EEC 216 Lecture #13: Thermal Design

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Outline

- **Announcements**
- **Heat Transfer**
- **Thermal Circuits**
- **Thermal Design Issues**

Announcements

- **Final Project presentations tomorrow**
- **Eight minutes per presentation (4 slides max including title slide)**
- **Two-page final project papers due tomorrow at 5 PM by email (electronic versions only)**
  - **PDF greatly preferred**

Heat Transfer Mechanisms I

- **Conduction**
  - Transfer medium is stationary
  - Heat transfers through vibratory motion of atoms, molecules
  - Ex: heat sink, thermoelectric generators
- **Convection**
  - Transfer occurs through mass movement – fluid flow (liquid or gas)
  - Natural: buoyancy created by temperature gradients causes fluid movement
  - Forced: mass flow created by pumps or fans
  - Ex: most computers use forced convection air cooling

Heat Transfer Mechanisms II

- **Radiation**
  - Heat energy is converted into electromagnetic radiation
  - Spectrum of radiation mostly lies in infrared region
  - Can create an *ideal radiator* using a hole in a heated cavity and measure the spectrum of emitted light
- **<u>Spectral radiancy</u> S(λ): define such that S(λ)dλ gives radiated power per unit area for differential wavelength interval λ to λ+dλ**

$$S(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

- **Conduction and convection most prevalent outside of space applications**

Circuit Models for Heat Transfer

- **Analyze heat transfer using same approaches (KCL, KVL, eigenvalues) which work for electrical circuits**
- **Applicable when conduction and convection dominate radiation**
  - Radiation is too complex to represent using linear circuit analogs
  - Design will be conservative since radiation removes more heat, unless devices are enclosed
- **Static and dynamic models may apply**

Thermal Resistance

- **Rate Q_{12} at which heat energy is transferred from body at temperature T_1 to temperature T_2 is linear proportional to temperature difference:**

$$Q_{12} = \frac{T_1 - T_2}{R_\Theta}$$

- **Define a <u>thermal resistance</u> R_Θ between bodies**
- **Analogous to Ohm's Law**

Thermal Variable Circuit Analogs

- **Q_{12} corresponds to current *i***
- **T_1, T_2 corresponds to voltage V_1, V_2**
- **R_Θ corresponds to resistance *R***
- **Note that the electrical analog of thermal power is *i*, <u>not</u> *vi***
  - If heat leaves a system only through interface characterized by R_Θ, then P_{diss} also corresponds to *i*
  - Q_{12} represents rate at which electrical energy is converted to heat
- **Thermal management problem is to design R_Θ to constrain $\Delta T = T_1 - T_2$**

Thermal Variable Units

- **Q has units of power, Watts (W)**
- **T has units of temperature, degrees Celsius (°C)**
- **Thermal resistance R_{Θ} has units (°C/W)**
- **Thermal resistances can be combined in series and parallel equivalent resistances, just like electrical resistance**

Thermal Resistivity

- **Thermal conduction and electrical conduction are intimately related**
  - Good electrical conductors are often good thermal conductors (Wiedeman-Franz Law)
- **Bulk material property analog of electrical resistivity is thermal resistivity ρ_Θ**
  - Units are °C-cm/W
- **Longitudinal thermal resistance is** $R_\Theta = \dfrac{\rho_\Theta l}{A}$
- ***l* is material length**
- ***A* is cross-sectional area**

Thermal Resistivity of Electrical Materials

MATERIAL	RESISTIVITY (°C-cm/W)
Still Air	3050
Mylar	635
Silicone grease	520
Mica	150
Filled silicone grease	130
Alumina (Al_2O_3)	6.0
Silicon	1.2
Beryllia (BeO)	1.0
Aluminum Nitride (AlN)	0.64
Aluminum	0.48
Copper	0.25

- **Kassakian, 1991**

Practical Thermal Interfaces

- **Mechanical interfaces deviate from ideal flatness**
  - Surface imperfections (pits, scratches, roughness)
  - <u>Run-out</u>: deviation from flatness over a unit lateral distance (Ex: 0.008 cm/cm for standard aluminum extrusion for heat sinks)
- **Thermal grease or "goop" (silicone impregnated with metal oxides) used to fill imperfections**
  - Misconception: more is better
  - Silicone grease very viscous and doesn't squeeze out, in which case a thin high thermal resistance layer might be left
  - Use grease sparingly (put on, wipe off excess)

Convective Thermal Resistance

$$Q_{12} = h(T,\upsilon)A(T_1 - T_2)$$

- **Model is somewhat more complicated than conduction, but can be described by similar relationship**
- **ν is fluid velocity**
- **h(T,ν) is film coefficient of heat transfer**
  - Depends on temperature and fluid velocity
- **A is cross-sectional area of interface**

Film Coefficient of Heat Transfer

- **Over usual temperature range of interest (-40 °C to +100 °C), h is fairly constant**
- **Significant changes in h occur when flow regime changes from laminar to turbulent**
  - Many fan systems use turbulent flow to improve convective heat transfer, usually noisy
  - Within each flow regime, h is relatively independent of velocity
- **Within these limits, product *hA* may be modeled as constant**
  - Equivalent thermal resistance is $R_{\Theta} = \dfrac{1}{hA}$
- **Similar rules apply**

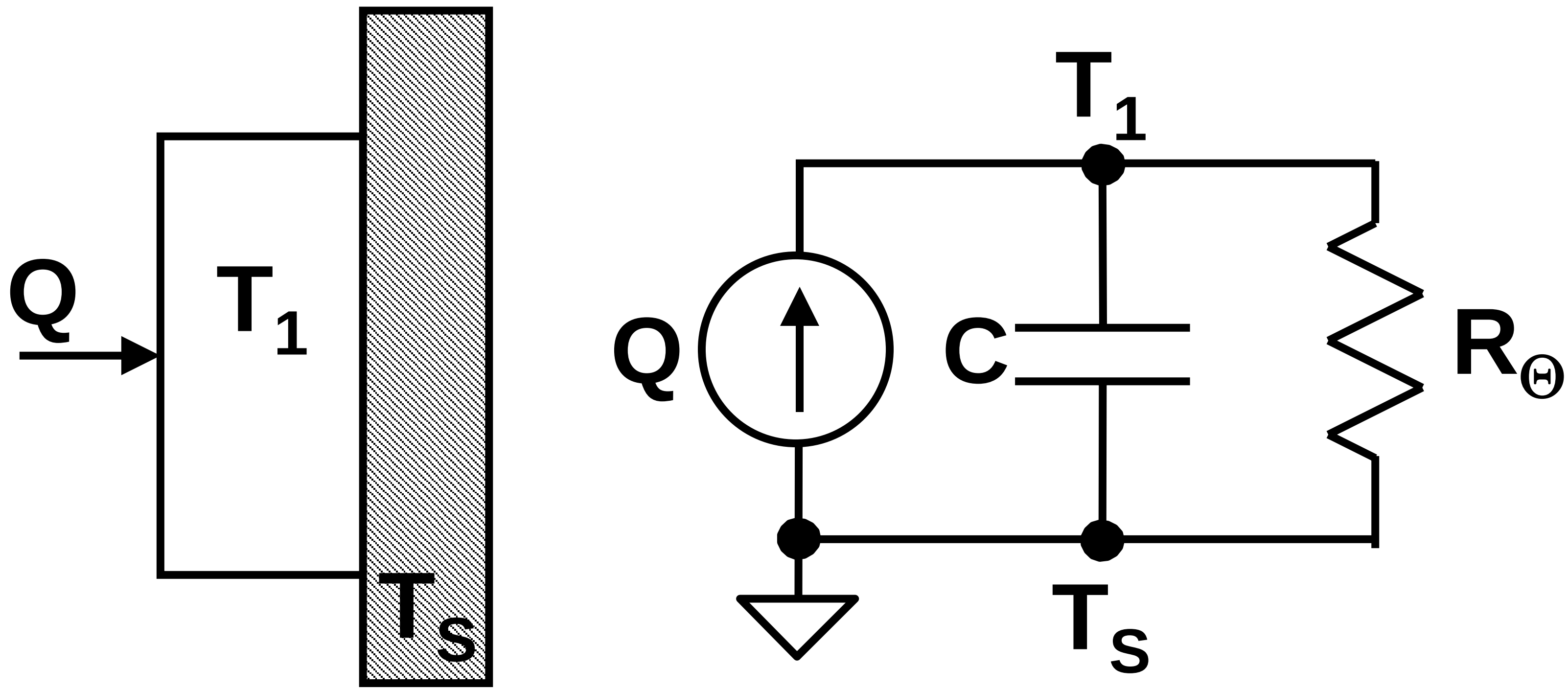
Transient Thermal Models

- **Temperature transients important during power-on, duty cycling**
  - Heat capacity of electronic components creates a lowpass filter
  - Enables instantaneous power dissipation to be higher than predicted by static thermal models
- **<u>Heat capacity</u>: energy required to raise the temperature of a mass by a specific amount**
  - SI units: J/°C-kg (Joules per degree Celsius/kg)
  - Ex: water at room temperature, 4.2×10^3 J/°C-kg

Thermal Capacitance

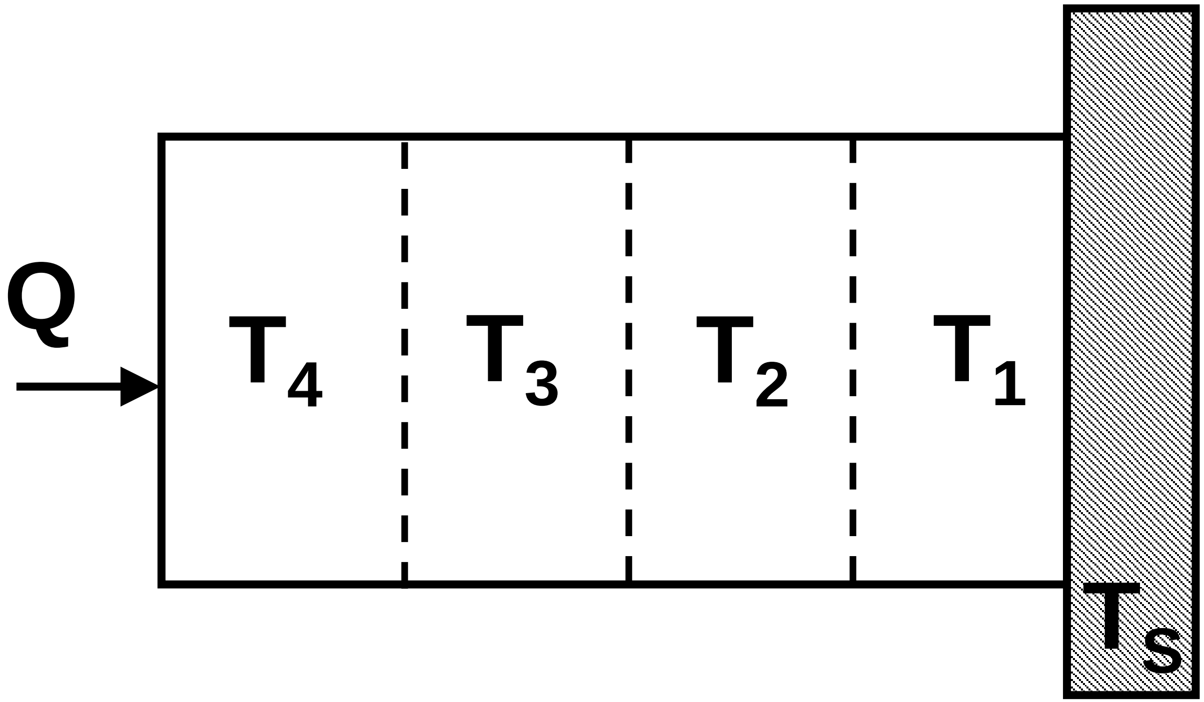
- **Masses in a thermal system constitute thermal energy storage devices**
  - Thermal systems containing mass exhibit dynamic behavior
  - Analog of electrical capacitance is thermal capacitance
  - Temperature indicates energy stored in mass
- **Simple form: dynamic model for mass being supplied with heat energy is an RC circuit**
- **Mass continuum, model as lumped RC network**

Thermal Circuit Example



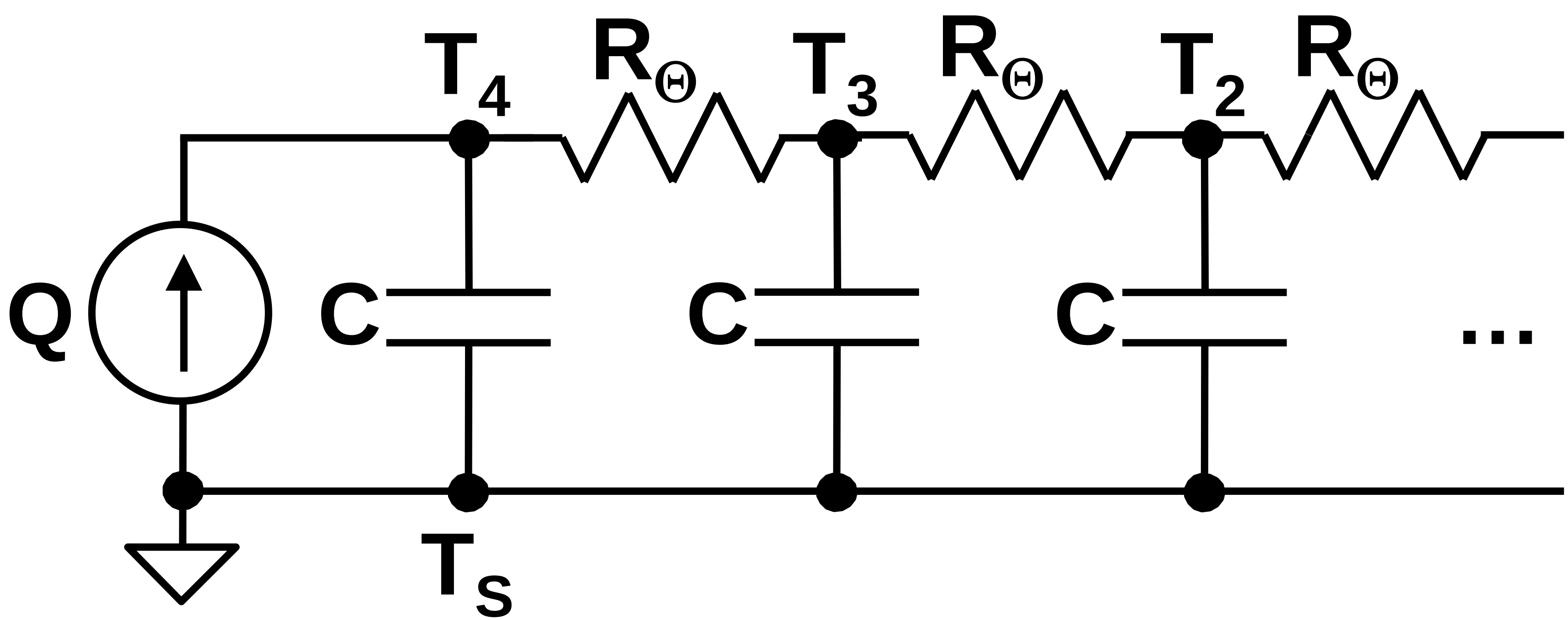
- Mass at temperature T_1, being supplied heat Q, in contact with sink at temperature T_S
- Final (steady-state) temperature: $T_1 = R_\Theta Q + T_S$

Lumped Element Thermal Model



- Divide large mass into smaller segments (lumps) at approximately constant temperature
- Number of lumps depends on bandwidth of Q
- Capture spatial and temporal variations

Lumped Element Circuit Model



- **RC ladder network models thermal dynamics of mass continuum**
- **Step response of any node temperature (voltage) is exponential**

2003 ITRS Projected Thermal Requirements

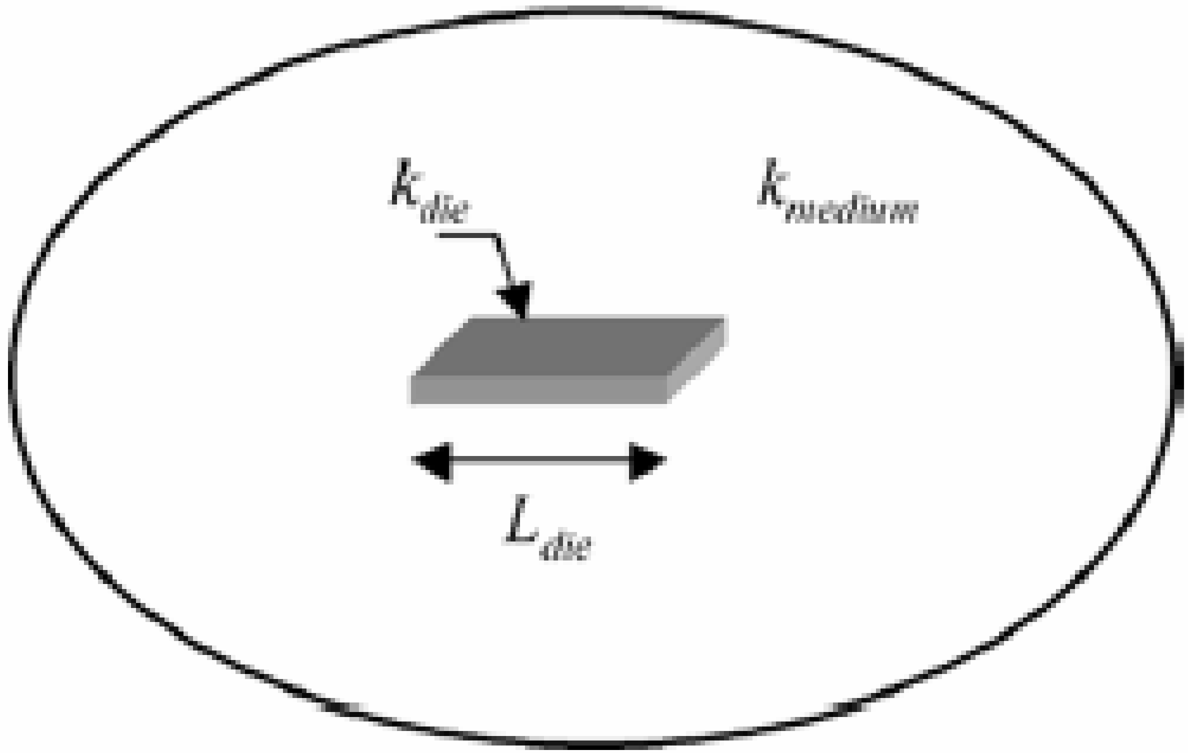
Year of Production	Near-term				Long-term			
	2003	2004	2005	2006	2007	2010	2013	2016
Maximum junction temperature (°C)								
Cost performance	85	85	85	85	85	85	85	85
High performance	85	85	85	85	85	85	85	85
Ambient temperature (°C)								
Cost performance	45	45	45	45	45	45	45	45
High performance	45	45	45	45	45	45	45	45
Power (W)								
Cost performance	81	85	92	98	104	120	138	158
High performance	150	160	170	180	190	218	251	288
Required thermal resistance (°C/W)								
Cost performance	0.49	0.47	0.43	0.41	0.38	0.33	0.29	0.25
High performance	0.27	0.25	0.24	0.22	0.21	0.18	0.16	0.14

- **Gurrum, 2004**

Pure Conduction Limit Model

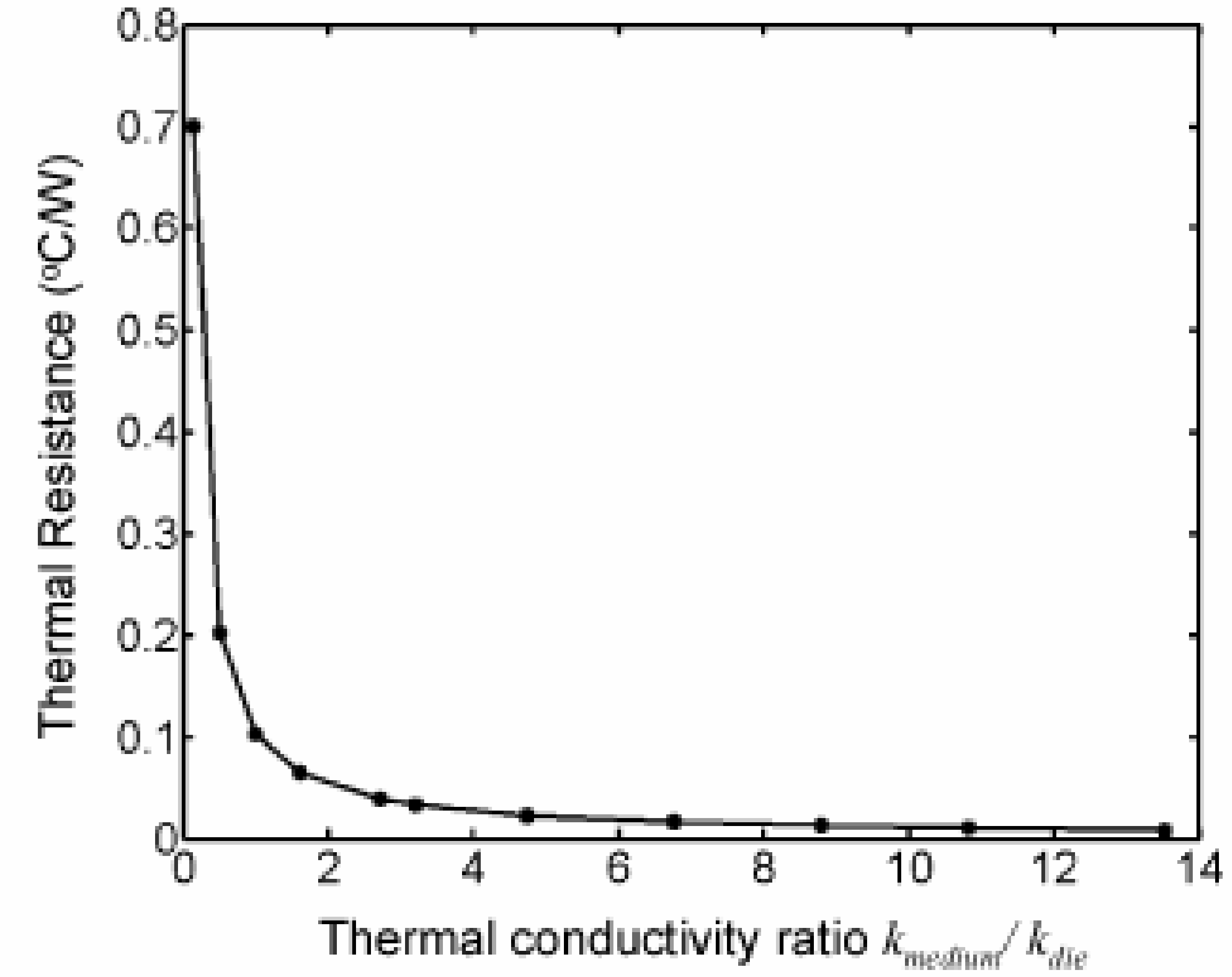
L_{die} = 17.6 mm
k_{die} = 148 W/mK
Die thickness = 0.5 mm

Gurrum, 2004



- **Chip embedded in infinite medium, thermal conductivity *k_{medium}***

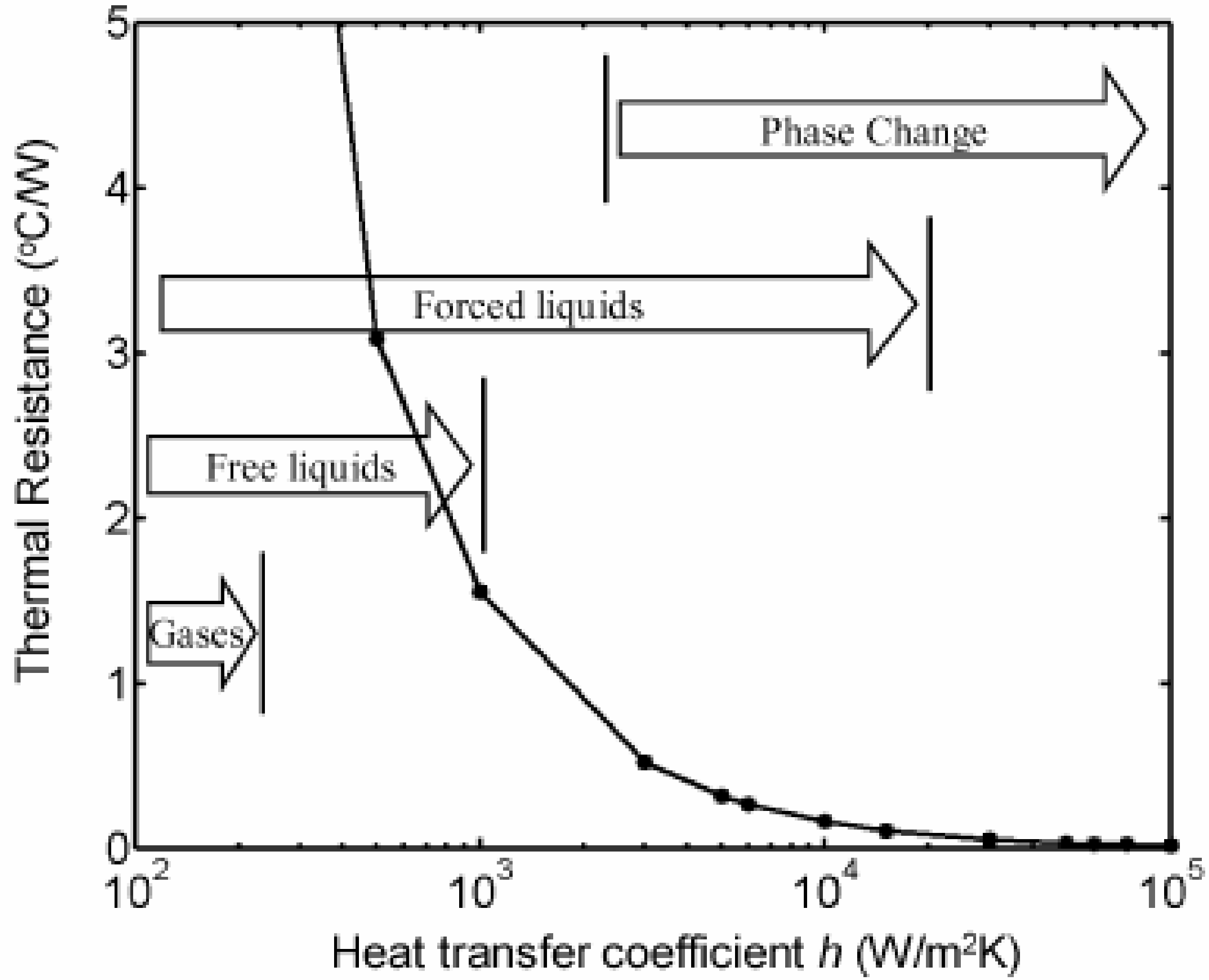
Pure Conduction Limit Results



- **System thermal resistance drops as medium resistance drops**

Gurrum, 2004

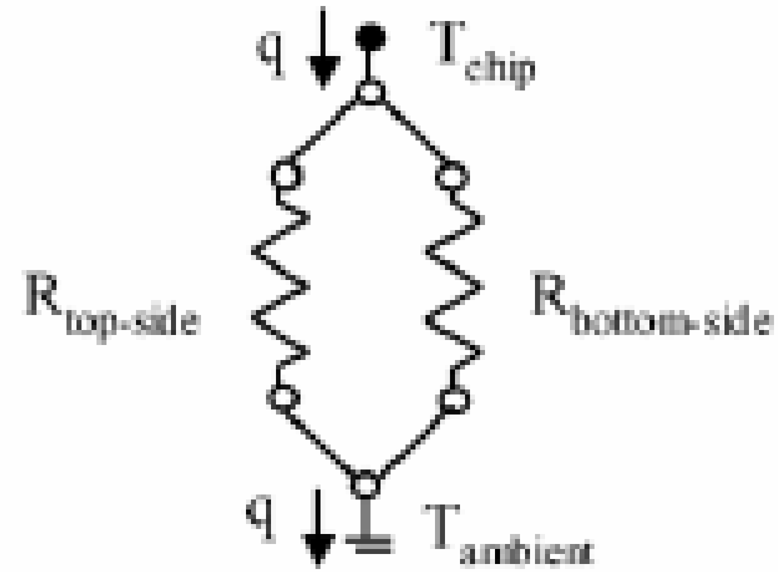
Pure Convection Limit Results



- **Chip immersed in flowing fluid**

Gurrum, 2004

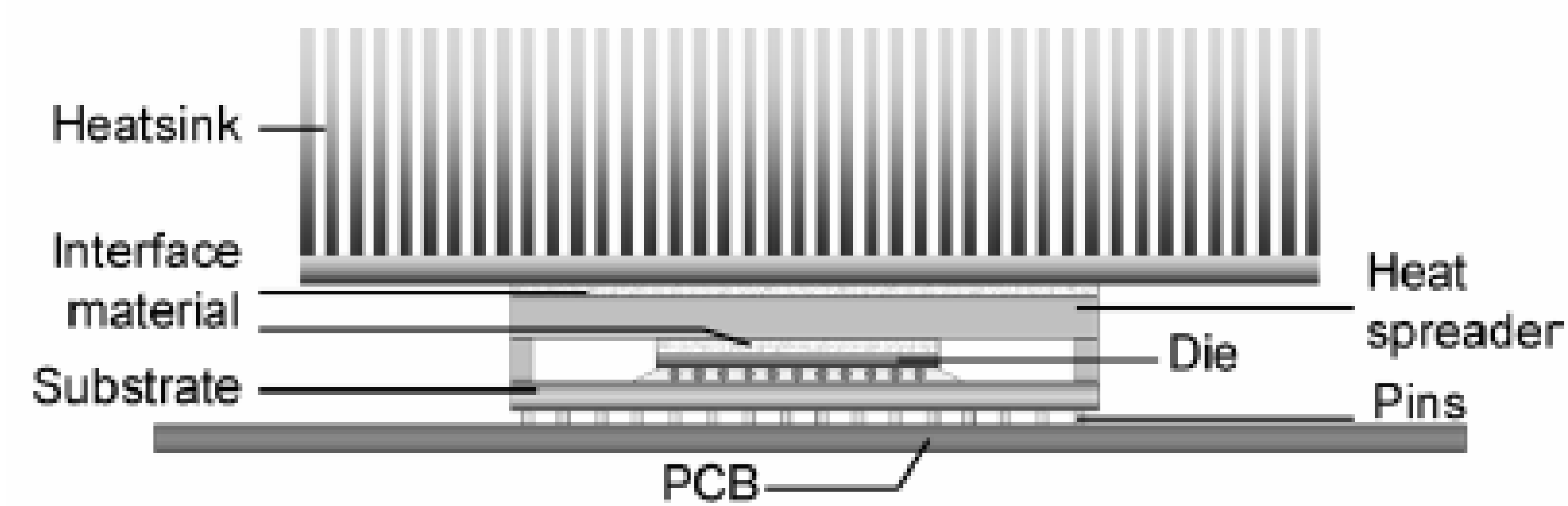
Microprocessor Package Thermal Circuit



- Heat flows out of top and bottom side of die, with two possible thermal resistances
- Edges of die typically too small an area for effective heat removal
- Packaging affects thermal resistance of each path

Gurrum, 2004

Typical Microprocessor Package



- **Heat spreader expands thermal interface between die and heat sink plate**
- **Fin spacing on heat sink optimized for air/liquid flow rate**
- **Thermal conduction through flip-chip bumps and package solder balls into PCB (another heat sink)**

Gurrum, 2004

Heat Sink Air Flow

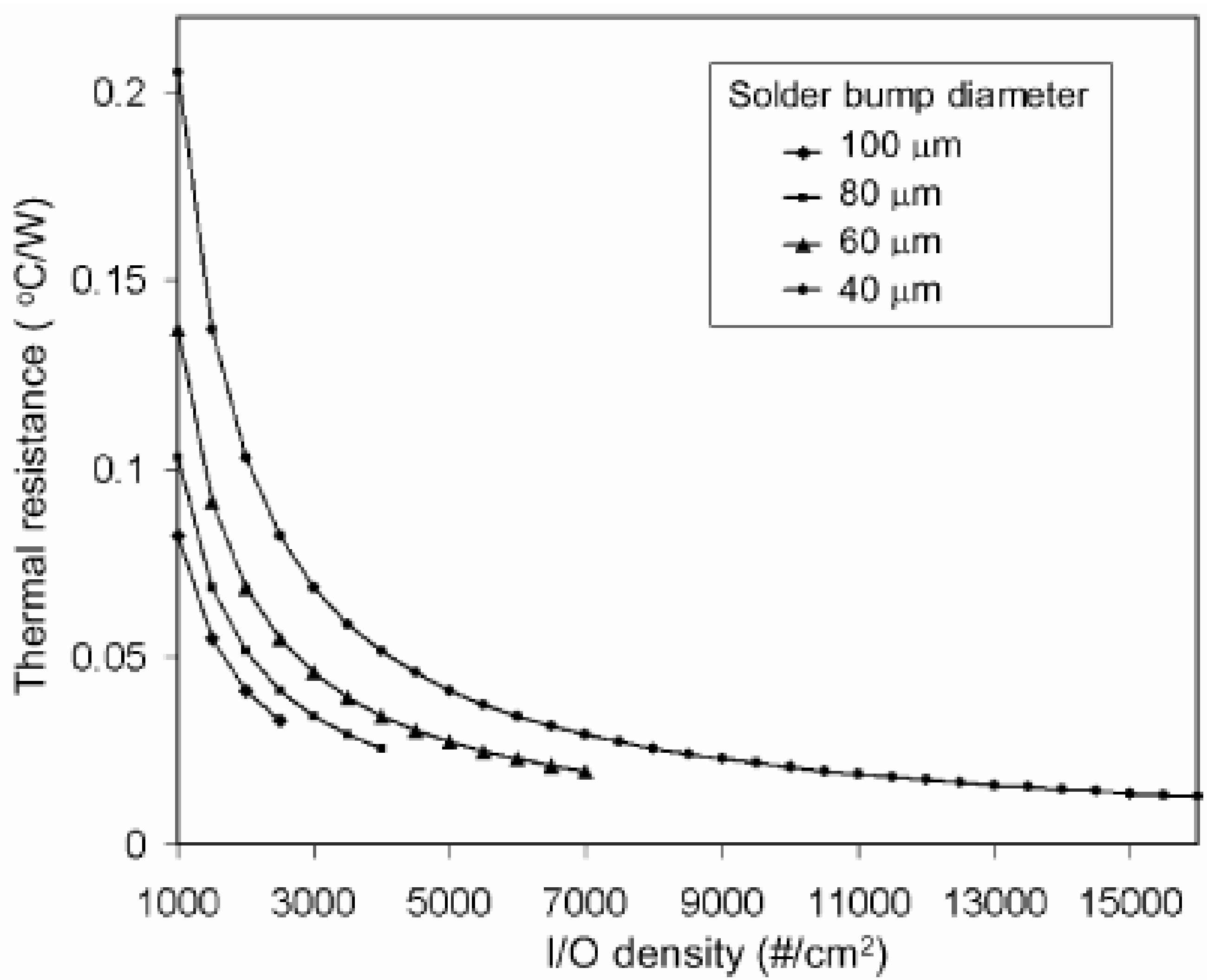
- **Critical issue is to ensure fluid flow between heat sink fins is turbulent instead of laminar**
  - Laminar flow implies fluid strata which don't mix, resulting in low value of heat transfer coefficient h
  - Turbulent flow implies a lot of mixing, high value of h
  - Alternative view: boundary layer next to fin surface prevents efficient heat transfer to moving fluid stream
- **Relationship among fin spacing, flow rate, and onset of turbulence is given by <u>Reynolds Number</u>**

Reynolds Number

$$\mathrm{Re} = \frac{\rho v w}{\eta}$$

- ν = **fluid velocity**
- **w = channel width (fin spacing for heat sink)**
- ρ = **fluid density**
- η = **fluid coefficient of viscosity**
- **High Reynolds number is characteristic of turbulent flow, low number is typical of laminar flow**
- **Wider channels enter turbulent flow at lower velocity**
  - Possibly more efficient than having many fins, small w

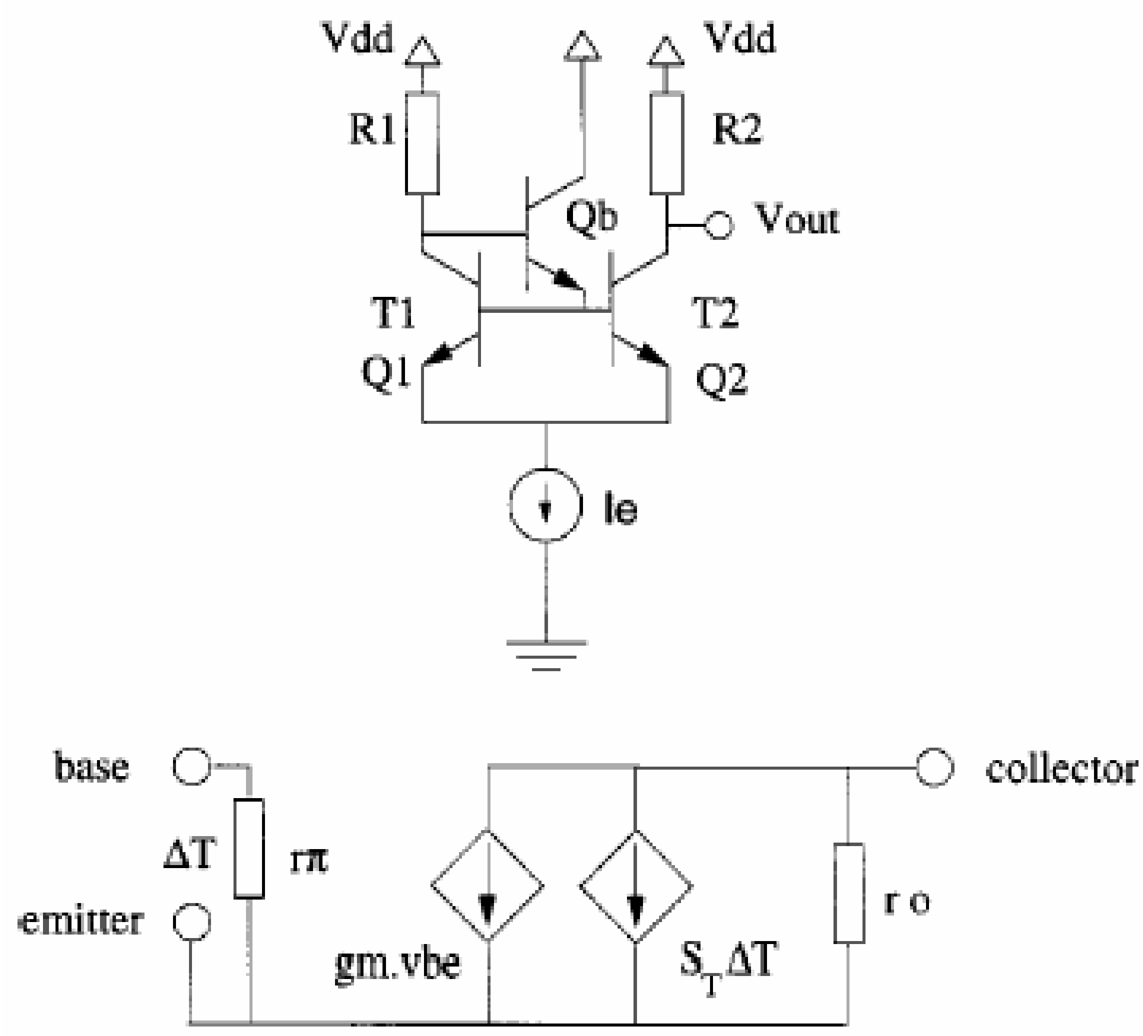
Chip Solder Bump I/Os Thermal Resistance



• **Large I/O count, better heat sinking to PCB (numbers quite large)**

Gurrum, 2004

Differential Temperature Sensor



- **Voltage difference proportional to T_1-T_2 and T_1+T_2**

Alltet, JSSC 2001

Conclusions

- **Model thermal systems using electrical circuit analogs**
  - Thermal resistance can account for conductive and convective heat flow
  - Thermal capacitance accounts for thermal energy storage of any mass
- **Heat removal an increasingly challenging problem as technology scales and speed increases**
  - Variety of mechanisms: heat spreader, heat sink, I/O connections from die to package and package to board
  - SOI makes problem worse since die substrate thermal conductivity poor
- **Simulations indicate ITRS targets can be met, but requires innovation in PCB thermal interface**