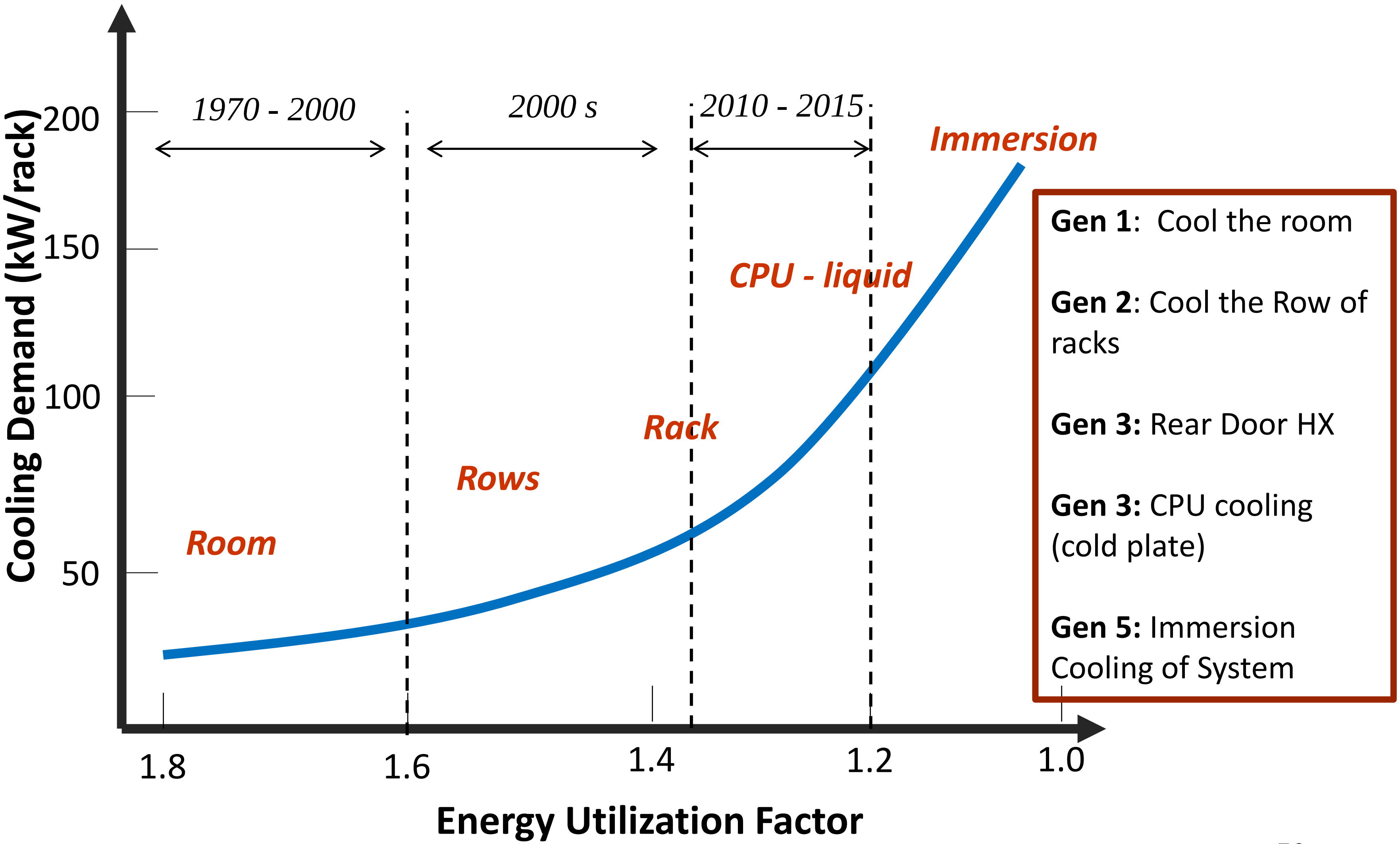
Thermal Management



Source: www.grcooling.com

Data Center Cooling - Evolution

Thermal Management



Thermal Management

Immersion Cooling

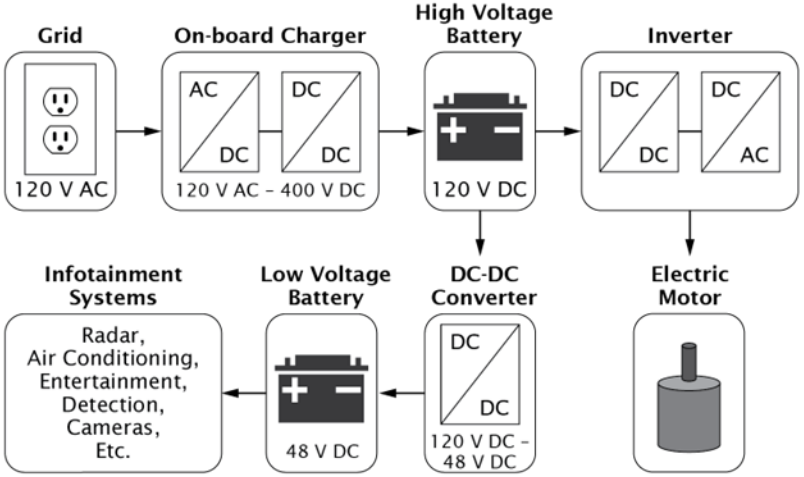
Source: *Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019*

PEZY/ExaScaler's Green500 winning immersion cooling systems cooled with a 3M Fluorinert dielectric fluid

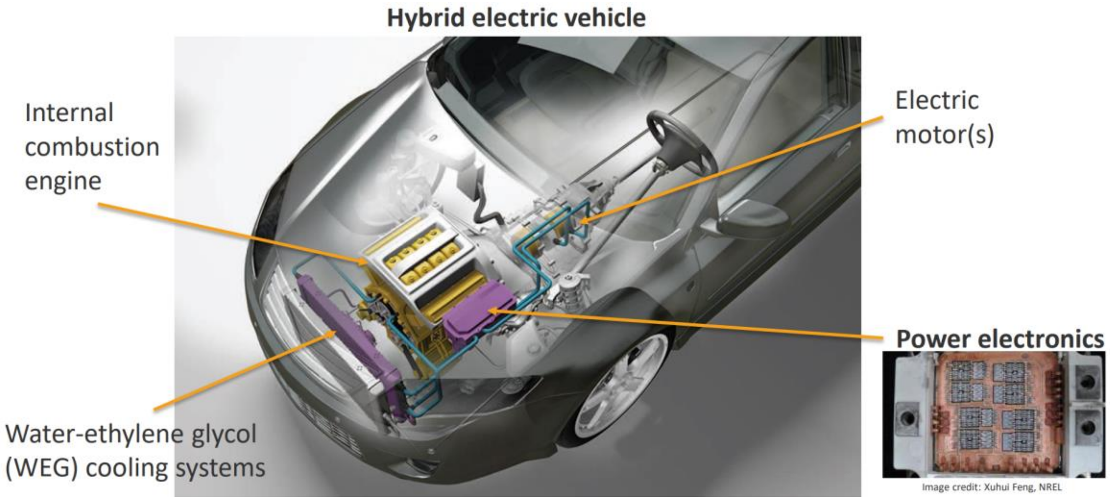
Source: Business Wire

Immersion Cooling becoming important

Power Electronics and EVs

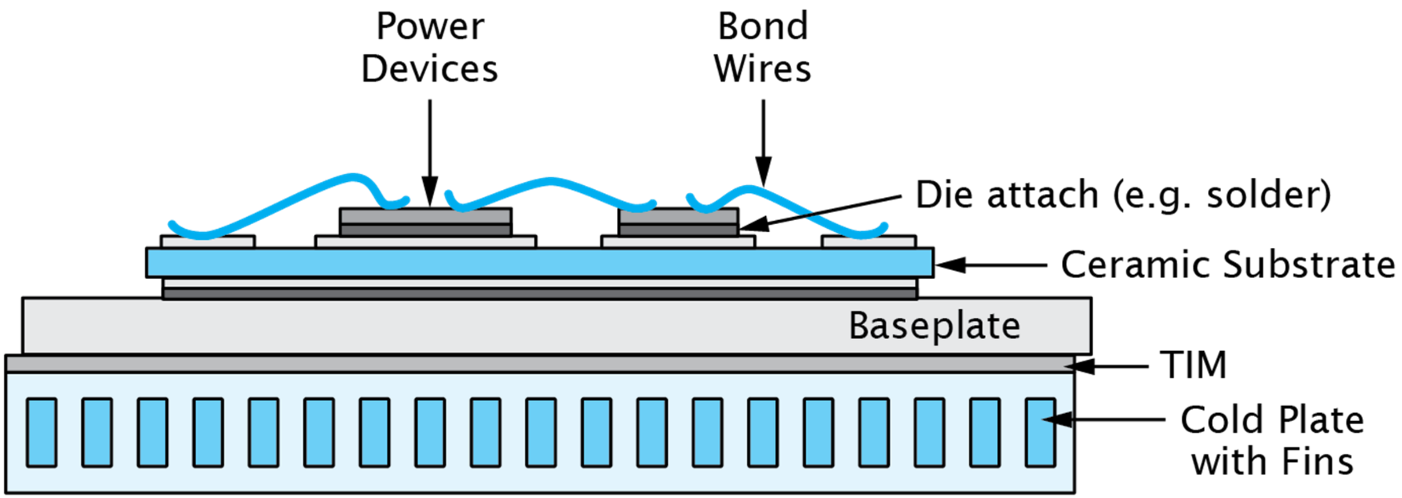


Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019



G. Moreno, S. Narumanchi, K. Bennion, S. Waye, and D. DeVoto. 2014. "Gaining Traction: Thermal Management and Reliability of Automotive Electric Traction-Drive Systems." *Electrification Magazine* 2 (2): 42–49. doi: 10.1109/MELE.2014.2314501.

Anatomy of Power Electronic package



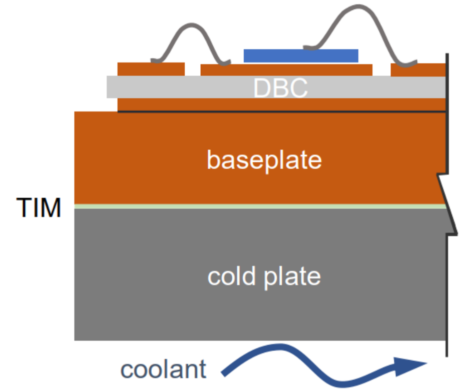
Source: Fundamentals of Device and Systems Packaging, Rao Tummala (ed), 2019

Cooling Techniques

Thermal Management

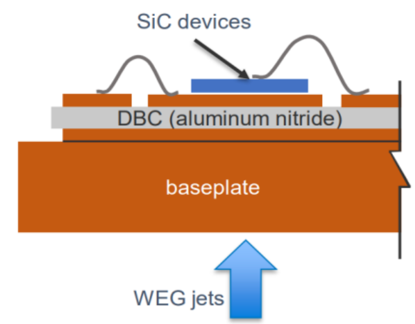
Cold Plate with coolant

Coolant flow through a cold plate



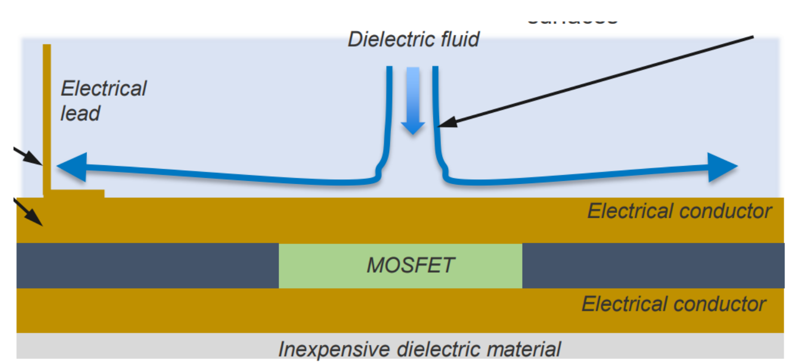
Jet Impingement with WEG

Uses a jet-impingement-on-module base plate cooling approach



Jet Impingement with Dielectric

Jet-impingement of dilectric fluid directly on components



Acknowledgment: Dr. Sreekant Narumanchi, NREL

Summary

Thermal Management

- Thermal management in electronics – an area full of challenges and opportunities
- Thermal design requires both device and system level perspectives
- Future thermal challenges include
  - Implementable CPU cooling alternatives
  - Low profile fans: move more air silently
  - Data Centre thermal innovations and energy efficiency
  - Compact cooling solutions for automotive power modules
  - High performance and reliable TIMs
- We need to continue to assess future demand and provide innovative thermal technologies

Need for innovative thermal technologies to address device and system level cooling challenges


Thank you