ON Semiconductor®

Electronics System Thermal Design and Characterization

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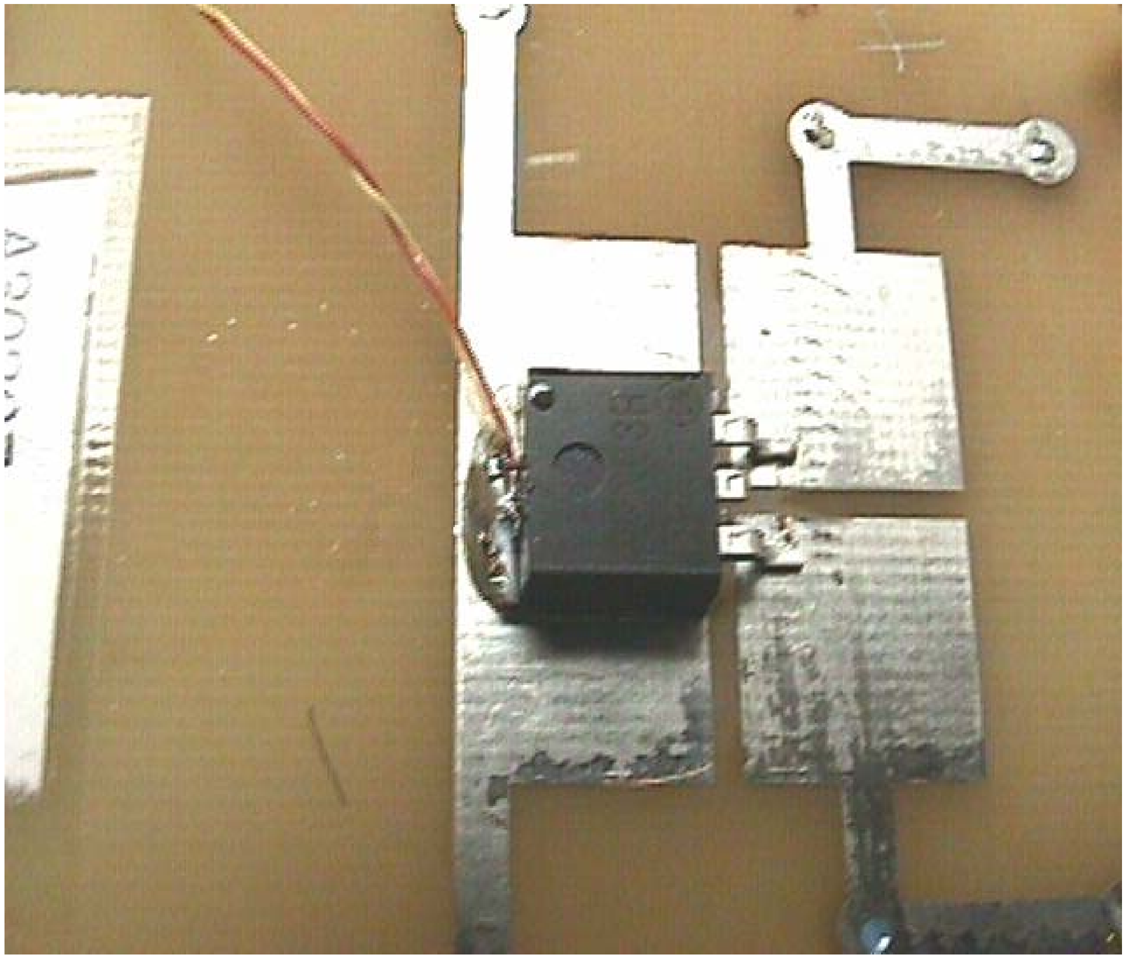
Course outline

- Introduction
- Experimental Techniques
- Linear Superposition
- Thermal Runaway
- References

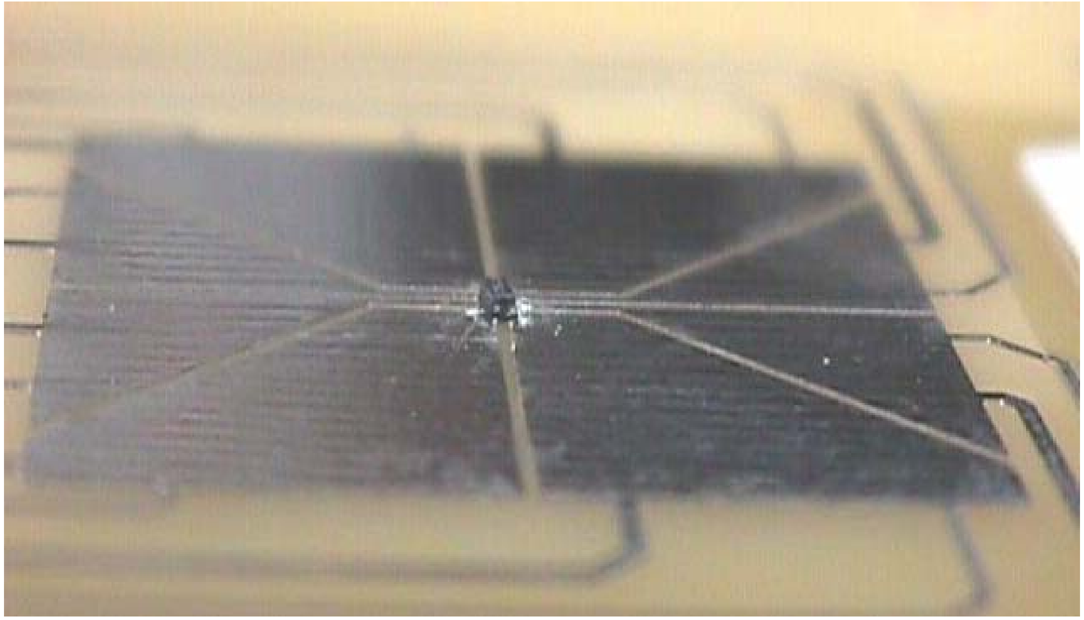
Introduction

- Why This Course?
- Terminology and Basic Principles
- Facts and Fallacies

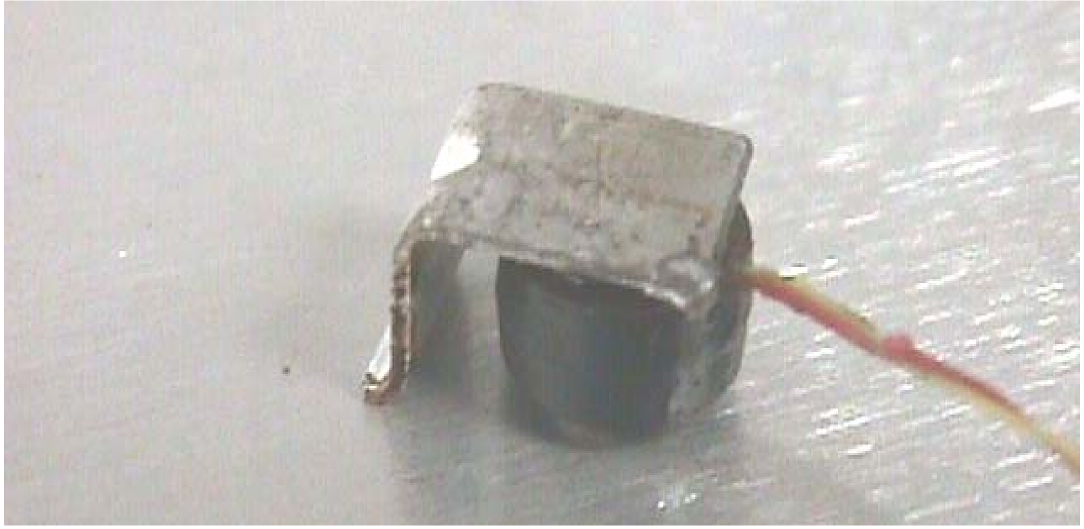
Can this device handle 2W?



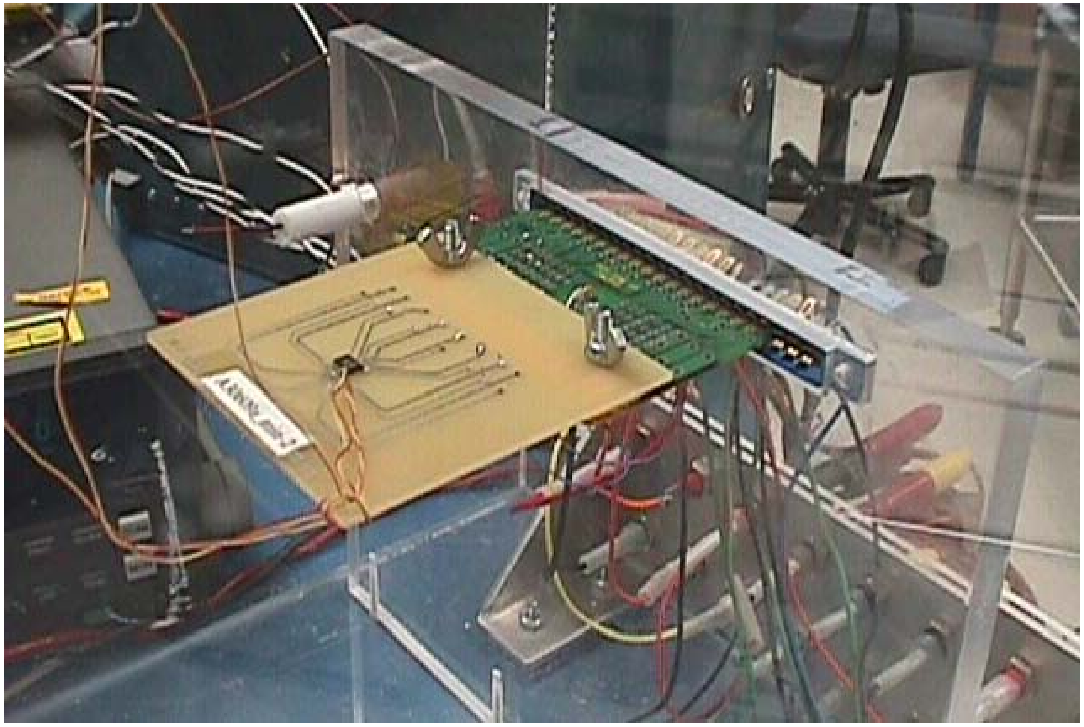
I'm putting 5A into this part. What's its junction temperature going to be?



I'm putting a 60W, 800ns pulse into this rectifier. How much copper area do I need to make this part work in my system?



I'm putting together a data sheet for this new device. What's theta-JA for this package?



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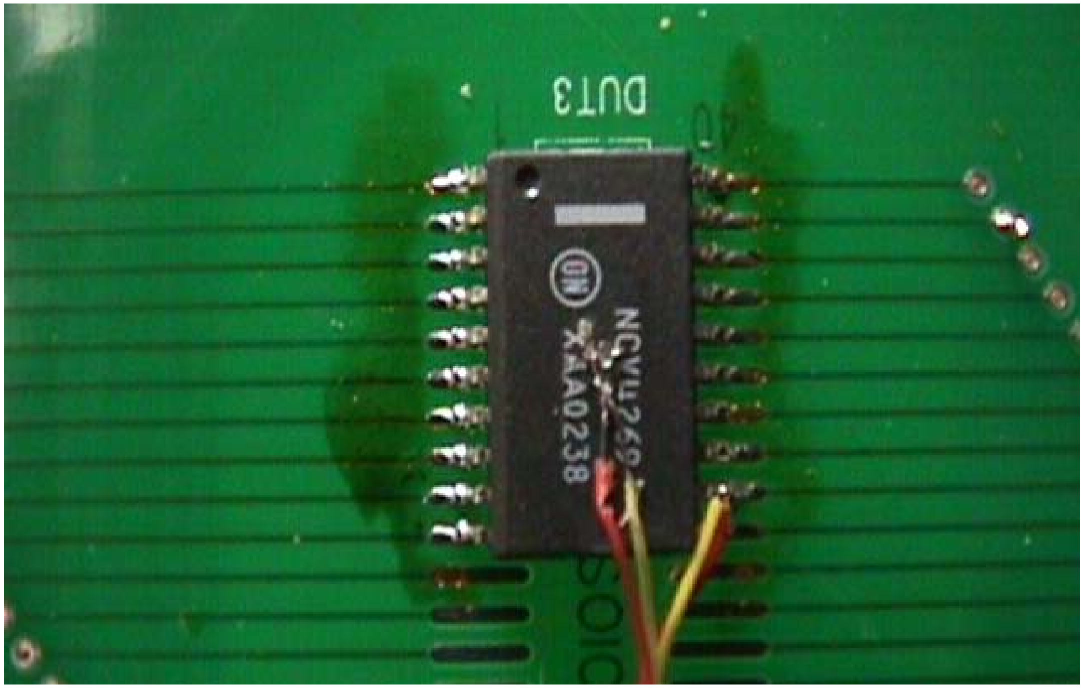
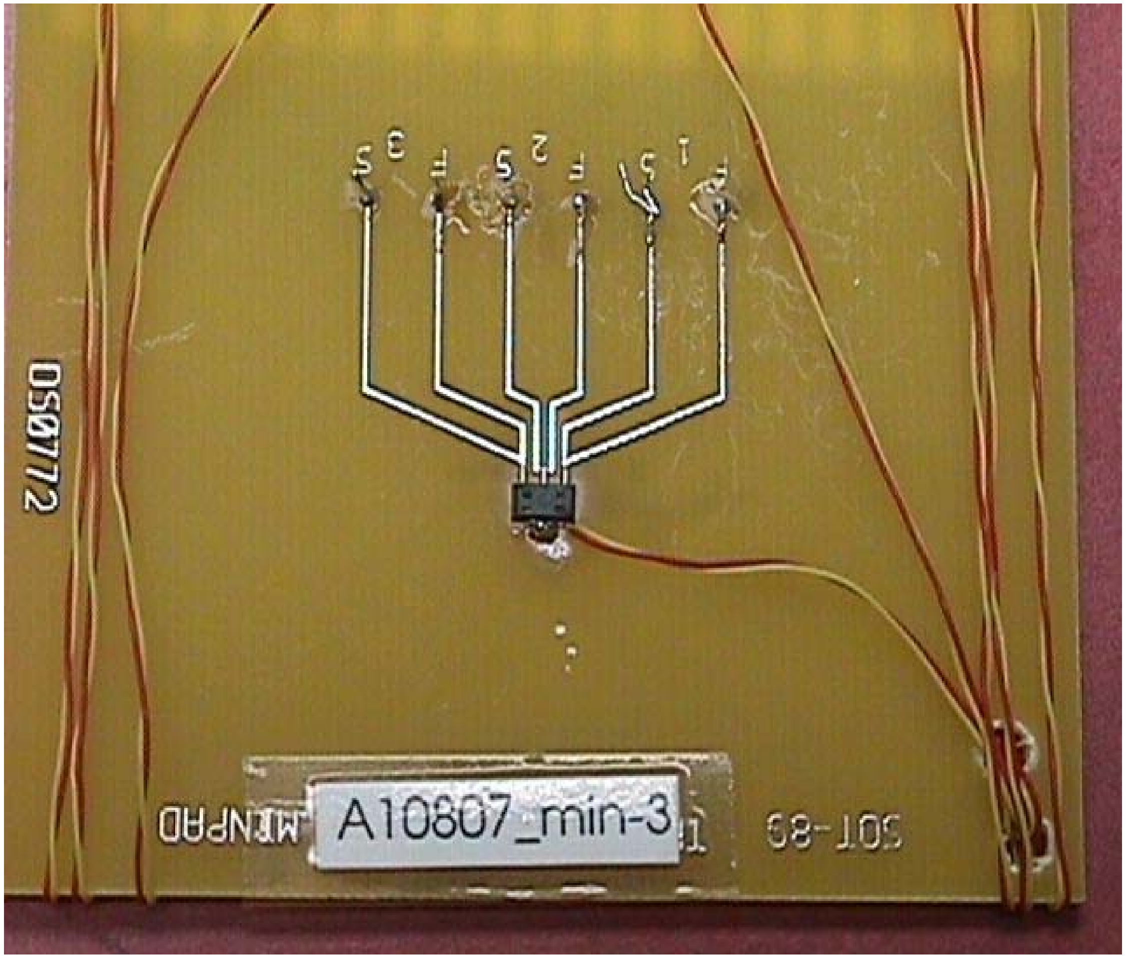


What's the *maximum power* rating on this part going to be?



What's the maximum power rating on *this* part going to be?

Why is our SOT-23 thermal number so much worse than our competition?

- Us
  - SOT-23 package
  - 60x60 die
  - solder D/A
  - copper leadframe
  - min-pad board
  - still air
- Them
  - SOT-23 package
  - 20x20 die
  - epoxy D/A
  - alloy 42 leadframe
  - 1” x 2oz spreader
  - big fan

Why θ_{JA} doesn't belong in the "Maximum Ratings"* table

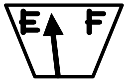
***let alone the "*Absolute* Maximum Ratings"**

It's like trying to sell your car (some bureaucrat says you *must* list its gas mileage in the ad)

For sale:

Geo Metro, 1999 model, excellent condition!

MAXIMUM RATINGS

Description	Symbol	Value	Units
Gas Mileage (Note 1)		4	mpg

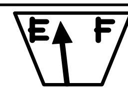
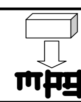
[1] 20% grade uphill, 75mph, back seat and trunk full of bricks

Gee, we'd better not be so "worst case," should we?

<u>For sale:</u>

Geo Metro, 1999 model, excellent condition!

MAXIMUM RATINGS

Description	Symbol	Value	Units
Gas Mileage (Note 1)		10	mpg
Mileage derating factor		0.002	mpg/brick

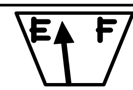
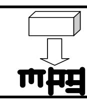
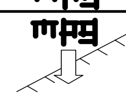
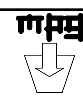
[1] 20% grade uphill, 75mph

Wait, they said "*maximum*". Maybe we're thinking about this all wrong …

<u>For sale:</u>

Geo Metro, 1999 model, excellent condition!

MAXIMUM RATINGS

Description	Symbol	Value	Units
Gas Mileage (Note 1)		110	mpg
BDF (brick derating factor)		0.002	mpg/brick
IDF (incline derating factor)		2	mpg/%
SDF (speed derating factor)		0.07	mpg/mph

[1] 20% grade downhill, empty vehicle (no bricks, not even a driver!), coasting

Frankly, $T_{j\text{-}max}$ is the only "thermal" specification that I think belongs in the Maximum Ratings table.

Terminology and basic principles

"Junction" temperature?

Historically, for discrete devices, the "junction" was literally the essential "pn" junction of the device. This is still true for basic rectifiers, bipolar transistors, and many other devices.

More generally, however, by "junction" these days we mean the hottest place in the device, which will be somewhere on the silicon (2nd Law of Thermodynamics).

This gets to be somewhat tricky to identify as we move to complex devices where different parts of the silicon do different jobs at different times.

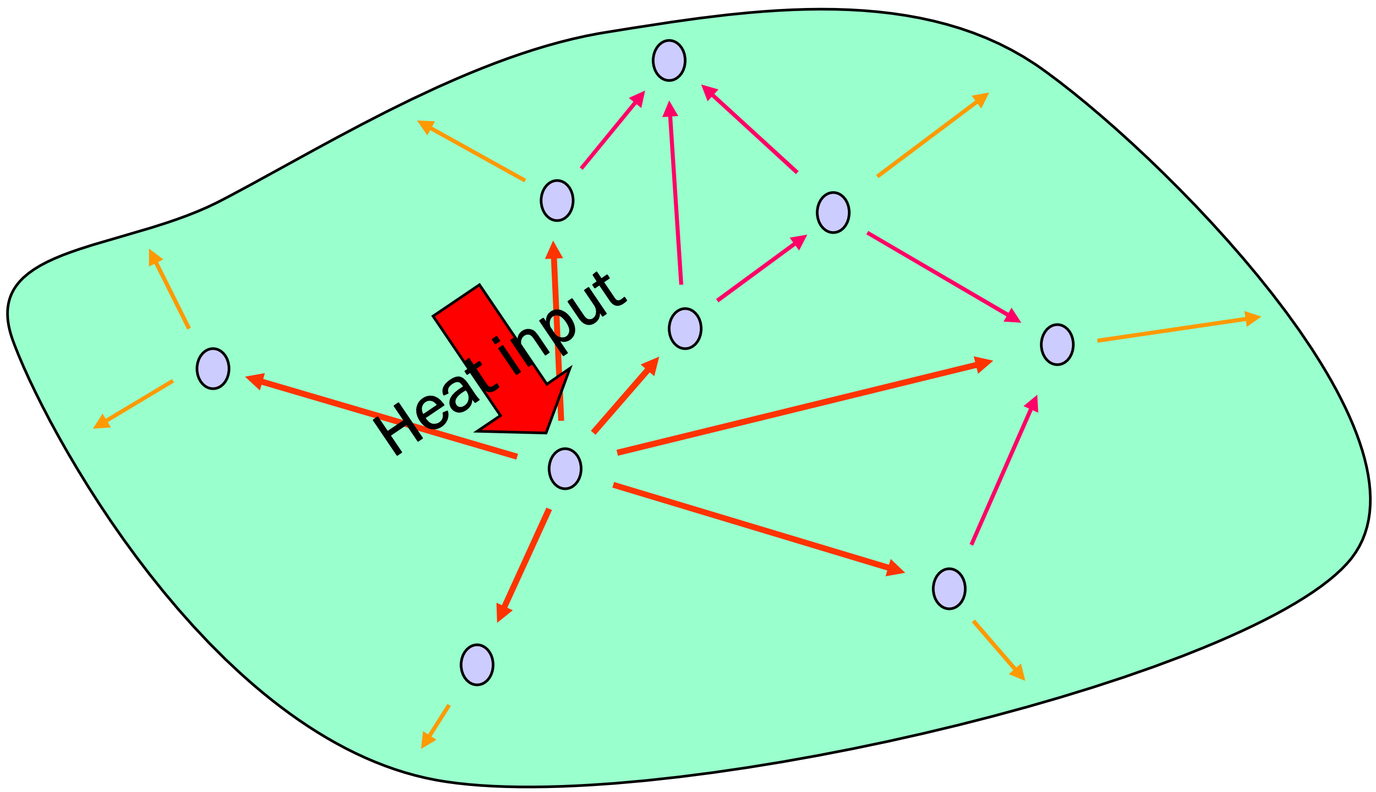
Thermal/electrical analogy

temperature	<=>	voltage
power	<=>	current
Δtemp/power	<=>	resistance
energy/degree	<=>	capacitance

Theta (θ) vs. psi (Ψ)

- JEDEC <http://www.jedec.org/> terminology
  - $Z_{\theta JX}$, $R_{\theta JA}$ older terms ref JESD23-3, 23-4
  - θ_{JA} ref JESD 51, 51-1
  - θ_{JMA} ref JESD 51-6
  - Ψ_{JT}, Ψ_{TA} ref JESD 51-2
  - Ψ_{JB}, Ψ_{BA} ref JESD 51-6, 51-8
  - $R_{\theta JB}$ ref JESD 51-8
  - **Great overview, all terms: JESD 51-12**

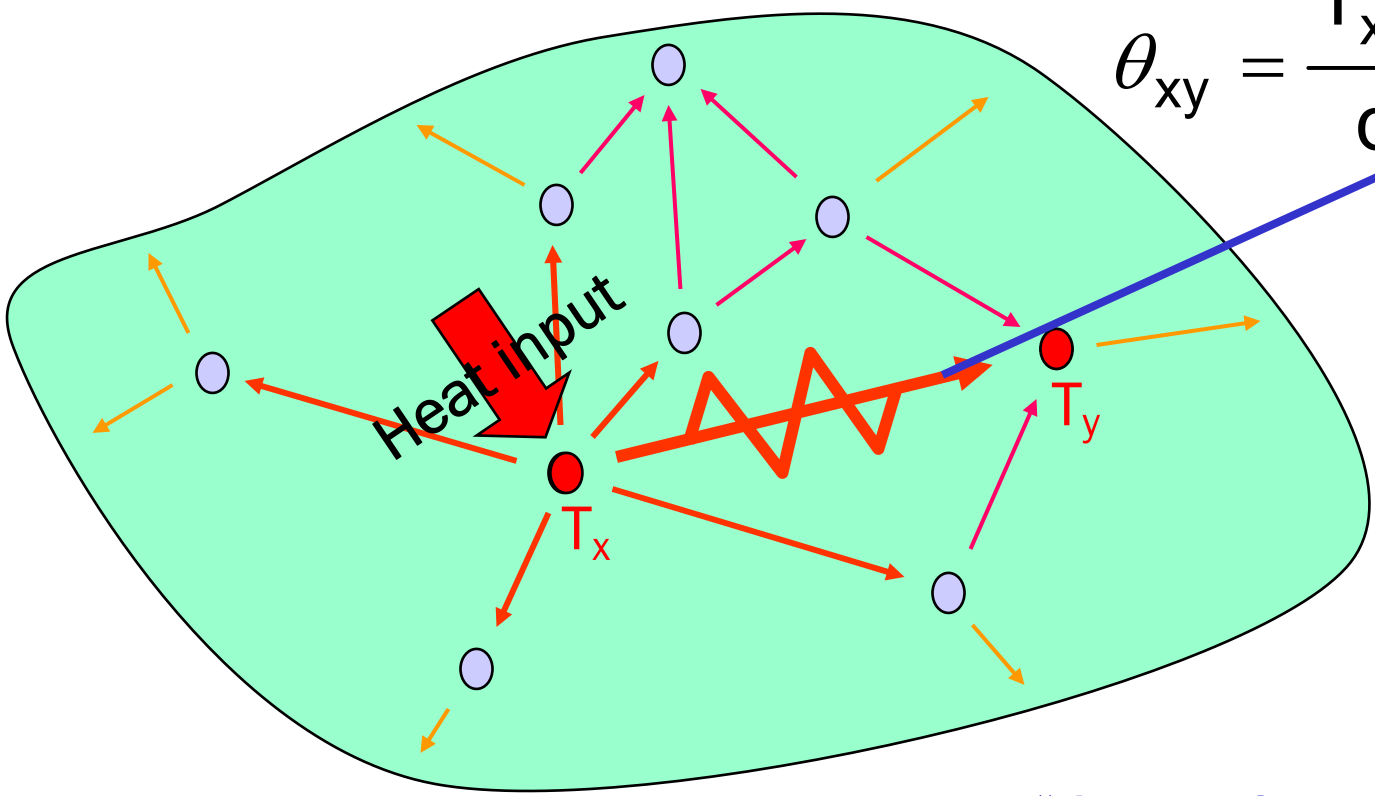
A generic thermal system



"Theta" (Greek letter θ)

We know actual heat flowing along path of interest

$$\theta_{xy} = \frac{T_x - T_y}{q_{path}}$$

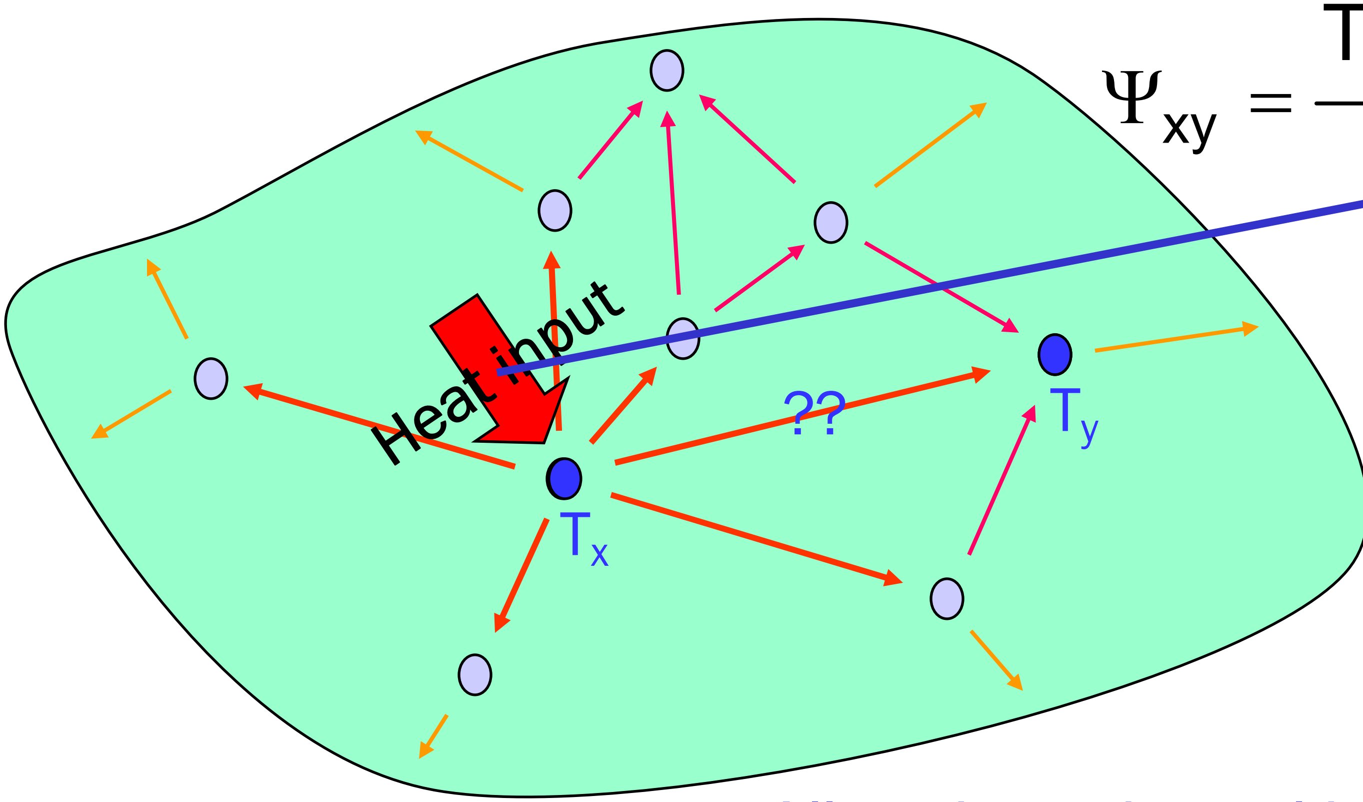


true "thermal resistance"

"Psi" (Greek letter Ψ)

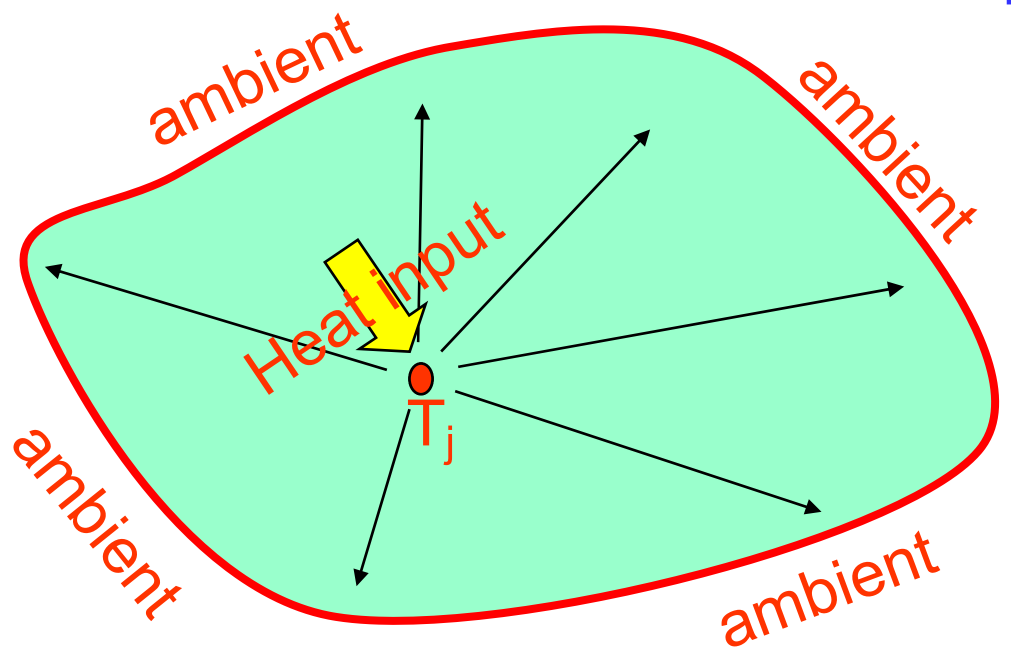
We *don't know* actual heat flowing along path of interest

$$\Psi_{xy} = \frac{T_x - T_y}{q_{total}}$$



All we know is total heat input

When Ψ becomes θ



Either or both "points" of interest are isotherms

$$T_x = T_j \quad \text{(a point)}$$

$$T_y = ambient \quad \text{(an isotherm)}$$

All heat flowing between them is known

$$Power_{path} = Power_{device}$$

$$\theta_{JA} = \frac{T_{\text{j}} - T_{\text{ambient}}}{Power_{\text{total}}} = \Psi_{xy}$$

An example of a device with two *different* "Max Power" ratings

- **Suppose a datasheet says:**
  - T_{jmax} = 150°C
  - θ_{JA} = 100°C/W
  - P_d = 1.25W (T_{amb}=25°C)

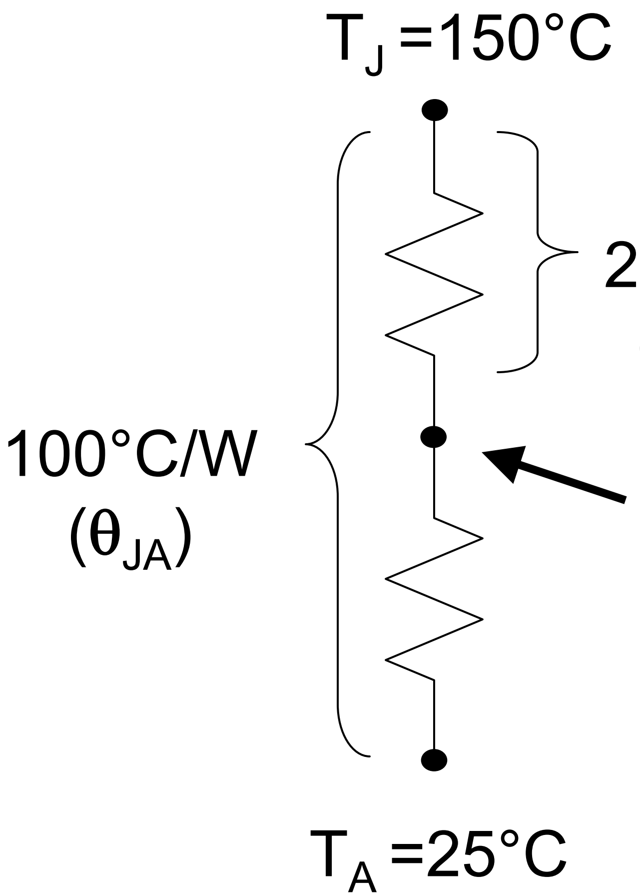
$$25 + 100 * 1.25$$
$$= 25 + 125 = 150$$

- **But it also says:**
  - Ψ_{JL} = 25°C/W
  - P_d = 3.0W (T_L=75°C)

$$75 + 25 * 3$$
$$= 75 + 75 = 150$$

Where's the "inconsistency"?

Where's the inconsistency?



What's T_L?

Not 75°C !!

(try about **119**°C)

…¾ of the way from
ambient to Tj

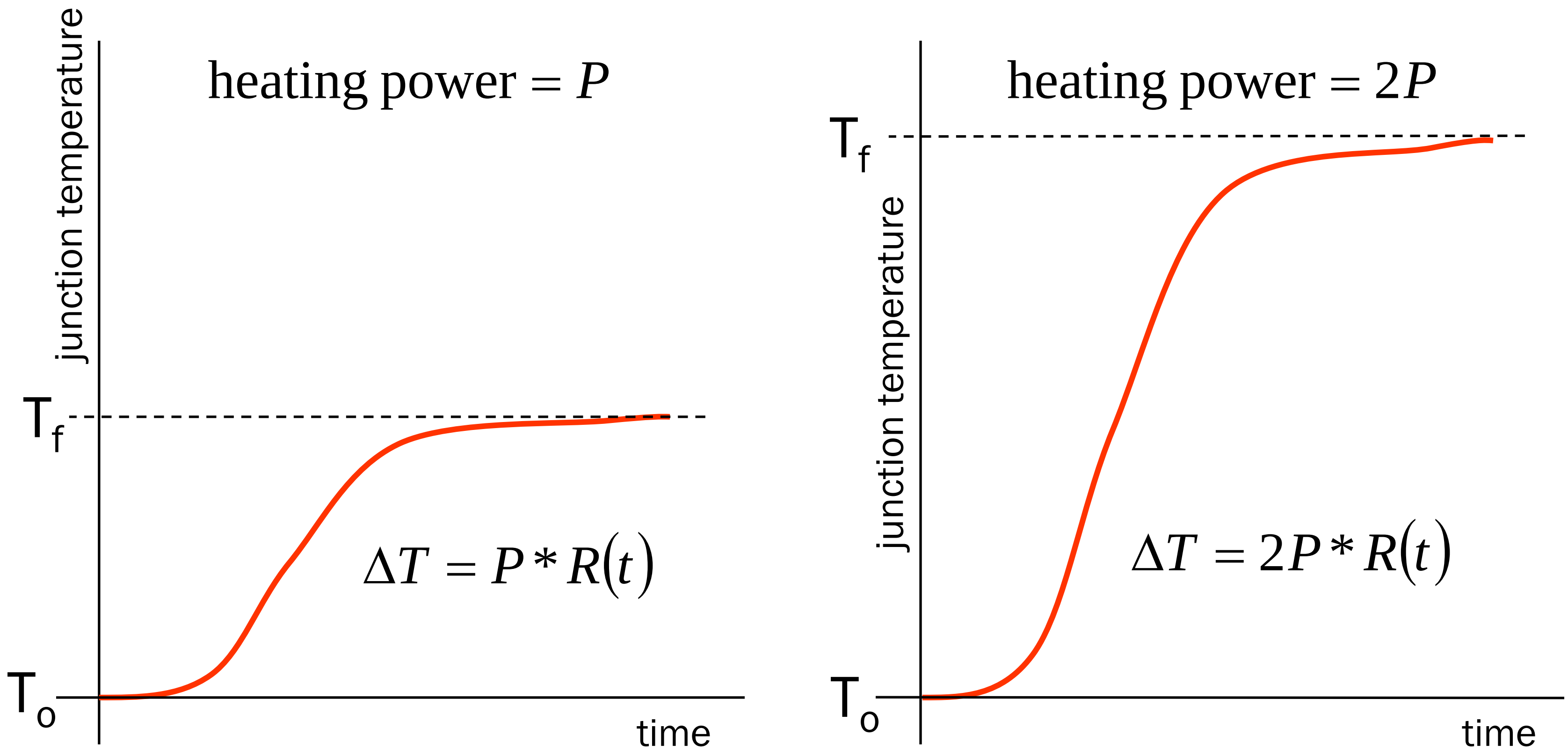
Facts and fallacies

Facts and fallacies

- Basic idea:
  - temperature difference is proportional to heat input

$$\Delta T \propto Power$$

twice the heat, twice the temperature rise



Facts and fallacies

- Basic idea:
  - temperature difference is proportional to heat input
- There are three modes of heat transfer
  - conduction
  - convection
  - radiation (electromagnetic/infrared)

Facts and fallacies

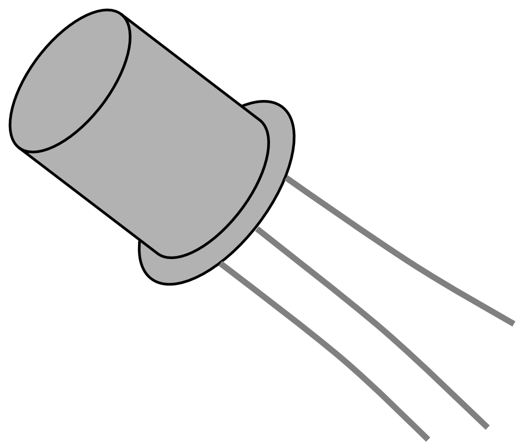
- Basic idea:
  - temperature difference is proportional to heat input
- Flaws in idea:
  - conduction effects (material properties)
    - depend on temperature
  - convection effects (esp. “still air”)
    - depend on temperature
  - radiation effects
    - depend on temperature

Facts and fallacies, cont'

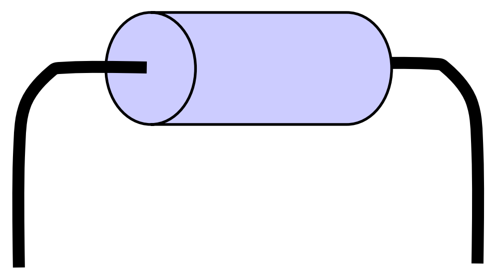
- Basic idea:
  - "thermal resistance" is an intrinsic property of a package

back in the good old days ...

metal can --
fair approximation of
"isothermal" surface



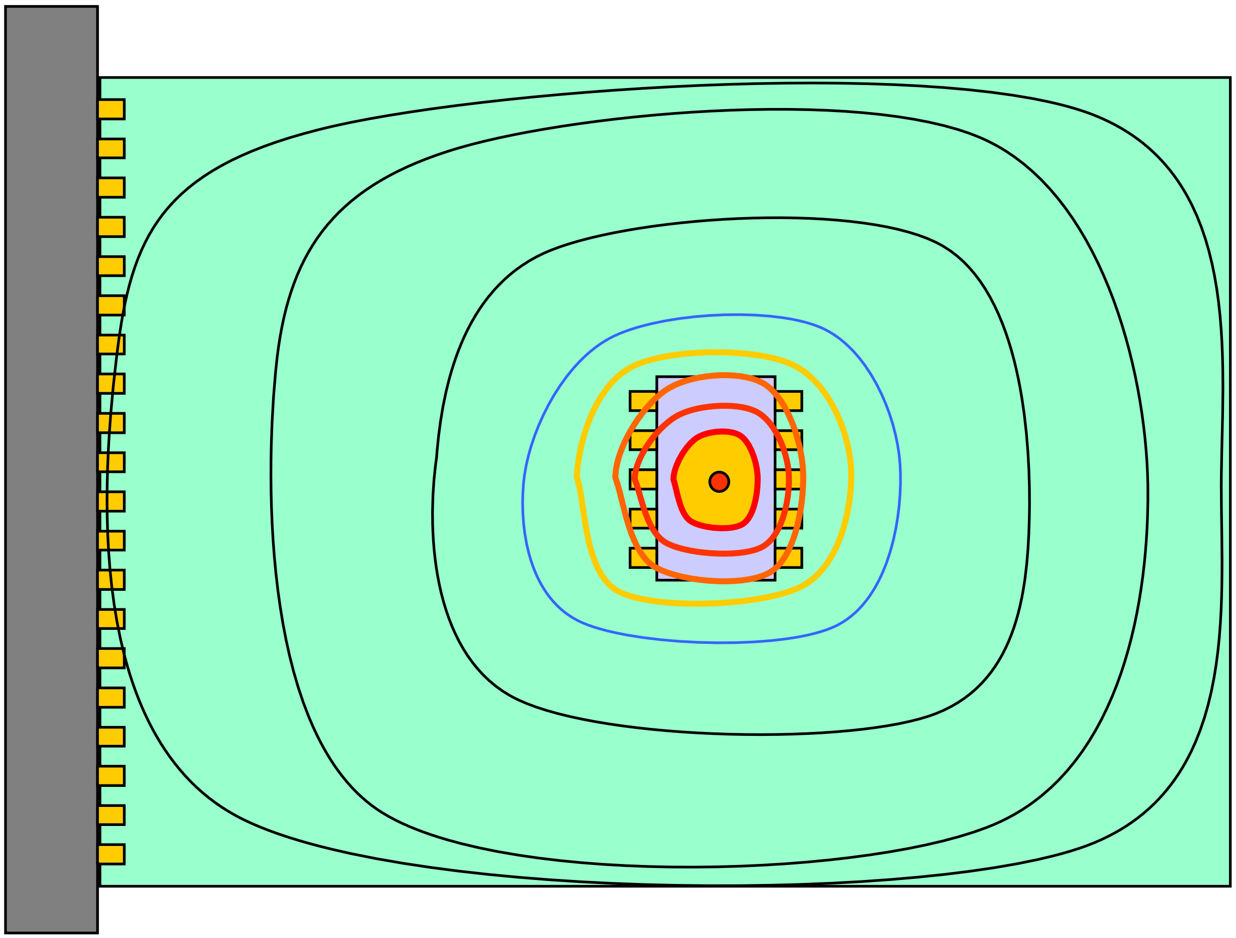
axial leaded device --
only two leads, heat
path fairly well defined



Facts and fallacies, cont'

- Basic idea:
  - "thermal resistance" is an intrinsic property of a package
- Flaws in idea:
  - there is no isothermal "surface", so you can't define a "case" temperature
    - Plastic body (especially) has big gradients
  - different leads are at different temperatures

Which lead? Where on case?



Facts and fallacies, cont'

- Basic idea:
  - "thermal resistance" is an intrinsic property of a package
- Flaws in idea:
  - there is no isothermal "surface", so you can't define a "case" temperature
    - Plastic body (especially) has big gradients
  - different leads are at different temperatures
  - multiple, parallel thermal paths out of package

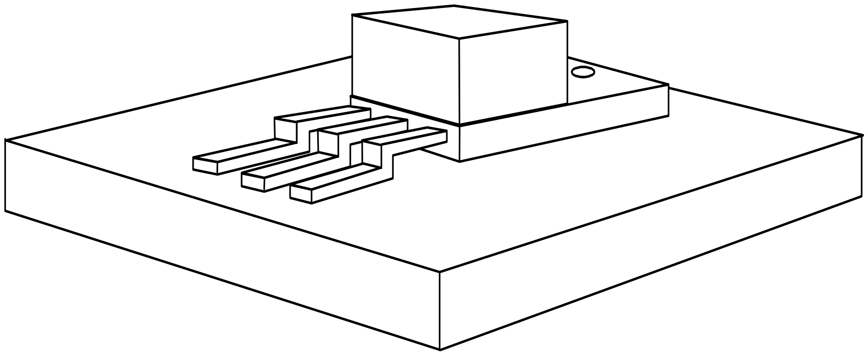
Same ref, different values

$\Psi_{J-tab} = 1.2°C/W$

$P_d = 50W$

$T_c = 25°C$

1GPM of H_2O

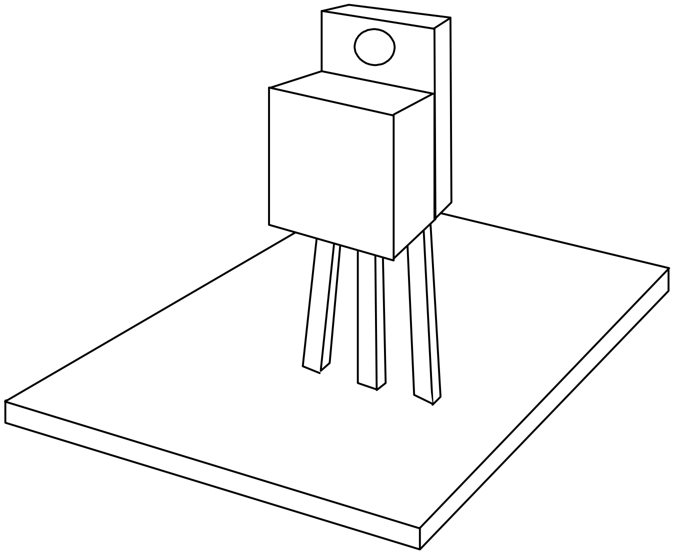


$\Psi_{J-tab} = 0.8°C/W$

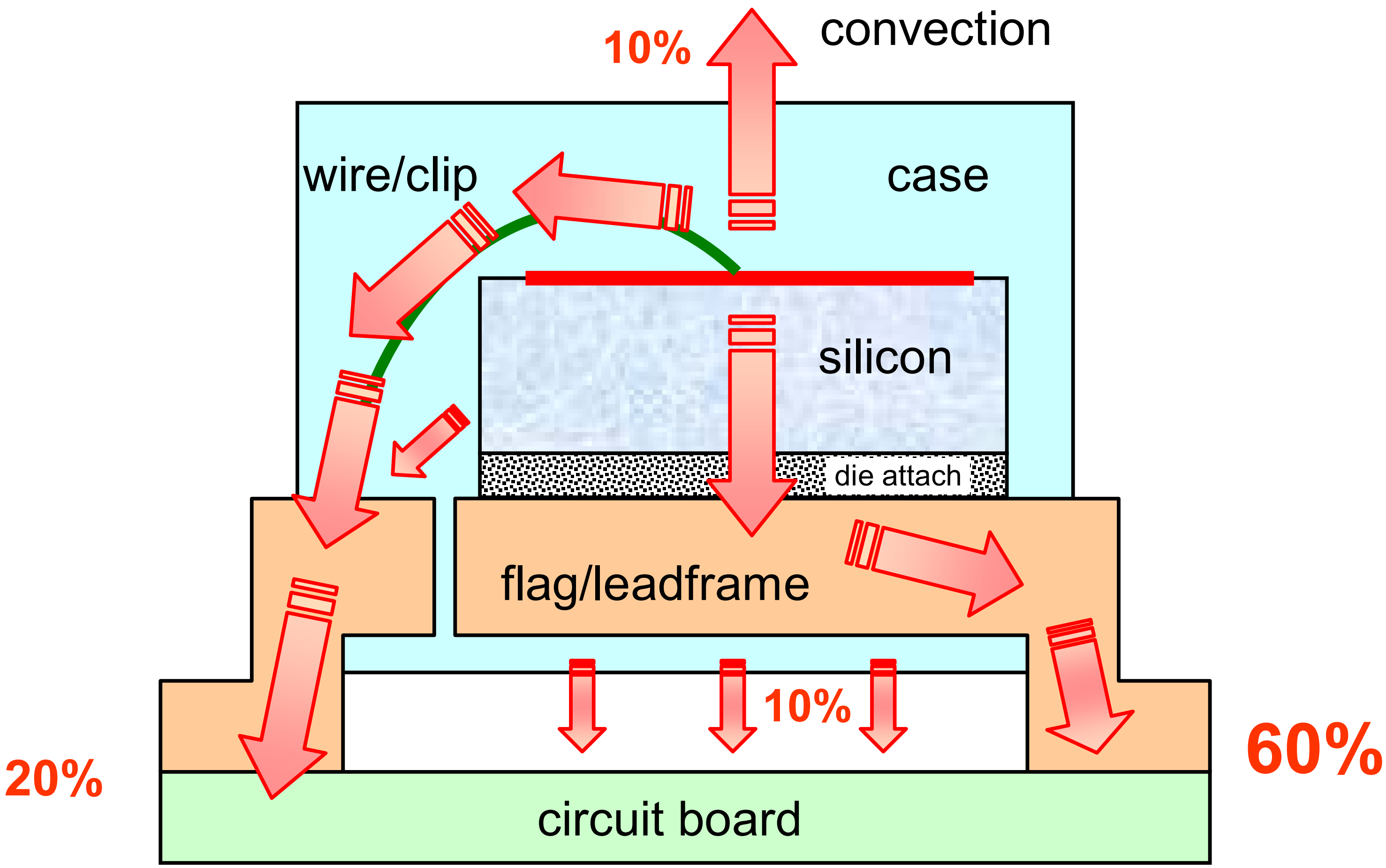
$P_d = 1.5W$

$T_c = 25°C$

still air

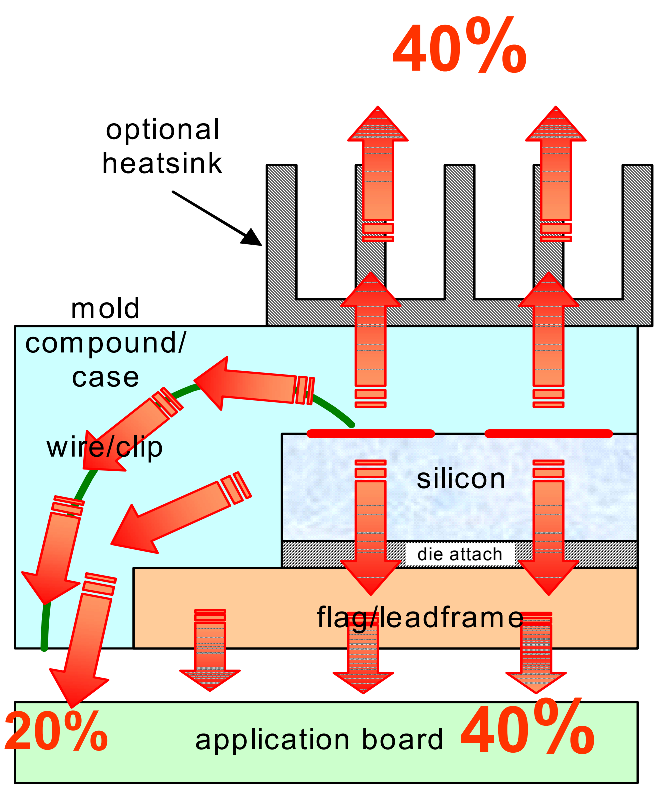


Archetypal package

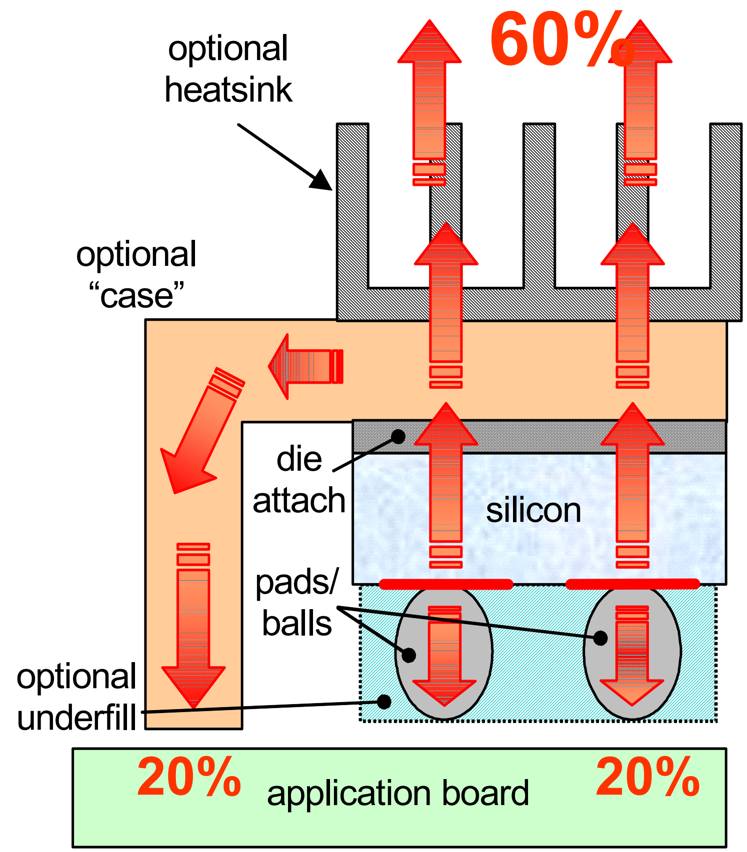


Then we change things …

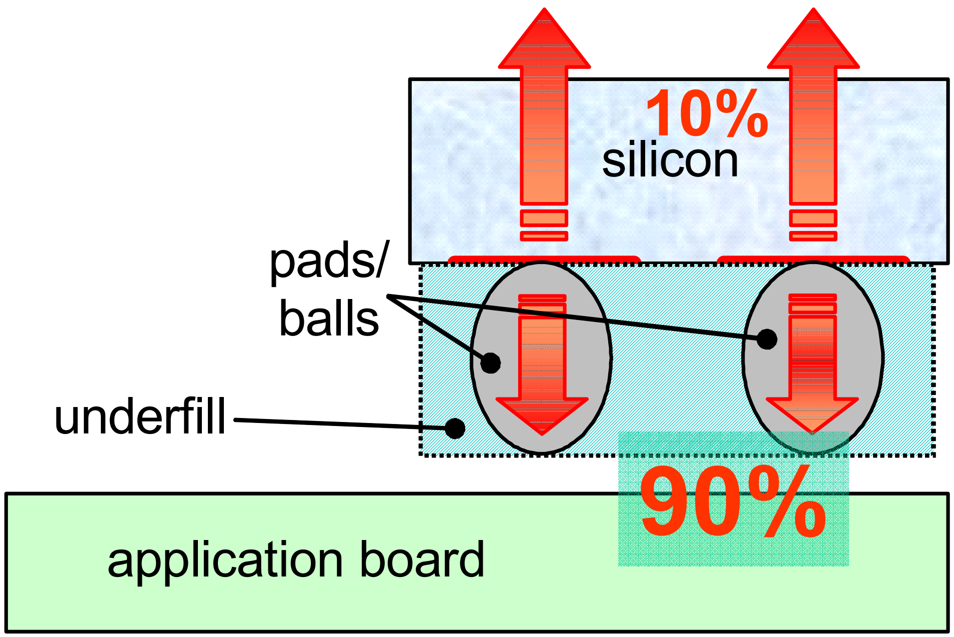
add an external heatsink …



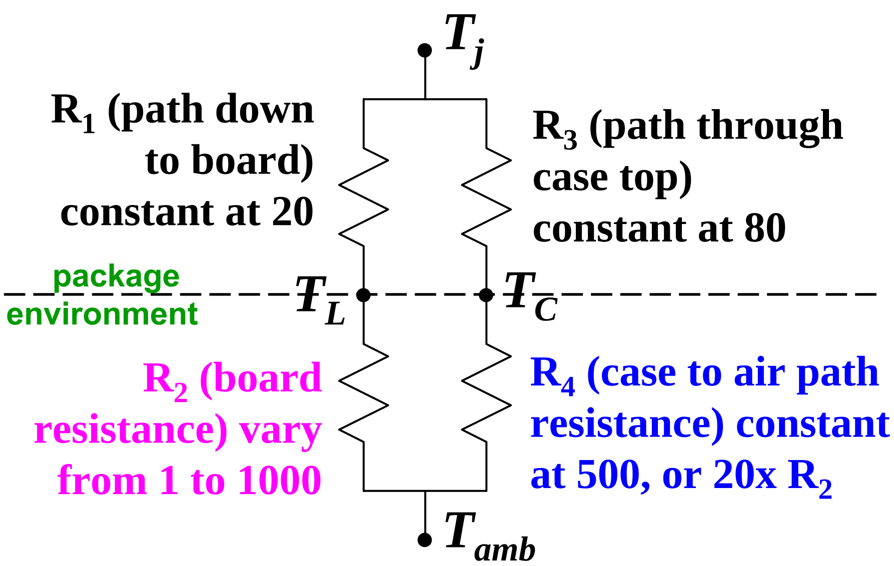
flip the die over …

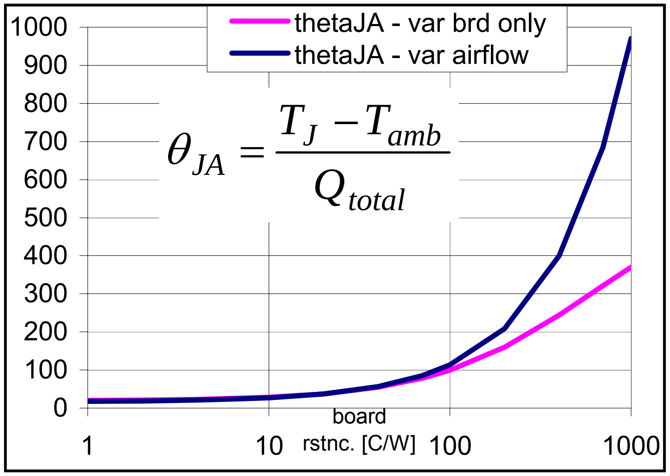


A bare “flip chip”



Even when it's constant, it's not!

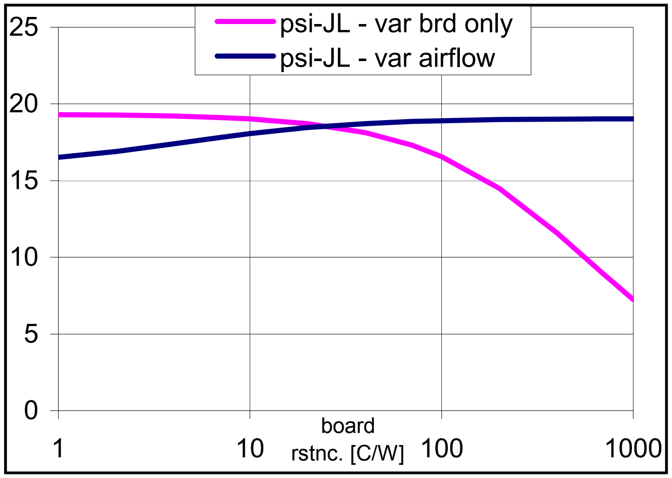




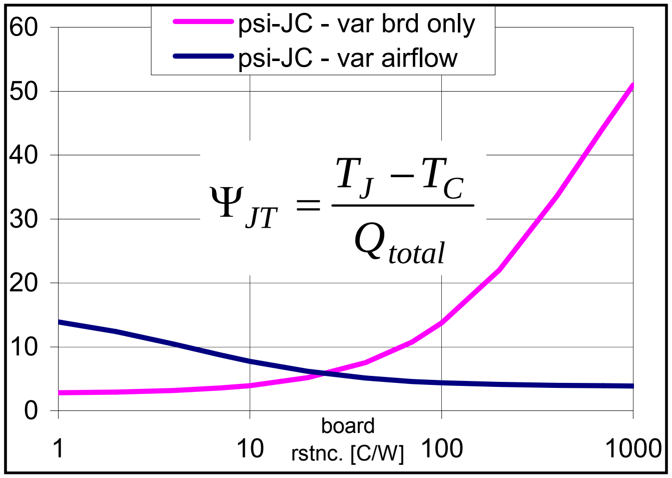
theta-JA

psi-JL

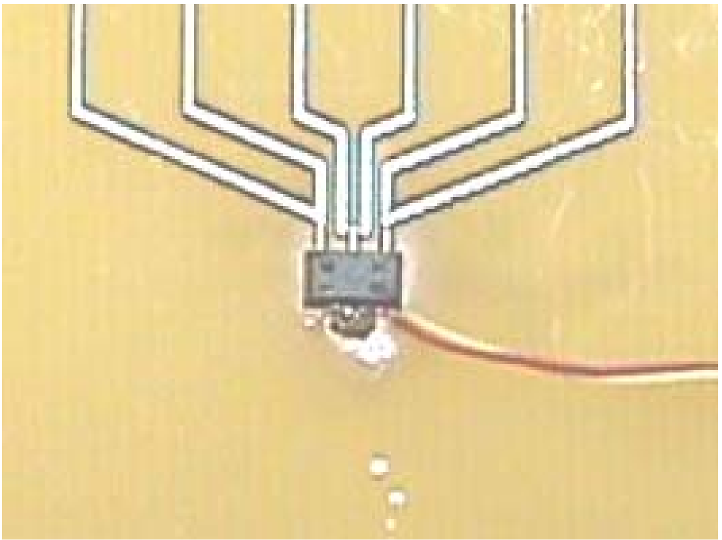
$$\Psi_{JL} = \frac{T_J - T_L}{Q_{total}}$$

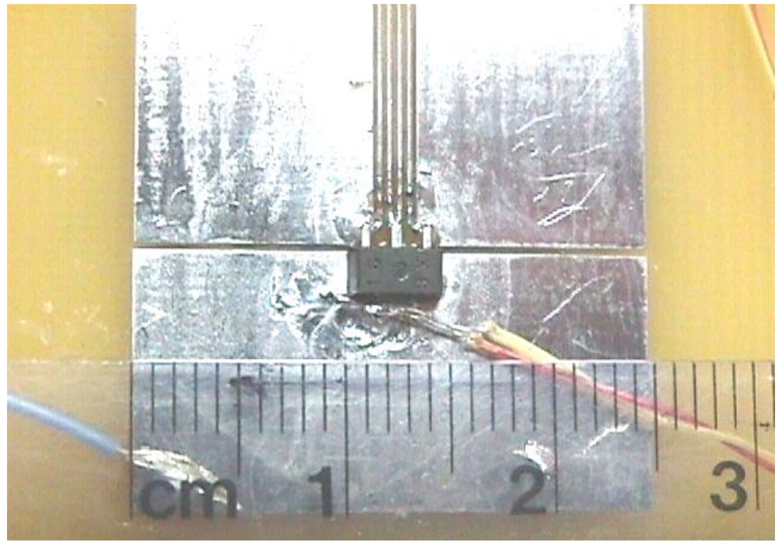


psi-JT



Typical thermal test board types





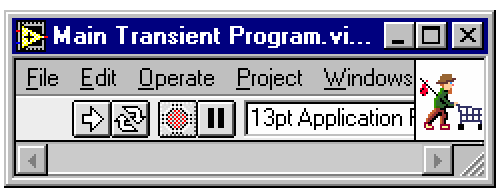
min-pad board

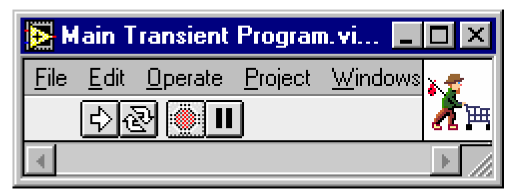
minimum metal area to attach device (plus traces to get signals and power in and out)

1-inch-pad board

device at center of 1”x1” metal area (typically 1-oz Cu); divided into sections based on lead count

Experimental Techniques





Experimental Techniques

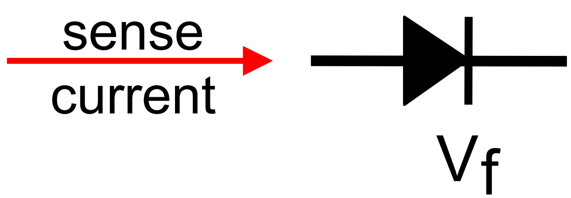
- Temperature Sensitive Parameters (TSPs)
- Different Device Types and How to Test Them
- Heating vs Cooling Curve Techniques
- Test Conditions

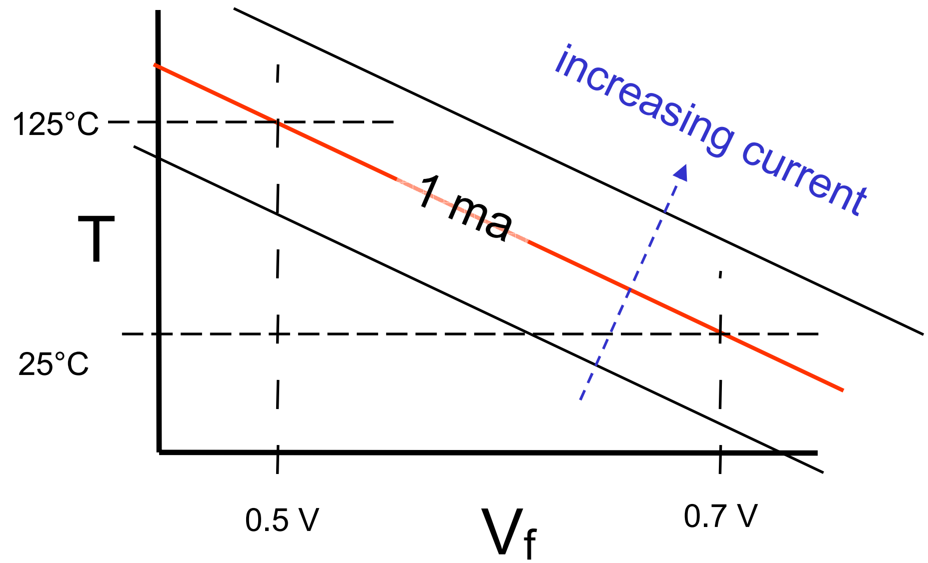
Temperature Sensitive Parameters

- JEDEC 51-1 good synopsis
- Basic diode physics (pg 5 of JESD 51-1)
  - At constant current, forward voltage goes down (linearly) with increasing temperature
- In principle, any device which has repeatable (not necessarily linear) voltage vs. temperature characteristics can be used
- Commercial thermal test equipment typically requires linear TSP behavior

Typical TSP Behavior

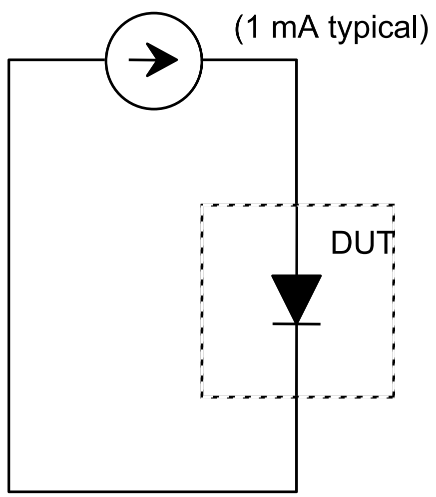
calibrate forward voltage at controlled,
small (say 1mA) sense current





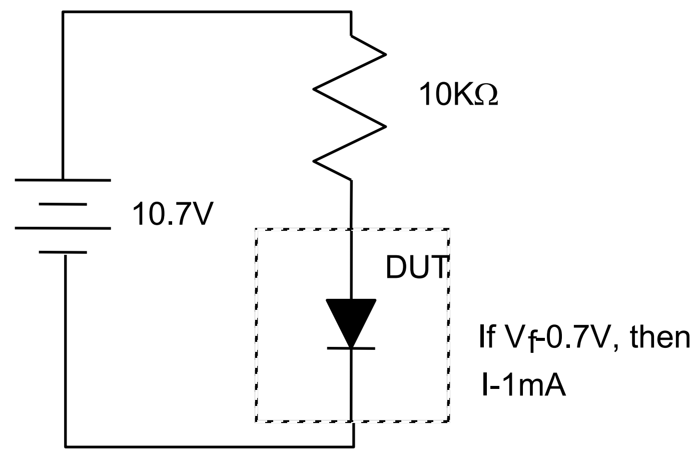
How to measure T_j

true const. current supply

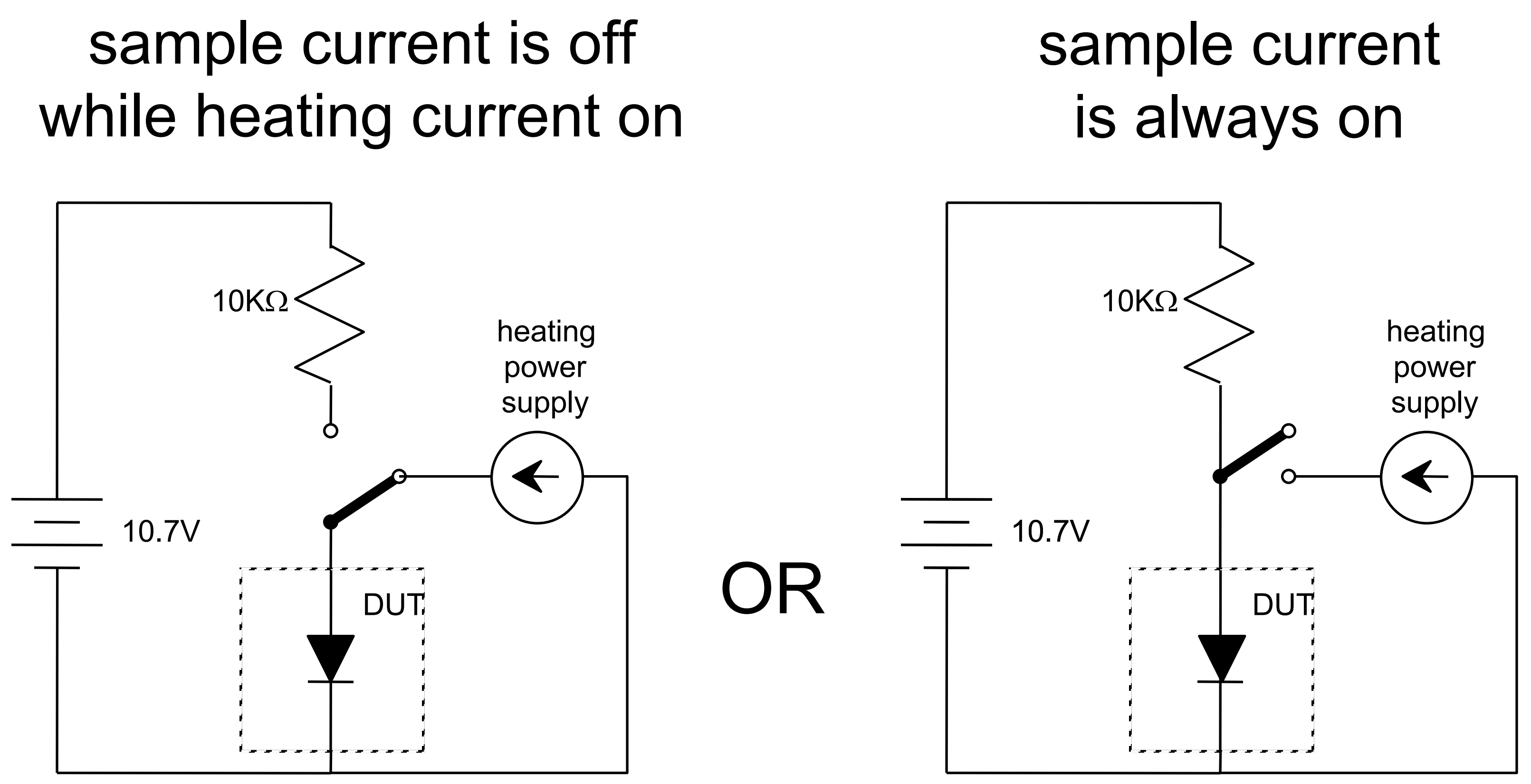


OR

approximate const. current supply



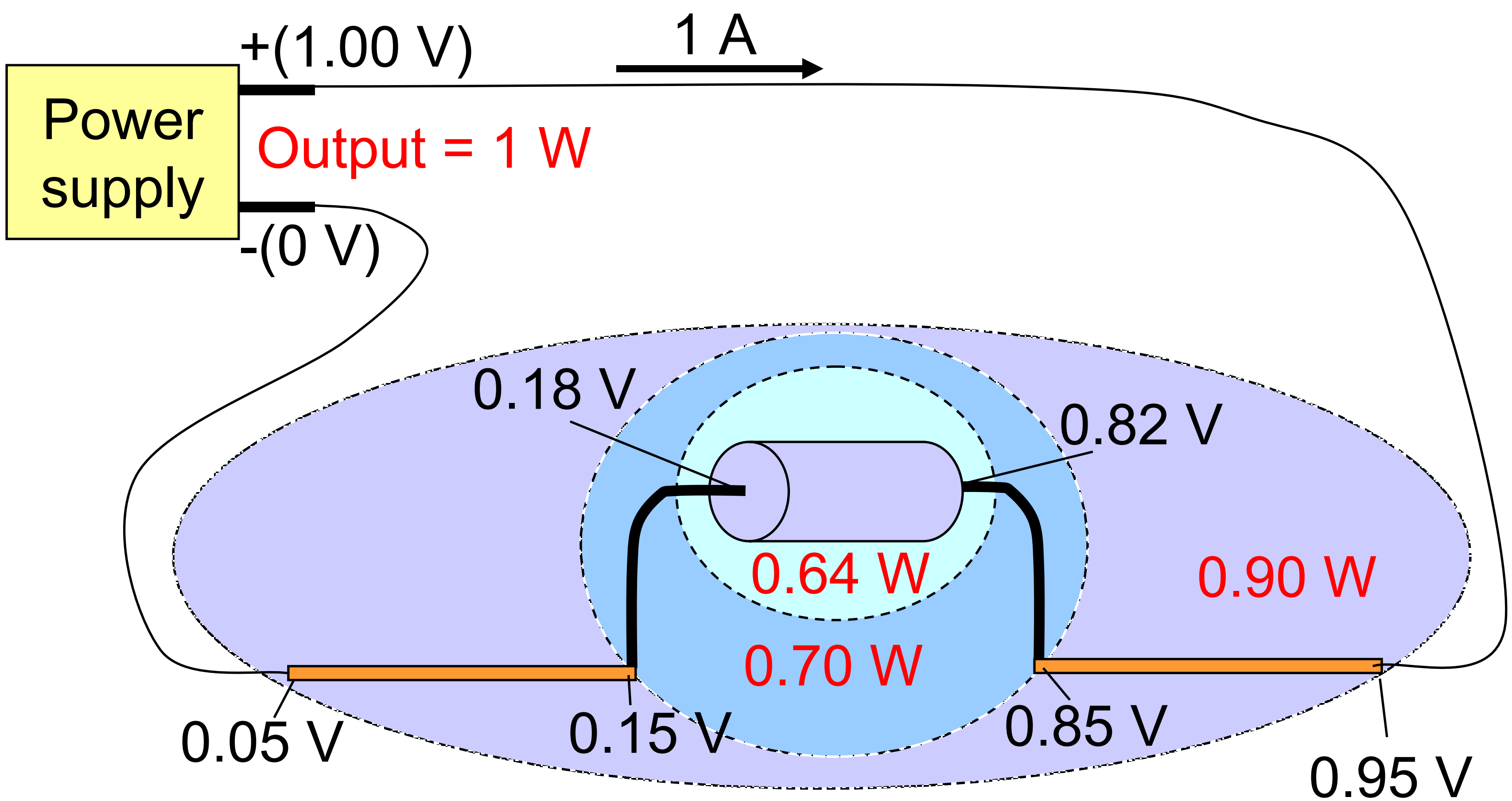
How to heat


sample current is off
while heating current on
10KΩ
heating
power
supply
10.7V
DUT
OR
sample current
is always on
10KΩ
heating
power
supply
10.7V
DUT

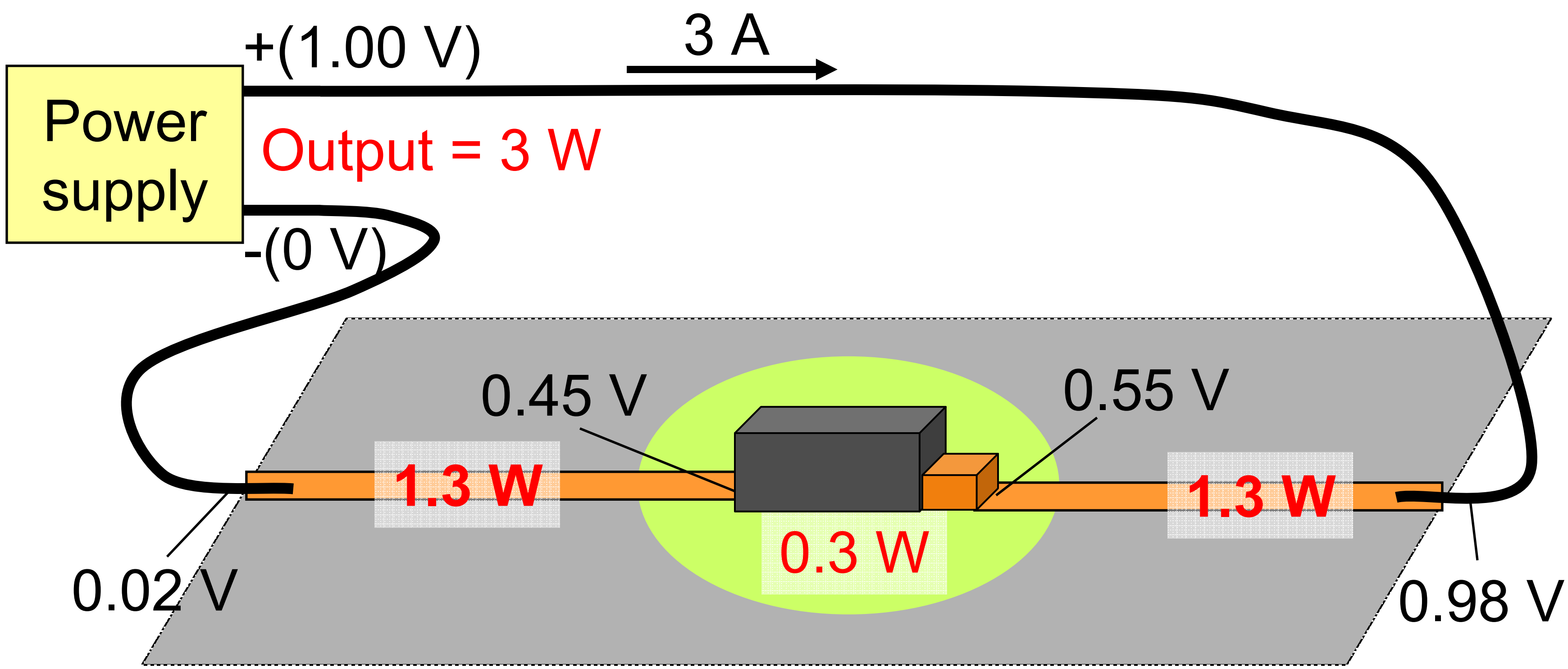
Superposition and TSP "self heating"

- Common warning:
  - Keep the TSP power low! "self heating is bad!"
- But is this really a problem?
  - If the "sample" power is always there, the "self heating" is the same during calibration as during test, so they cancel out
- You might unwittingly overheat the junction
- You might not be able to keep the "measurement" current on during the heating
  - But if this is a serious issue, reduce the effective "test" power by the amount of "measurement" power

The Importance of 4-wire measurements



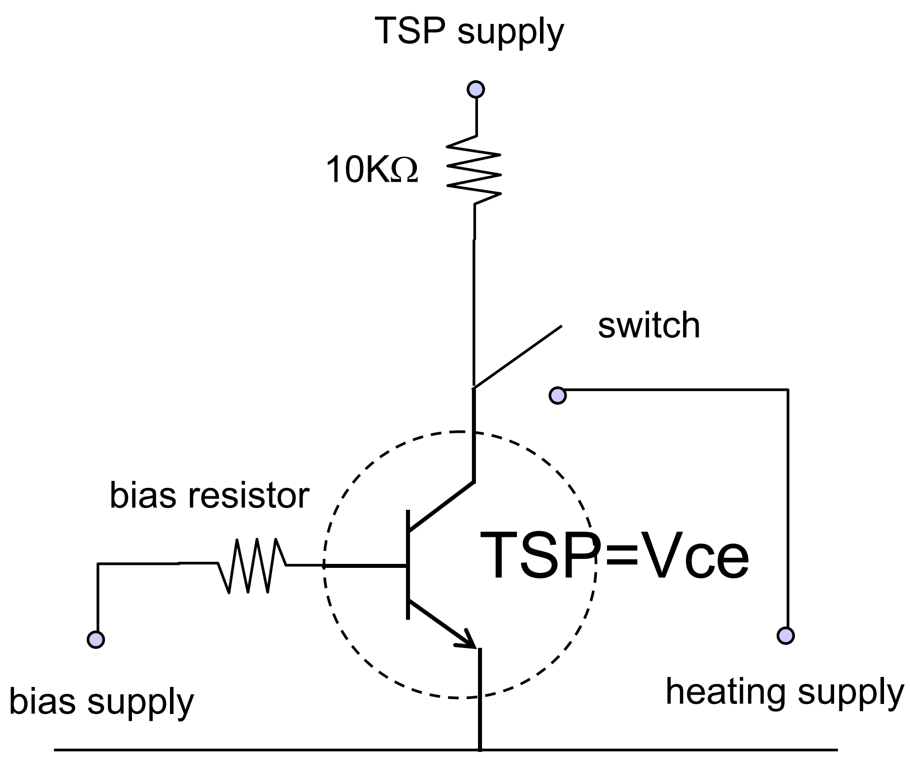
Which raises an interesting question:



Is this a fair characterization of a low-Rds-on device?

Bipolar transistor

- TSP is Vce at designated "constant" current
- Heating is through Vce
- Choose a base current which permits adequate heating

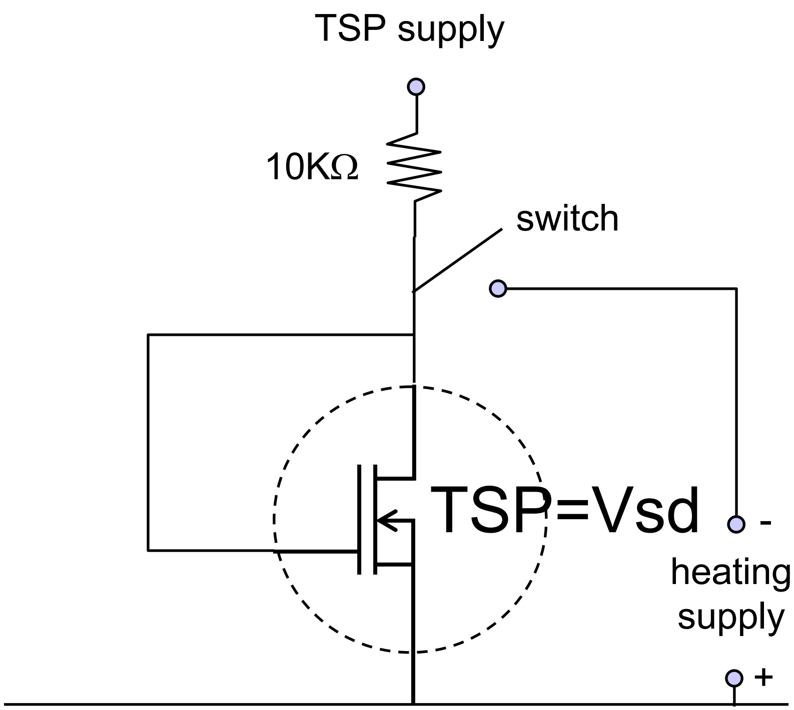


Schottky diode

- TSP is forward voltage at "low" current
- Voltages are typically very small (especially as temperature goes up)
- Highly non-linear, though maybe better as TSP current increases; because voltage is low, higher TSP current may be acceptable
- Heating current will be large

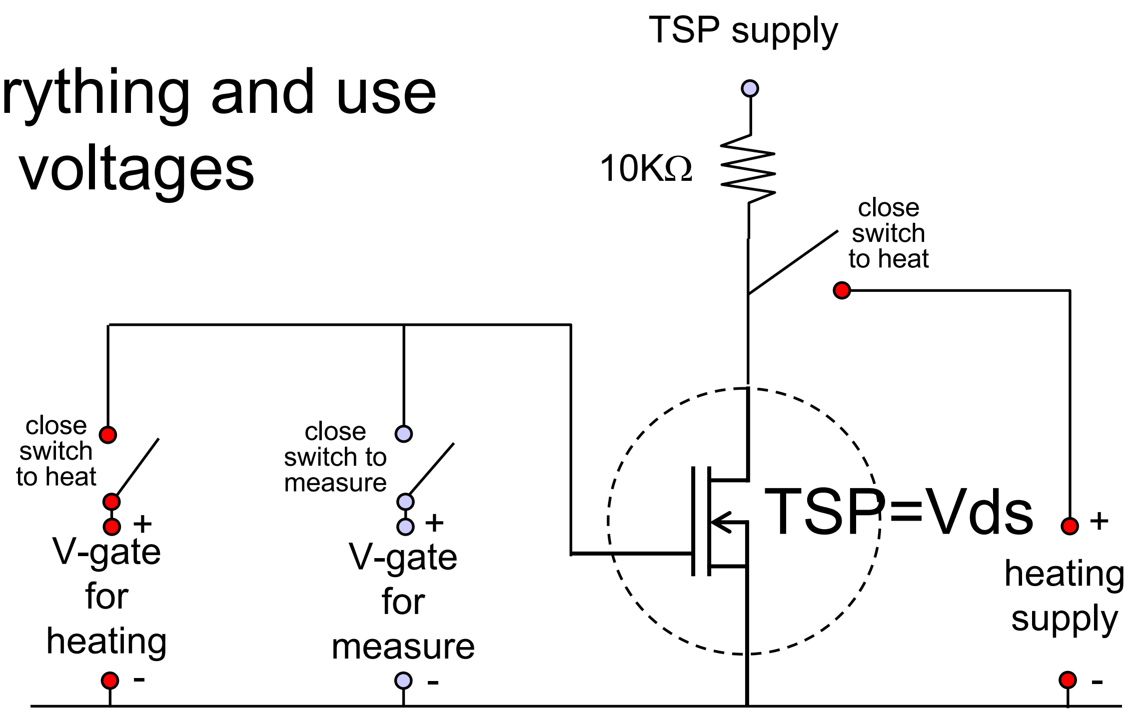
MOSFET / TMOS

- Typically, use reverse bias “back body diode” for both TSP and for heating
- May need to tie gate to source (or drain) for reliable TSP characteristic



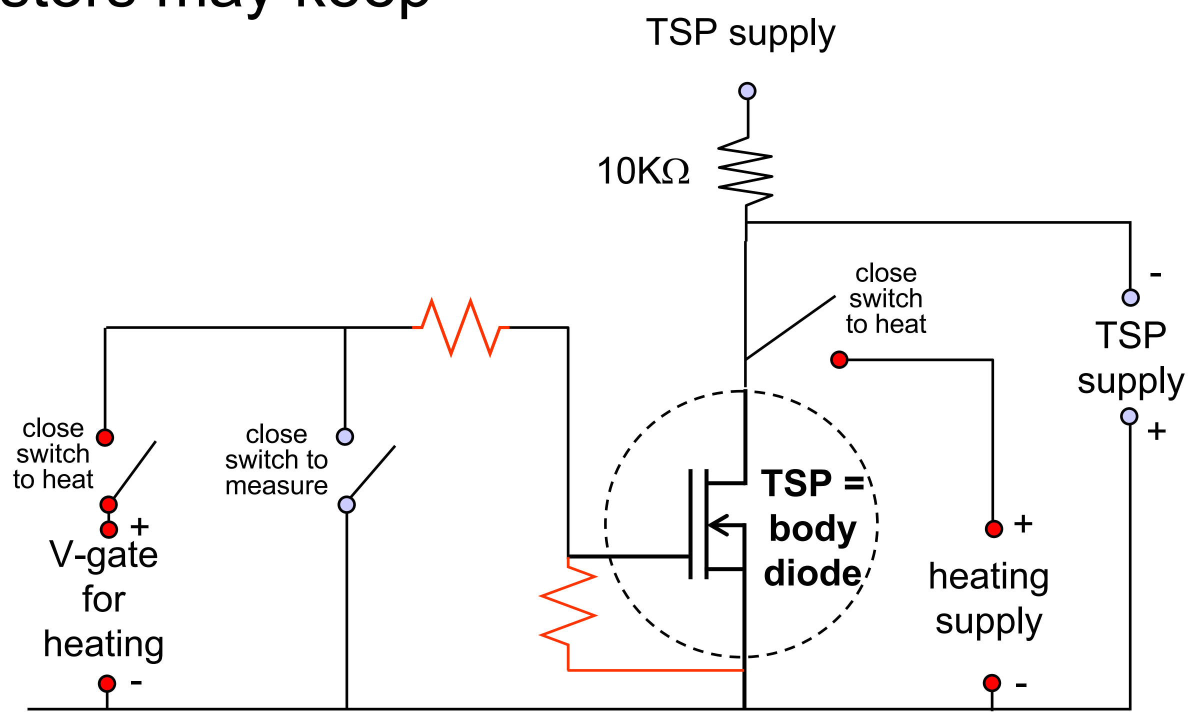
MOSFET / TMOS method 2

- If you have fast switches and stable supplies
- Forward bias everything and use two different gate voltages



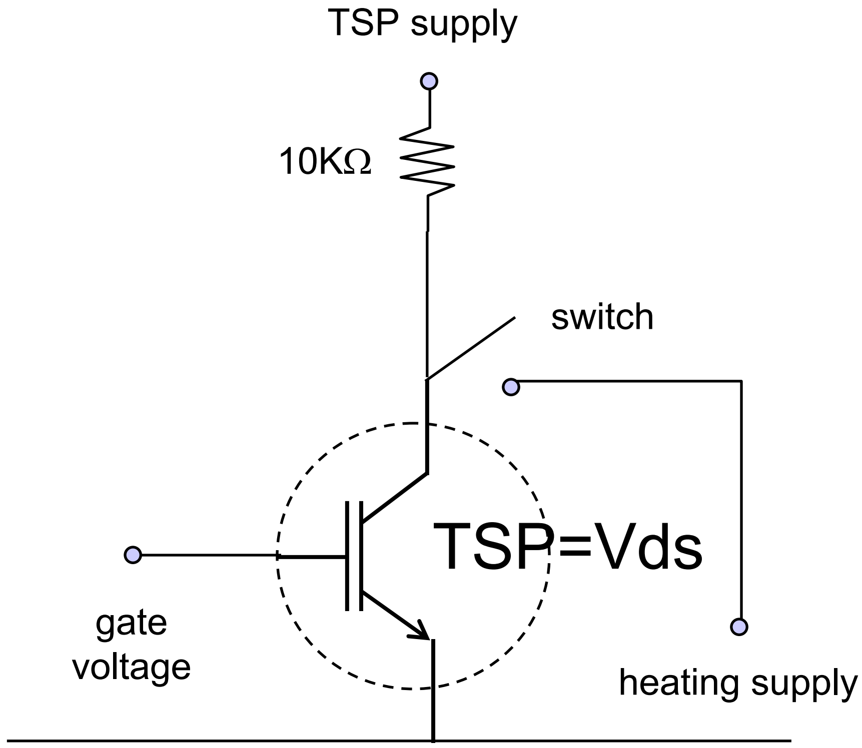
RF MOS

- They exist to amplify high frequencies (i.e. noise)!
- Feedback resistors may keep them in DC



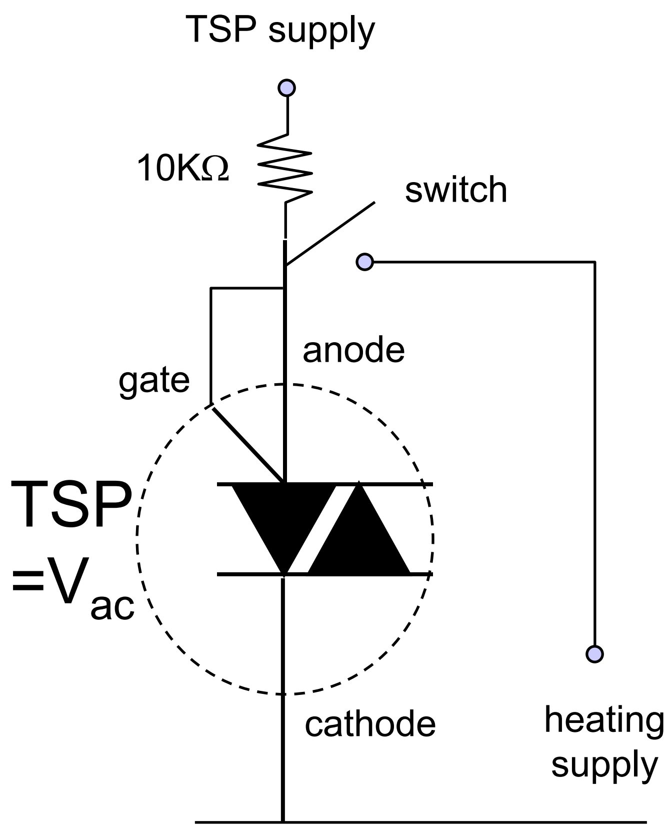
IGBT

- Drain-source channel used for both TSP and heating
- Find a gate voltage which “turns on” the drain-source channel enough for heating purposes
- Use same gate voltage, but typically low TSP current for temperature measurement



Thyristor

- Anode--to-cathode voltage path used both for TSP and for heating
- typical TSP current probably lower than “holding” current, so gate must be turned on for TSP readings; try tying it to the anode (even so, we used 20mA to test SCR2146)
- Hopefully, with anode tied to gate, enough power can be dissipated to heat device without exceeding gate voltage limit



Logic and analog

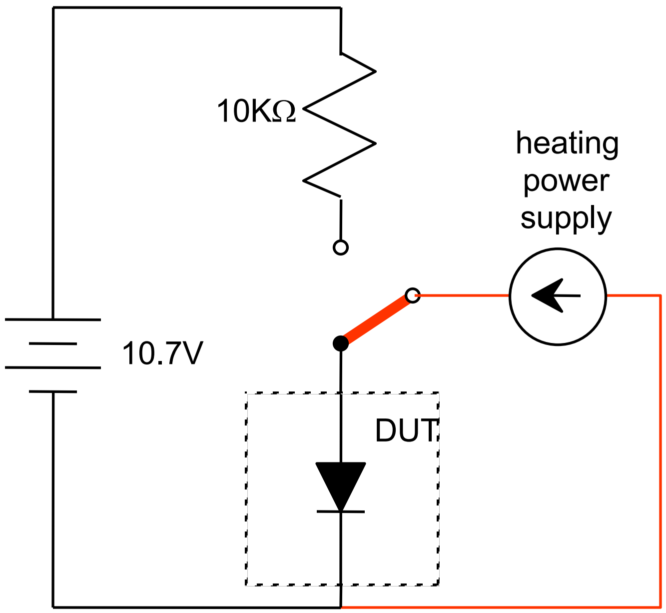
- Find any TSP you can
  - ESD diodes on inputs or outputs
  - Body diodes somewhere
- Heat wherever you can
  - High voltage limits on Vcc, Vee, whatever
  - Body diodes or output drivers
  - Live loads on outputs
    - (be very careful how you measure power!)

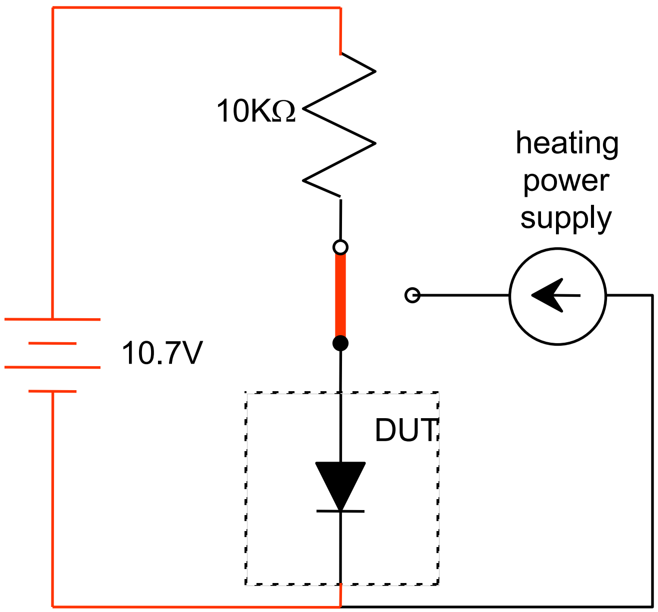
Heating curve method
vs.
cooling curve method

Quick review: Basic T_j measurement

first we heat

then we measure





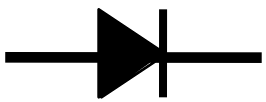
Question

- What happens when you switch from “heat” to “measure”?

Answer: stuff changes

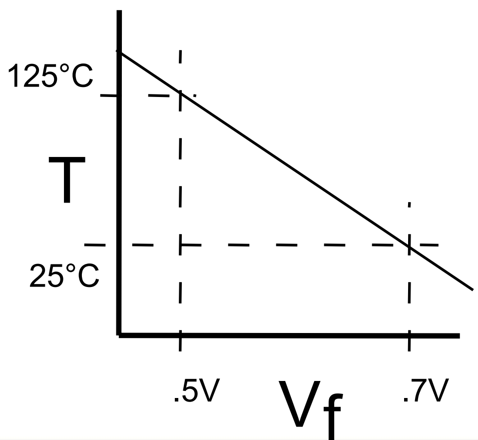
- More specifically, while the electrical signal is stabilizing, the junction starts to cool down

Basic “Heating Curve” Transient Method

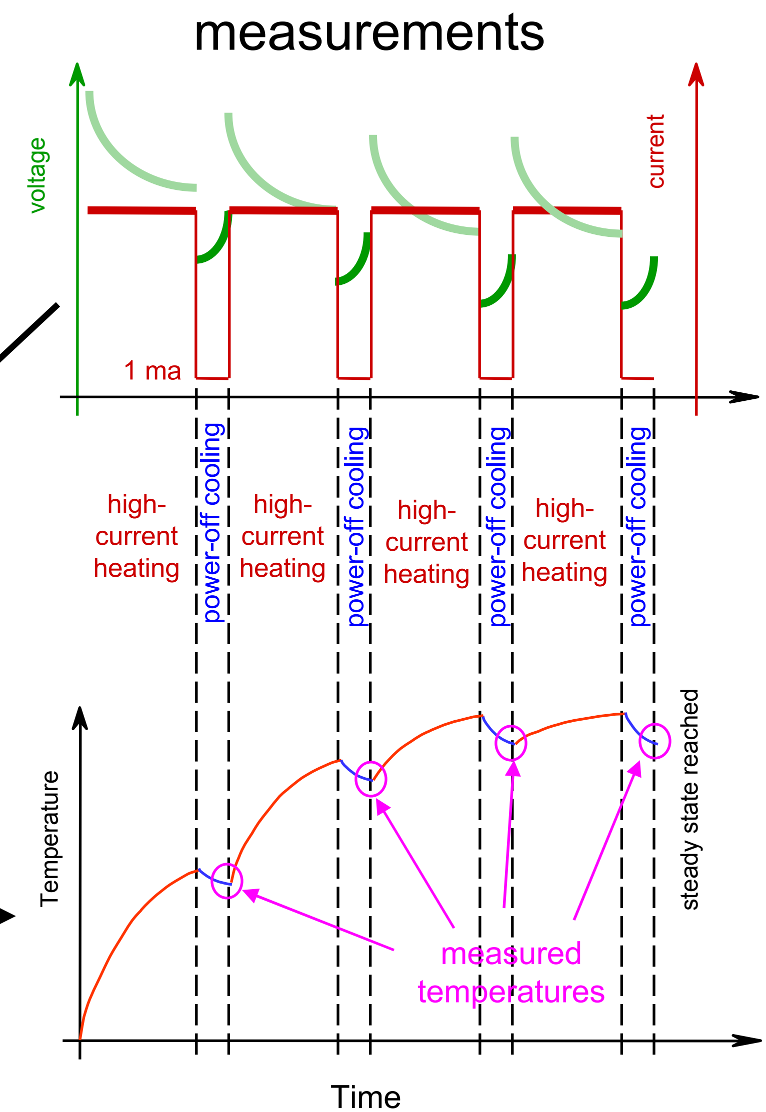


Vf

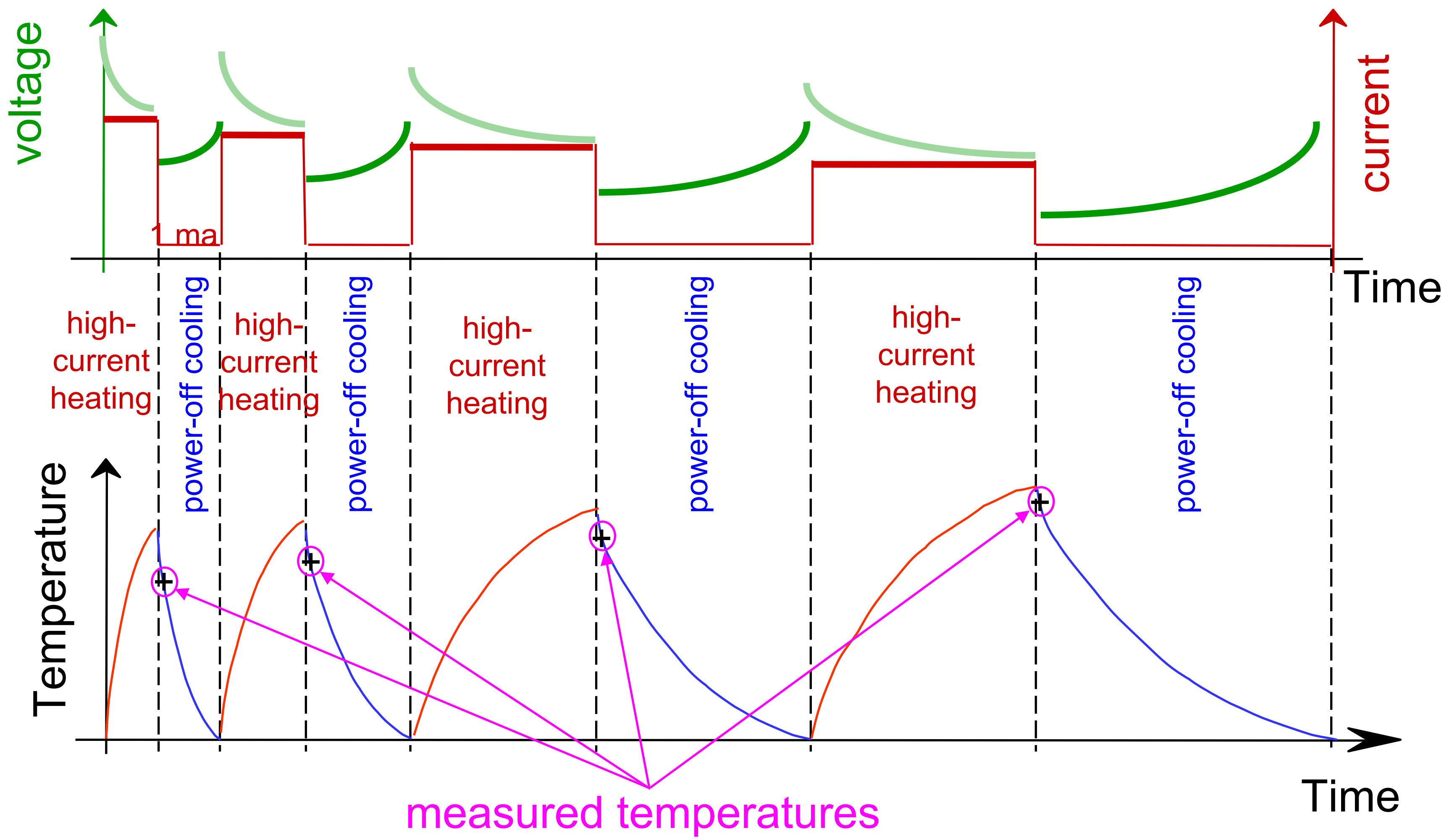
calibrate forward voltage
@ 1mA sense currrent



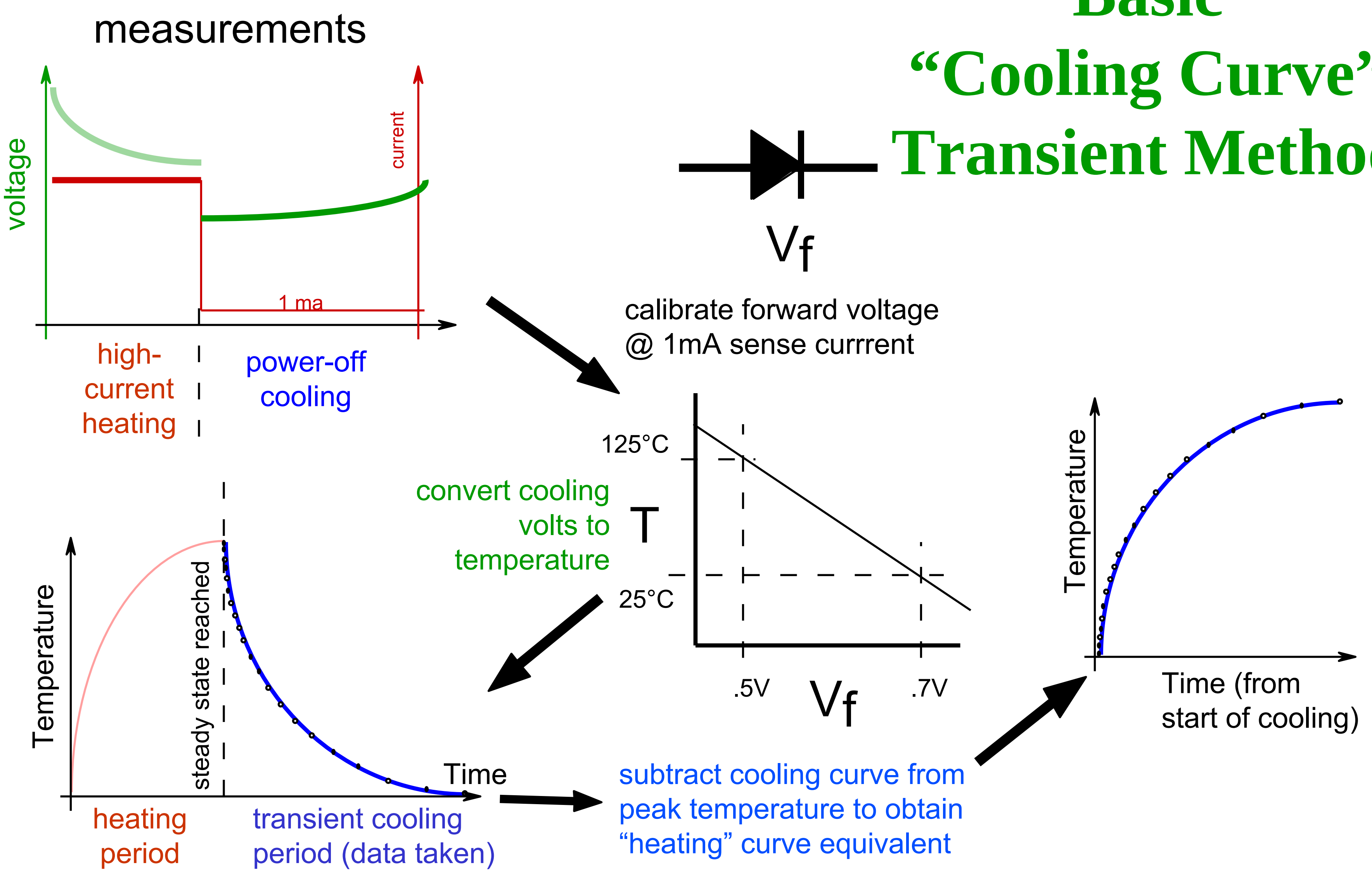
convert cooling volts to temperature



Heating curve method #2



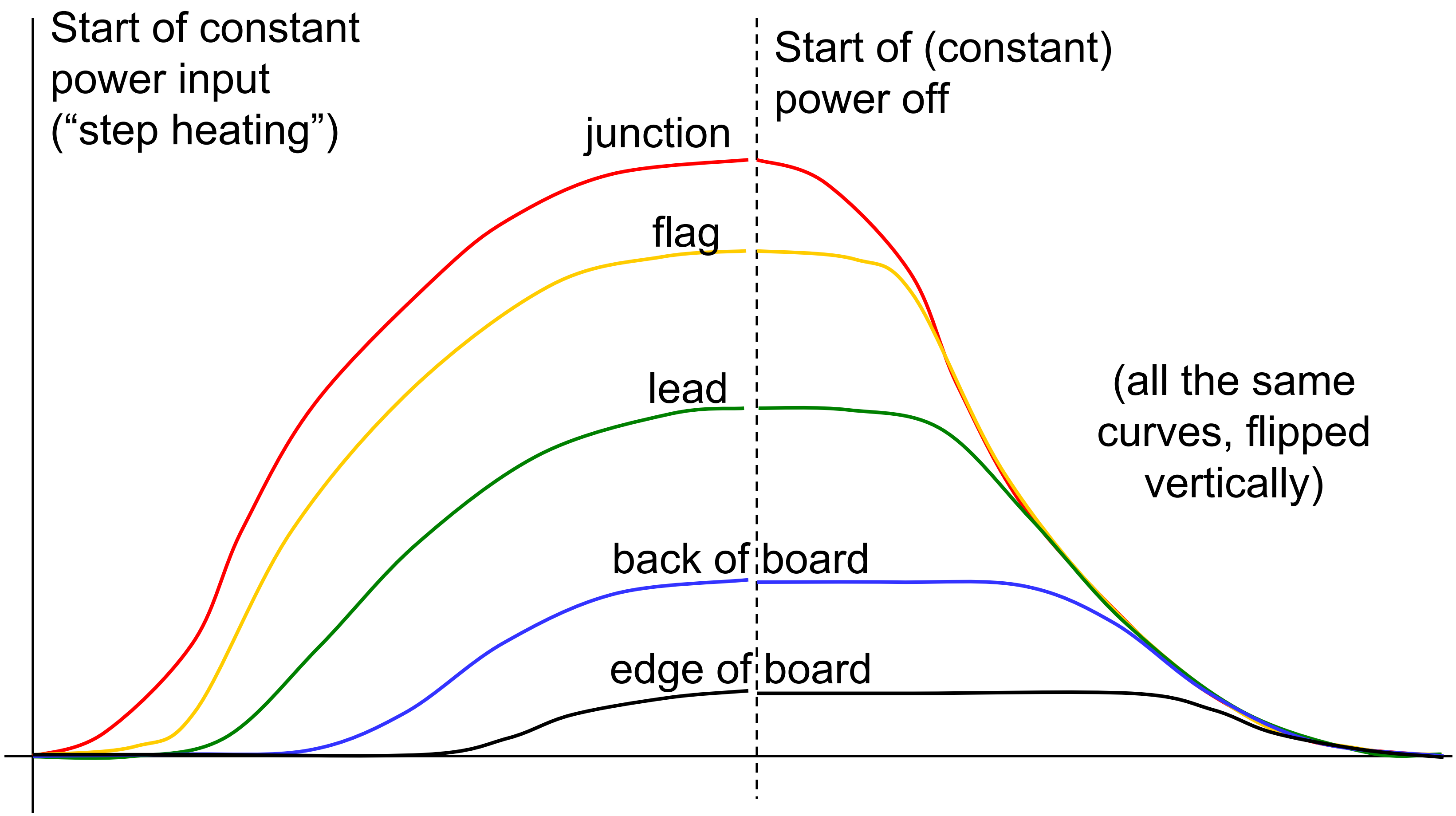
Basic “Cooling Curve” Transient Method



Whoa!
… that last step, there ...

- Heating vs. cooling
  - Physics is symmetric, as long as the material and system properties are independent of temperature

Heating vs. cooling symmetry



(cooling)

- For a theoretically valid cooling curve, you must begin at true thermal equilibrium (not uniform temperature, but steady state)
- So whatever your θ_{JA}, max power is limited to:

$$power = \frac{T_{j\max} - T_{\text{ambient}}}{\theta_{JA}}$$

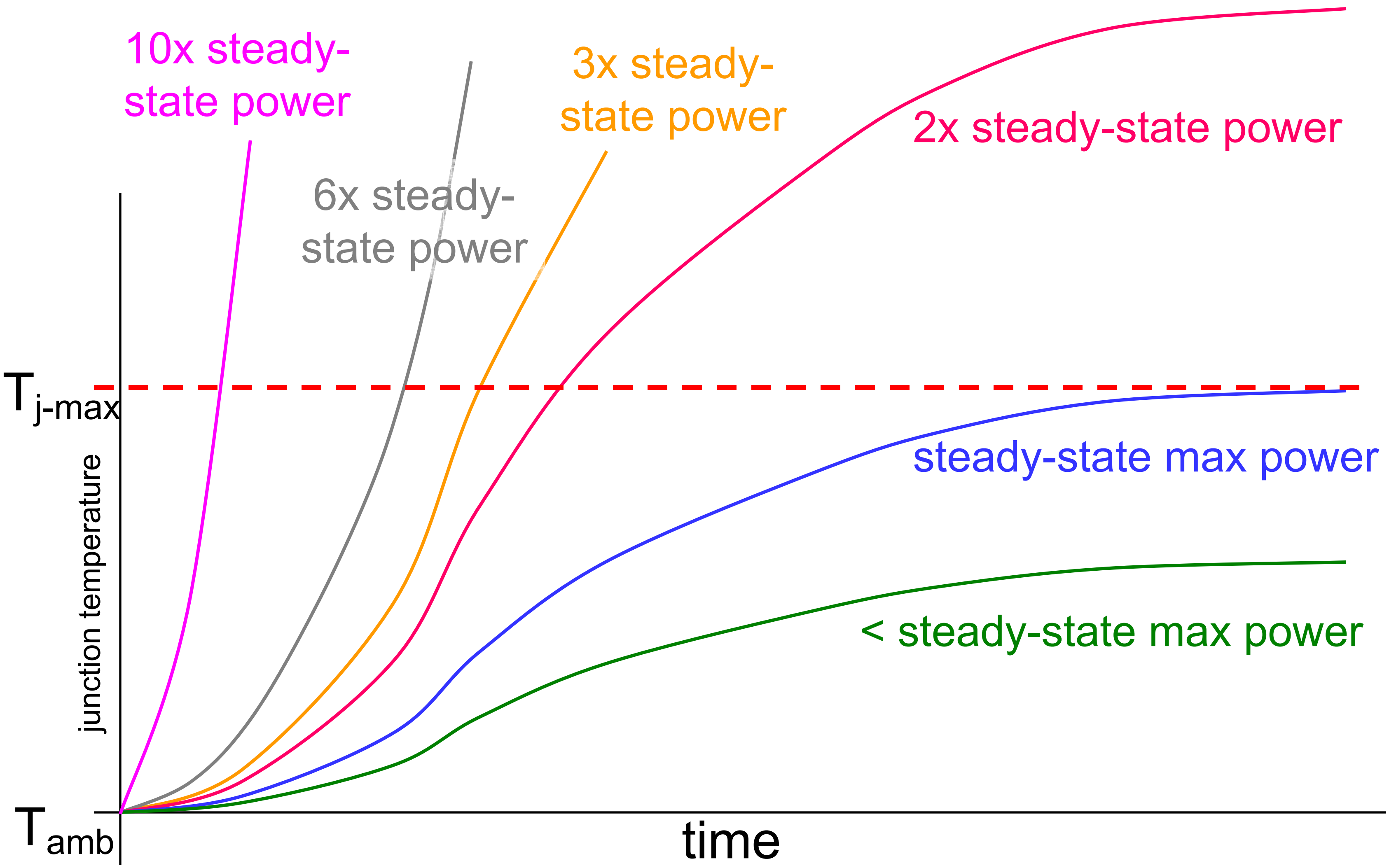
(cooling)

By the way …

- Since you must have the device at steady state in order to make a full transient cooling-curve measurement, steady-state θ_{JA} is a freebie.

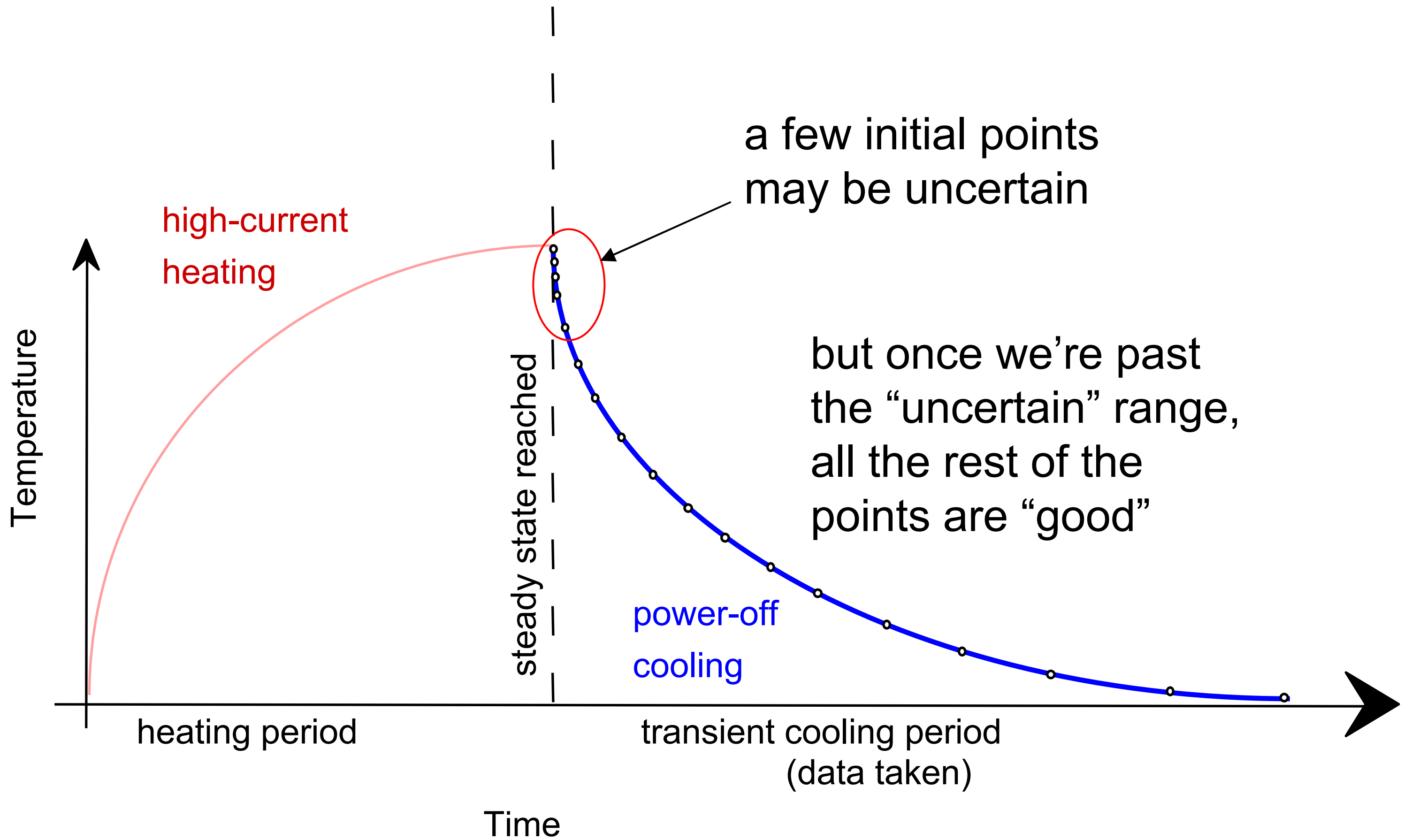
  (given that you account for the slight cooling which took place before your first good measurement occurred)

Effect of power on heating curve



(cooling)

Some initial uncertainty



Heating vs. cooling tradeoffs

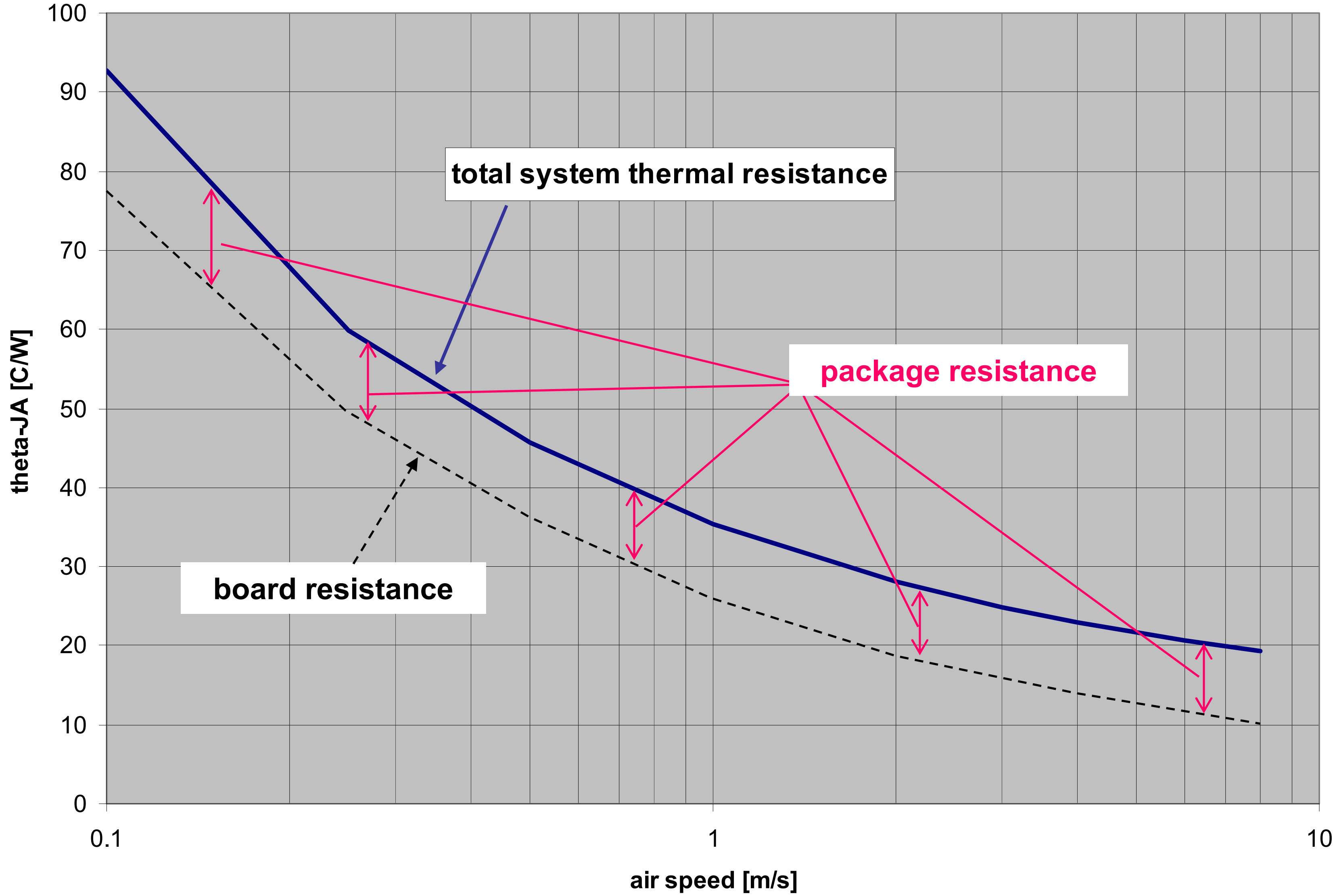
	HEATING	COOLING
starting temperature	ambient	?
heating power	limited by tester	limited to steady-state
temperature of fastest data	closer to ambient	closer to $T_{j\text{-}max}$
error control	all points similar error	error limited to first few points

Test Conditions

- Still air, moving air
- Various mounting configurations
  - Min-pad board
  - 1" heat spreader board
- Coldplate testing
  - Single, dual, "ring"

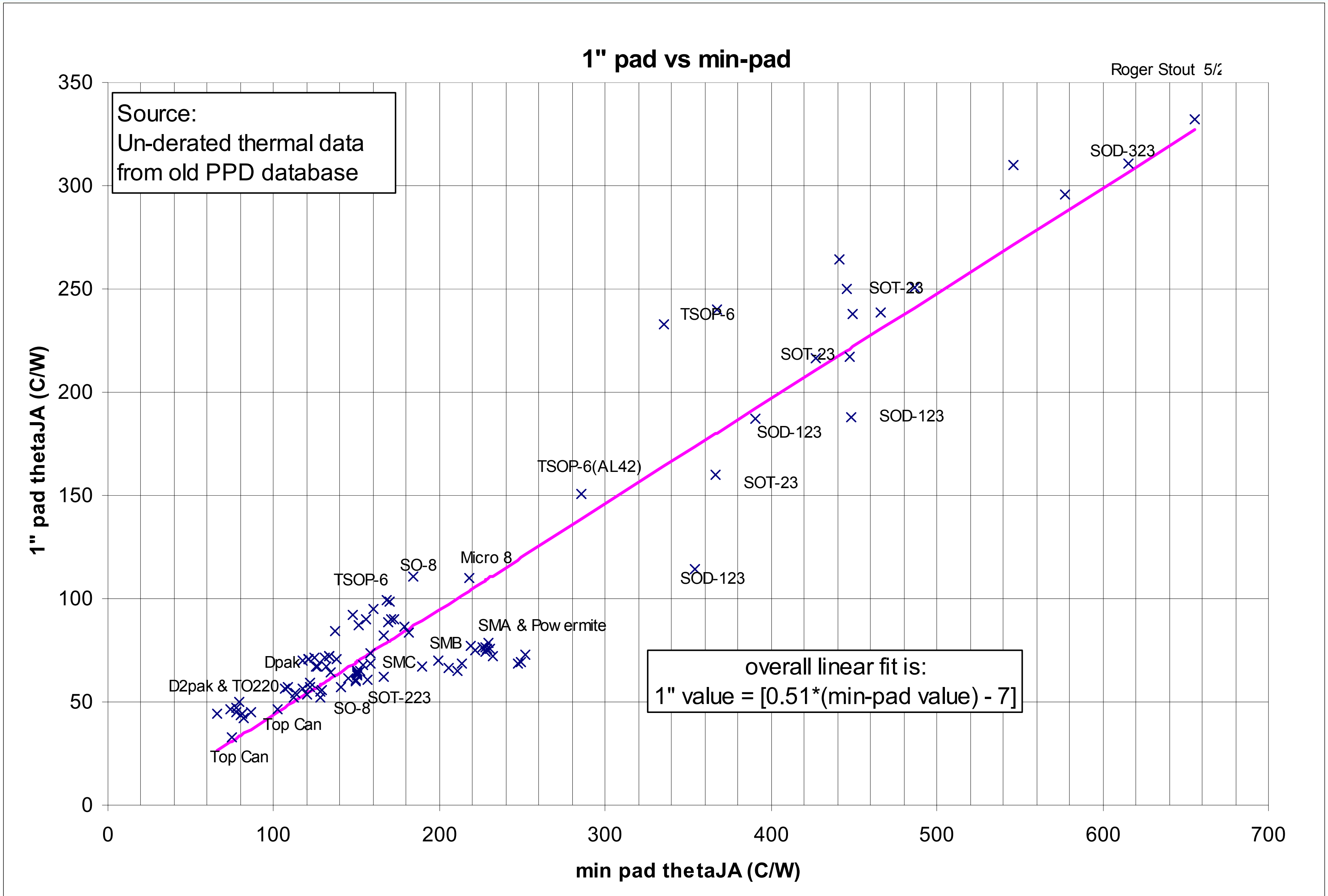
Still air vs. moving air

- Varying the air speed is mainly varying the heat loss from the test board surface area, not from the package itself
- You just keep re-measuring your board's characteristics


total system thermal resistance
package resistance
board resistance
theta-JA [C/W]
air speed [m/s]
100
90
80
70
60
50
40
30
20
10
0
0.1
1
10

Different boards

- min-pad board
- 1” heat spreader board
- you’re mainly characterizing how copper area affects *every* package and board, not how a *particular* package depends on copper area

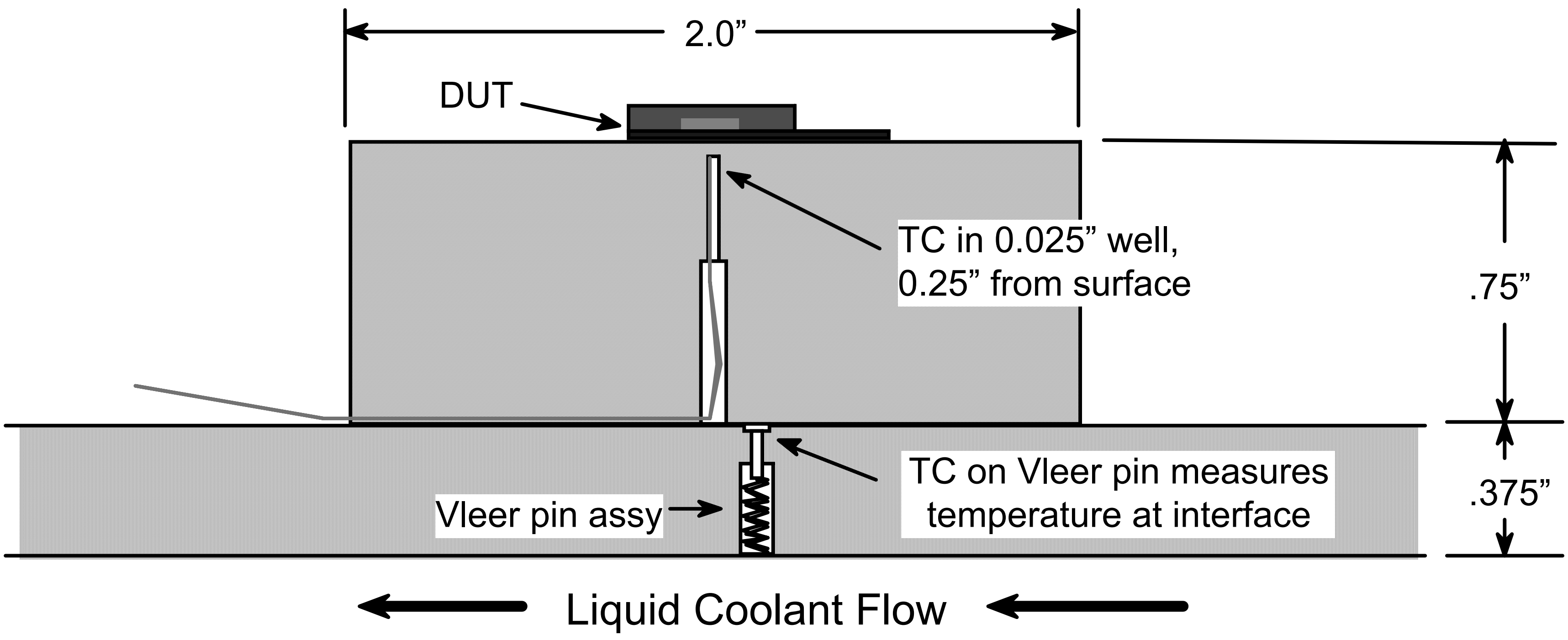

1" pad vs min-pad
Roger Stout 5/2
Source:
Un-derated thermal data
from old PPD database
1" pad thetaJA (C/W)
min pad thetaJA (C/W)
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
SOD-323
TSOP-6
SOT-23
SOT-23
SOD-123
SOD-123
TSOP-6(AL42)
SOT-23
SOD-123
SO-8
Micro 8
TSOP-6
SMA & Powermite
SMB
Dpak
SMC
D2pak & TO220
SOT-223
SO-8
Top Can
Top Can
overall linear fit is:
1" value = [0.51*(min-pad value) - 7]

Standard coldplate testing

- “infinite” heatsink (that really isn’t) for measuring theta-JC on high-power devices
- If both power and coldplate temperature are independently controlled, “two parameter” compact models may be created

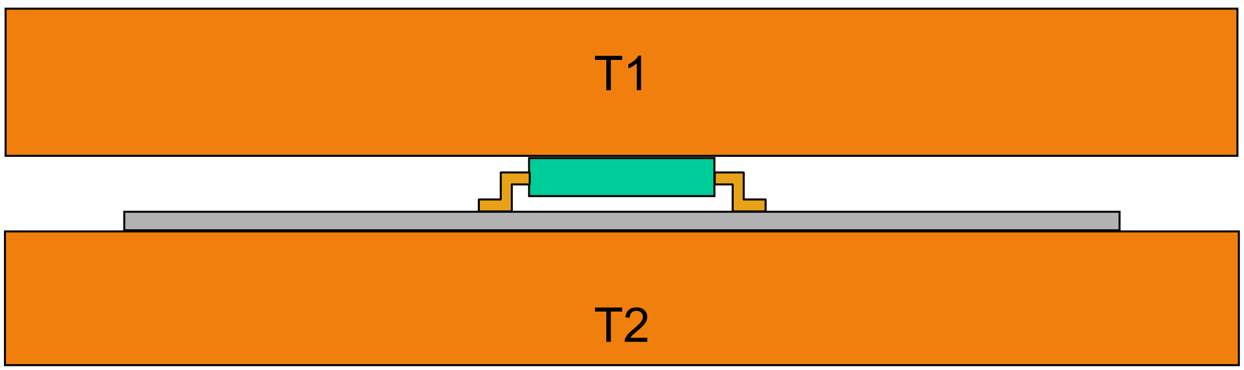
Standard coldplate testing

- Detailed design and placement of “case” TC can have significant effect on measured value



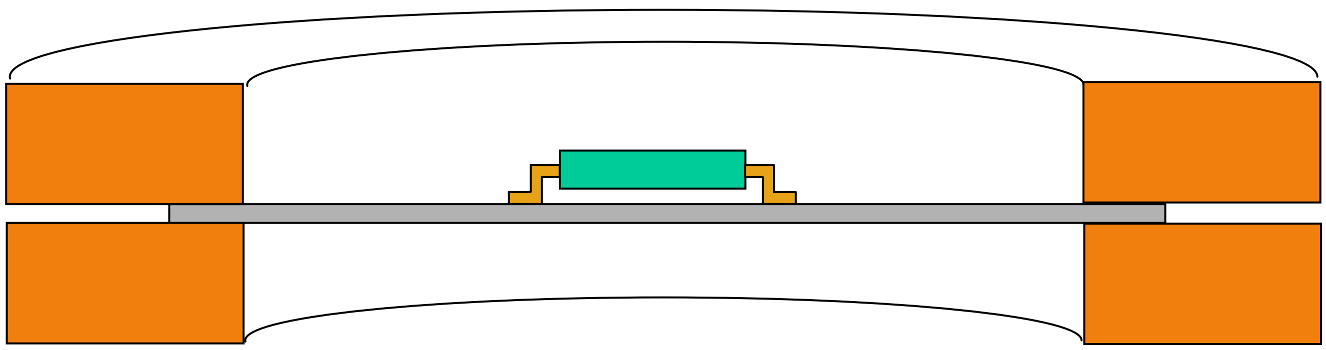
"Dual" coldplate testing

- Alternative method for "two-parameter" characterization methods where two independent "isothermal" boundary conditions are desired

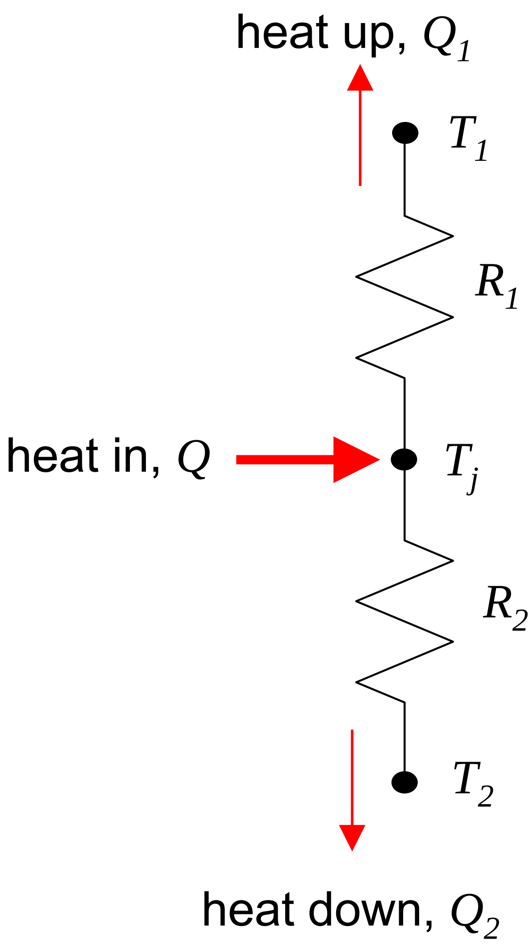


"Ring" coldplate

- For making somewhat higher-power board-mounted measurements; "ring" coldplate is clamped around outer edge of test board to constrain board temperature



2-parameter data reduction



$$Q = Q_1 + Q_2$$

$$Q = \frac{1}{R_1}\left(T_j - T_1\right) + \frac{1}{R_2}\left(T_j - T_2\right)$$

This has the form of a two-variable linear equation:

$$y = m_1 x_1 + m_2 x_2 + b$$

where:

$$m_1 = \frac{1}{R_1} \qquad x_1 = \left(T_j - T_1\right)$$

$$m_2 = \frac{1}{R_2} \qquad x_2 = \left(T_j - T_2\right)$$

$$b \equiv 0$$

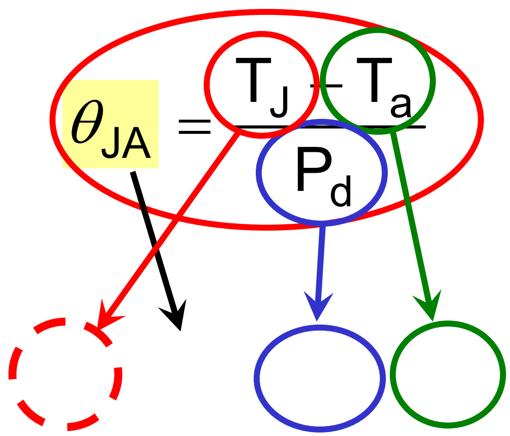
What's wrong with theta-JA?

THERMAL RATINGS

Parameter	Test Conditions Typical Value		Units
SO−8 Package	**Min−Pad Board** (Note 1)	**1.0 in Pad Board** (Note 2)	
Junction−to−Tab (psi−JL2, Ψ_{JL2}) (Note 3)	48	43	°C/W
Junction−to−Ambient ($R_{\theta JA}$, θ_{JA})	183	120	°C/W

1. 1 oz copper, 54 mm^2 copper area, 0.062" thick FR4.
2. 1 oz copper, 714 mm^2 copper area, 0.062" thick FR4.
3. psi−JL2 temperature was made at foot of lead #2.

$$\theta_{JA} = \frac{T_J - T_a}{P_d}$$



$$\Psi_{Jtab} = \frac{T_J - T_{tab}}{P_d}$$

$$T_J = \Psi_{Jtab} \cdot P_d + T_{tab}$$

Theta-JA vs copper area

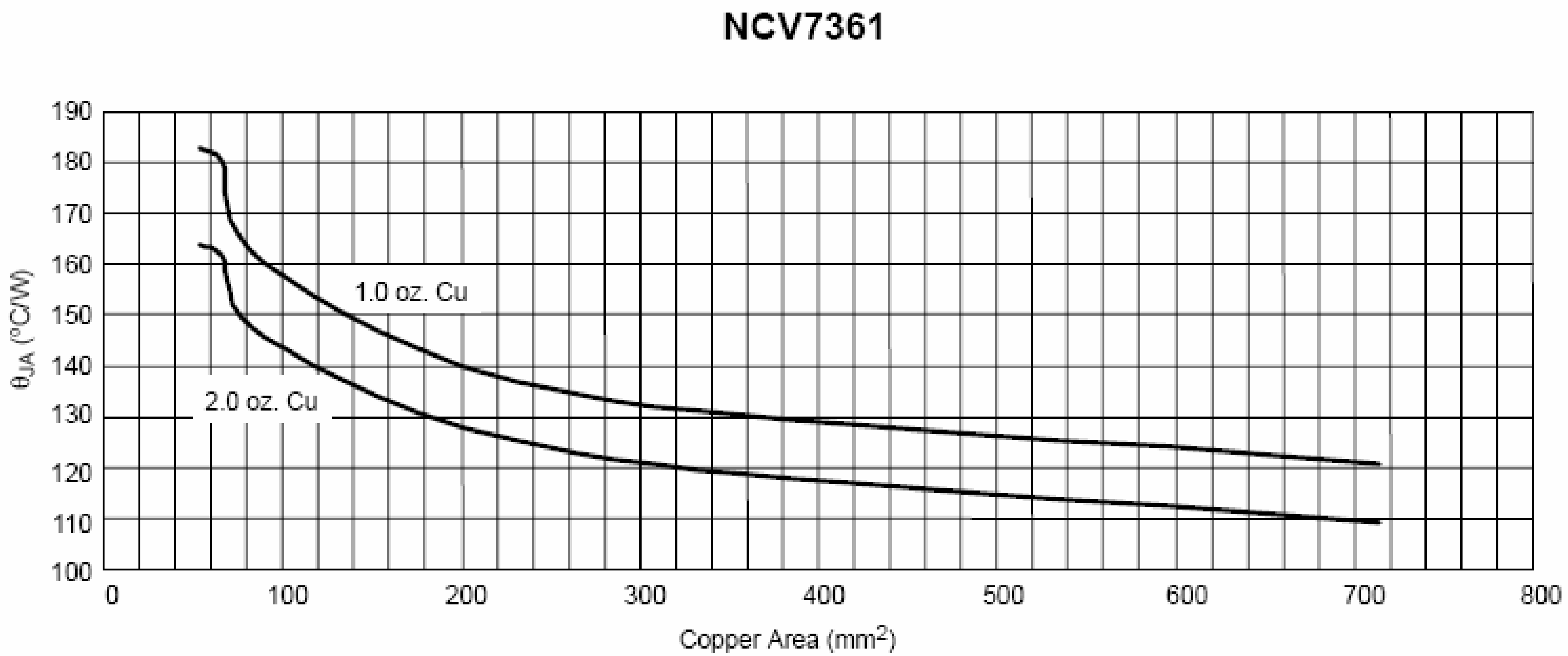
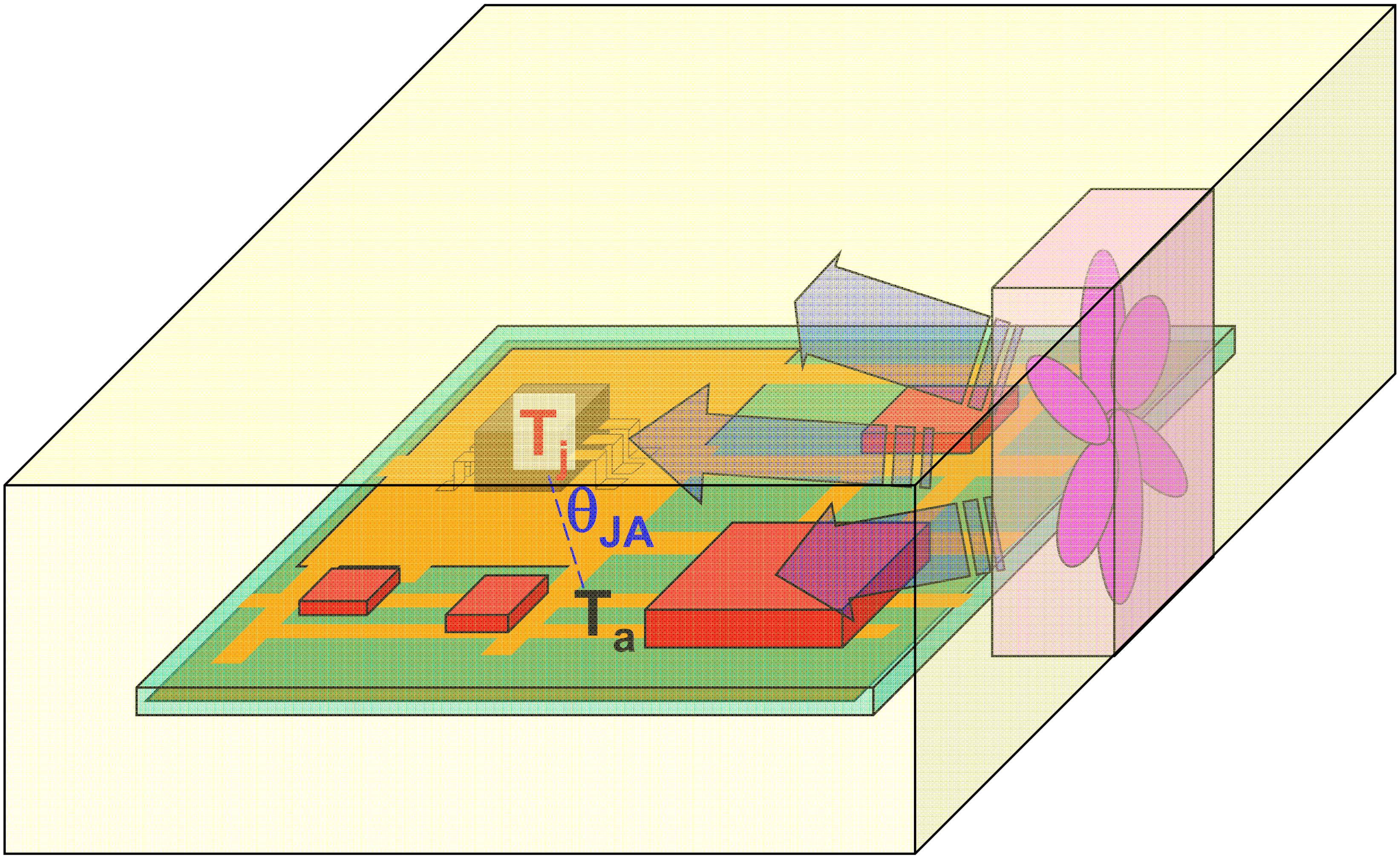


Figure 21. SO−8, θ_{JA} as a Function of the Pad Copper Area Including Traces, Board Material

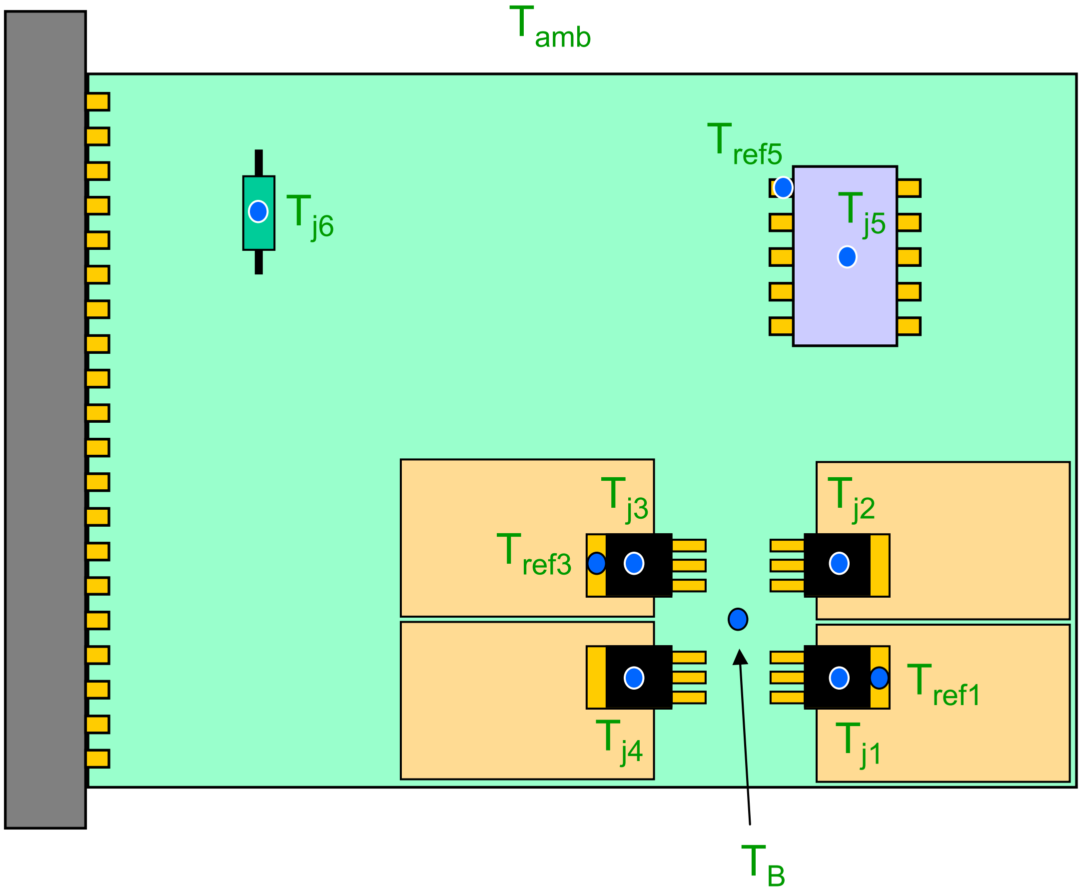
Linear superposition


Tj
θJA
Ta

Facts and fallacies redux

- Basic idea:
  - "thermal resistance" is an intrinsic property of a package
- Flaws in idea:
  - there is no isothermal "surface", so you can't define a "case" temperature
    - Plastic body (especially) has big gradients
  - different leads are at different temperatures
  - multiple, parallel thermal paths out of package
  - other heat sources change everything

Our case-study will be this 6-component thermal system



Linear superposition – what is it?

- The total response of a point within the system, to excitations at all points of the system, is the sum of the individual responses to each excitation taken independently.

$$\Delta T_{composite} = \Delta T_{source\ 1} + \Delta T_{source\ 2} + \cdots + \Delta T_{source\ n}$$

Linear superposition – when does it apply?

- The system must be "linear" – in brief, all individual responses must be proportional to all individual excitations.

$$\Delta T_{net\ A} = \underbrace{\Delta T_{A \leftarrow B}} + \underbrace{\Delta T_{A \leftarrow C}} + \underbrace{\Delta T_{A \leftarrow D}}$$

$$= 2 \cdot q_B + 3 \cdot q_C + 1.2 \cdot q_D$$

Linear superposition doesn't apply if the system isn't *linear*.

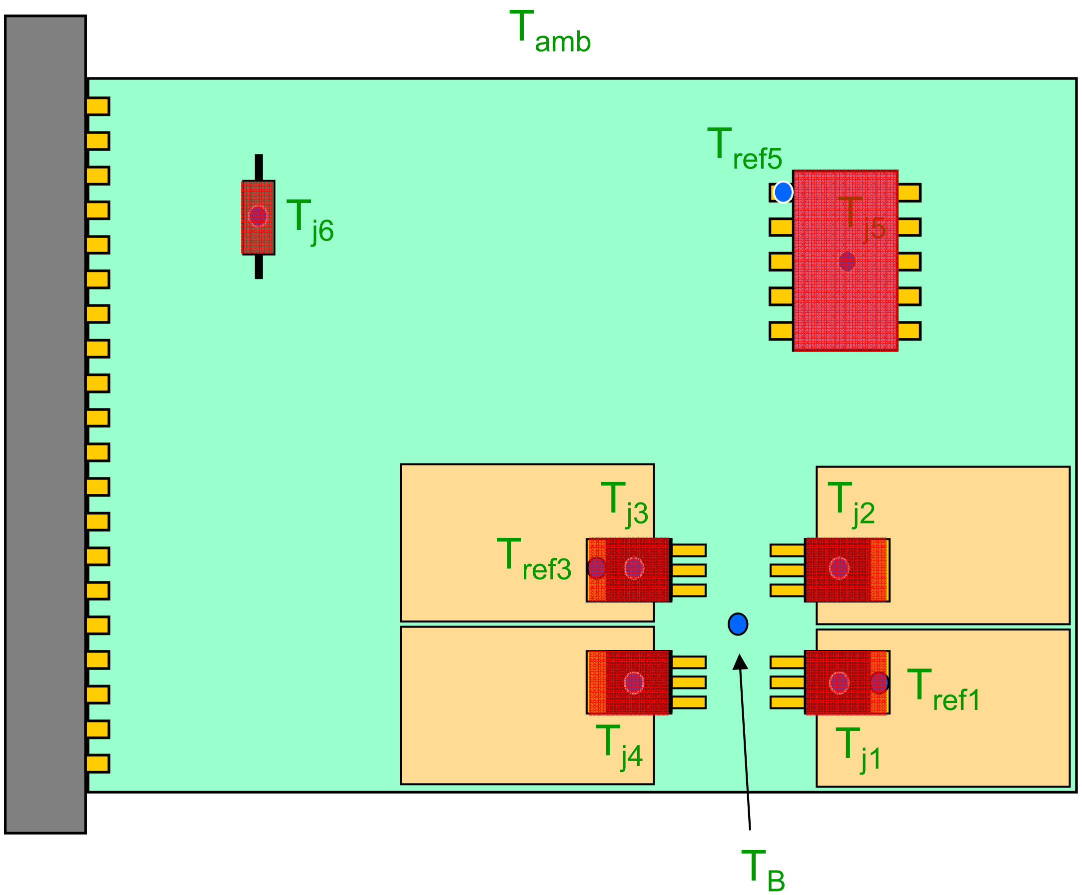
$$\Delta T = a(T, q_1) \cdot q_1 + b(T, q_2) \cdot q_2 + \cdots$$

$$\Delta T = a \cdot q_1^{n1} + b \cdot q_2^{n2} + \cdots$$

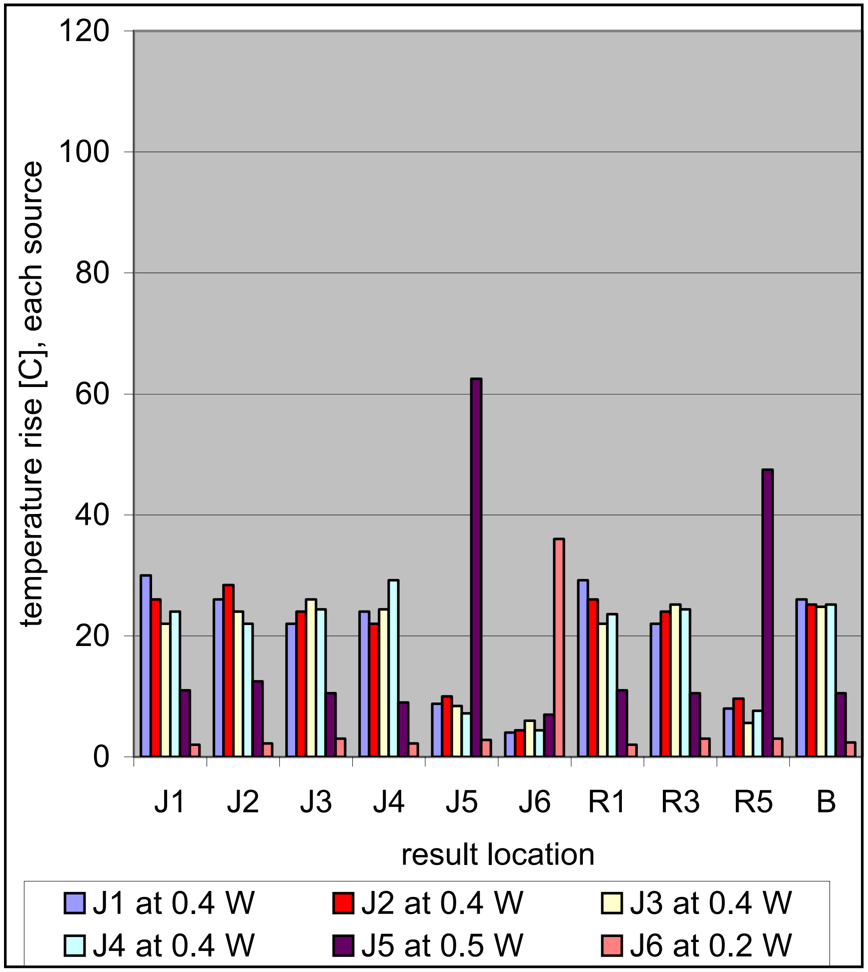
Linear superposition – when would you use it?

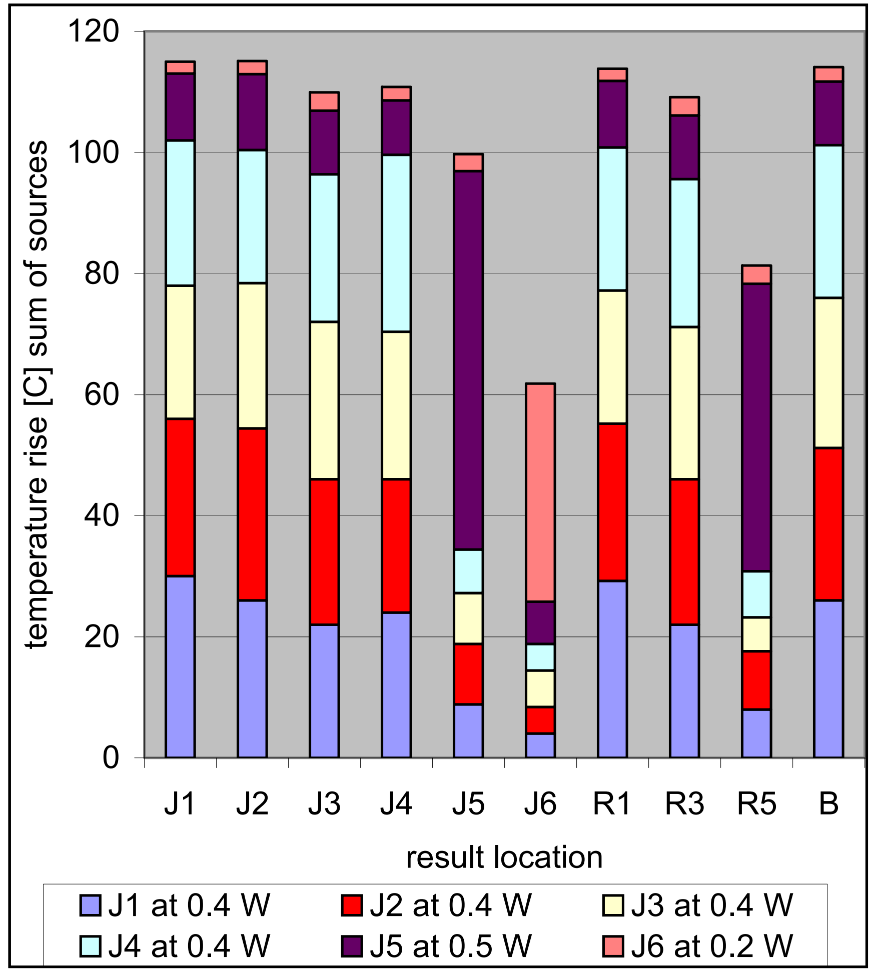
When you have multiple heat sources
(that is, all the time!)

Linear superposition – how do you use it?

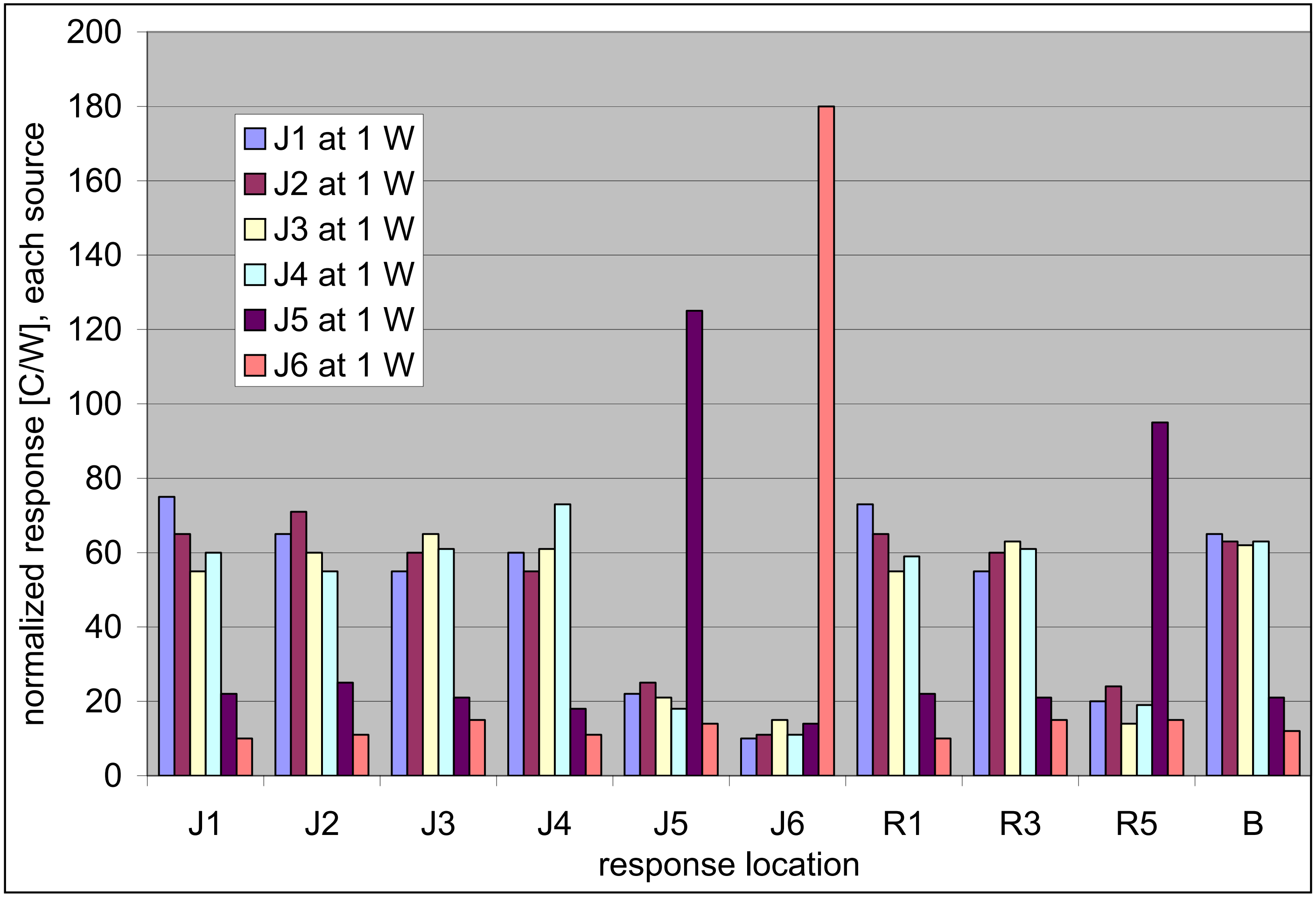


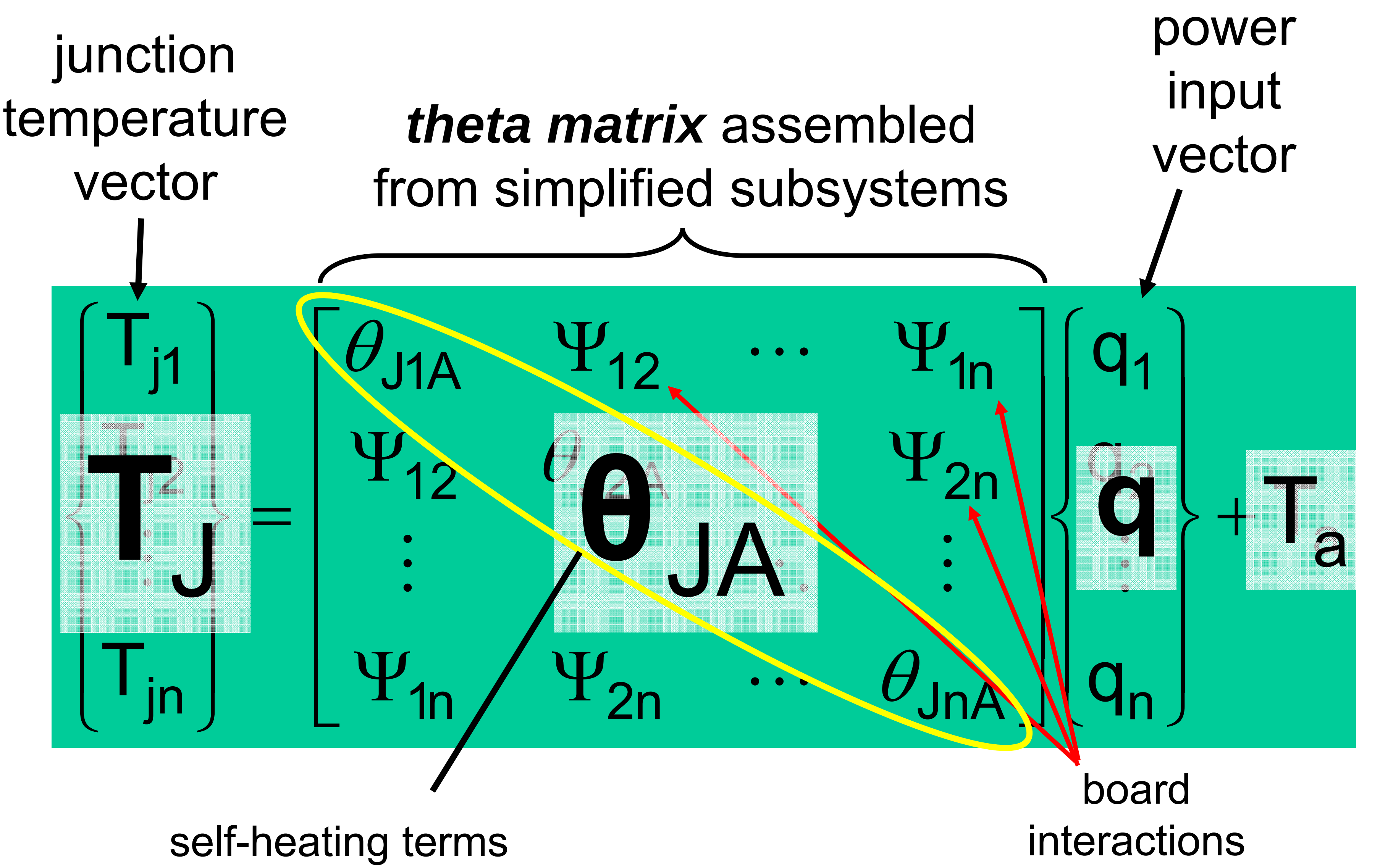
Temperature direct contributions and totals





Normalized responses at each location due to each source





$$\begin{Bmatrix} T_{j1} \\ T_{j2} \\ \vdots \\ T_{jn} \end{Bmatrix} = \begin{bmatrix} \theta_{J1A} & \Psi_{12} & \cdots & \Psi_{1n} \\ \Psi_{12} & \theta_{J2A} & & \Psi_{2n} \\ \vdots & & & \vdots \\ \Psi_{1n} & \Psi_{2n} & \cdots & \theta_{JnA} \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{Bmatrix} + T_a$$

$$\mathbf{T}_J = \boldsymbol{\theta}_{JA} \, \mathbf{q} + T_a$$

junction temperature vector

theta matrix assembled from simplified subsystems

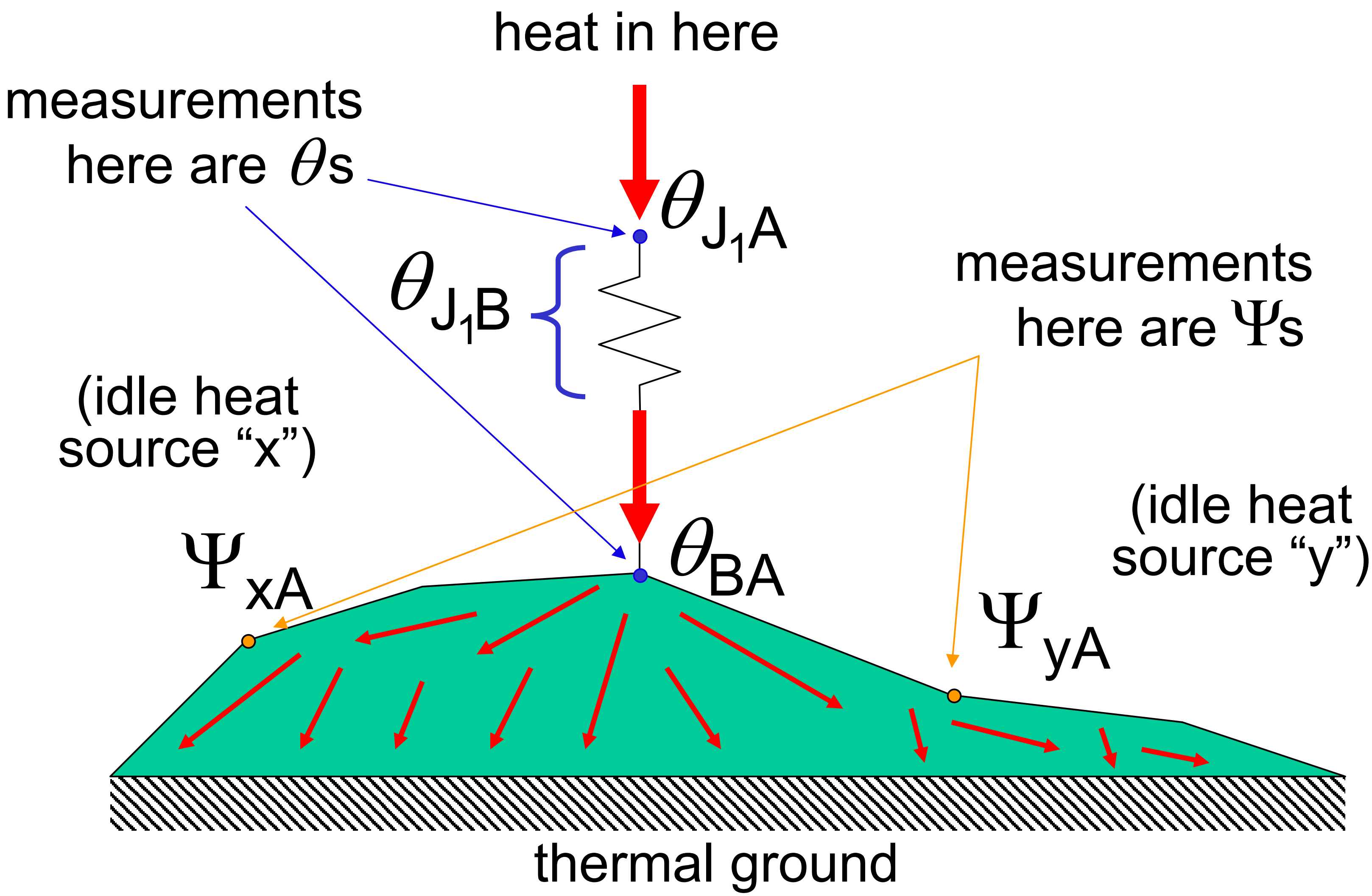
power input vector

$$\begin{Bmatrix} T_{j1} \\ T_{j2} \\ \vdots \\ T_{jn} \end{Bmatrix} = \begin{bmatrix} \theta_{JB1} + \theta_{BA1} & \Psi_{12} & \cdots & \Psi_{1n} \\ \Psi_{12} & \theta_{JB2} + \theta_{BA2} & & \Psi_{2n} \\ \vdots & & \ddots & \vdots \\ \Psi_{1n} & \Psi_{2n} & \cdots & \theta_{JBn} + \theta_{BAn} \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{Bmatrix} + T_a$$

device resistance

board resistance

visualizing theta and psi



theta matrix doesn't have to be square

junction temperature vector

one column for each heat source

power input vector

$$\begin{pmatrix} \theta_{JA1} & \Psi_{21} & \Psi_{31} \\ \Psi_{12} & \theta_{JA2} & \Psi_{32} \\ \Psi_{1x} & \Psi_{2x} & \Psi_{3x} \\ \Psi_{1L1} & \Psi_{2L1} & \Psi_{3L1} \\ \Psi_{1B} & \Psi_{2B} & \Psi_{3B} \end{pmatrix}$$

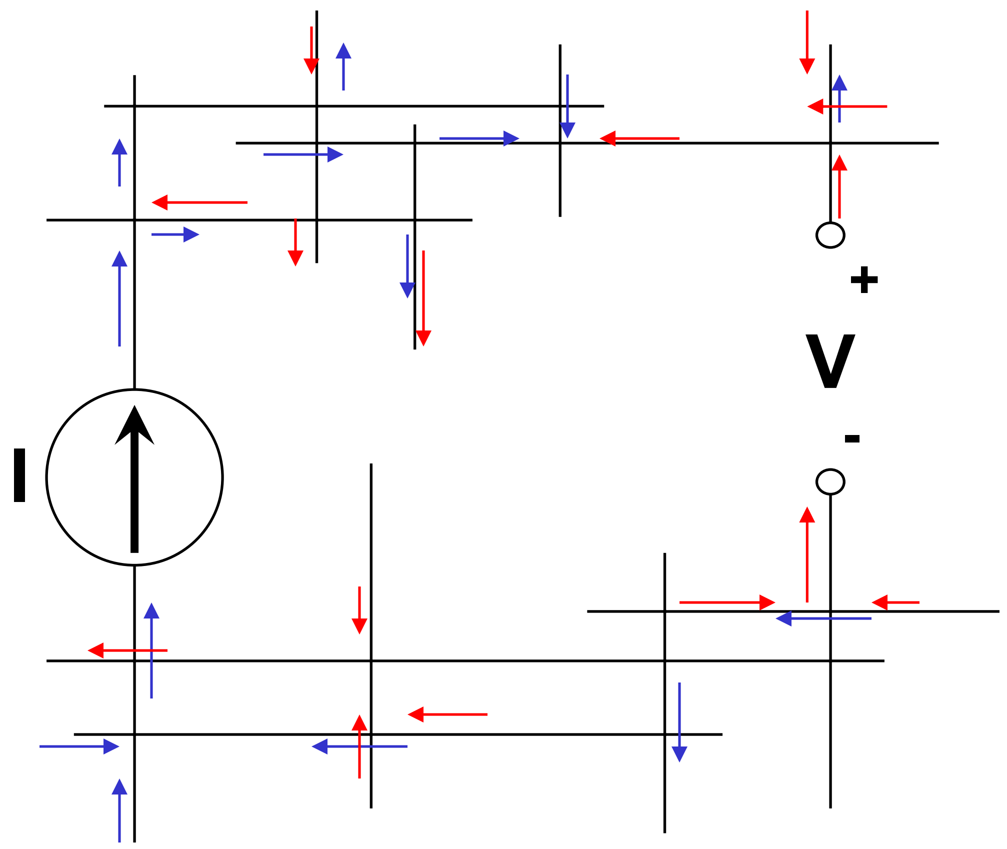
one row for each heat source

one row for each temperature location of interest

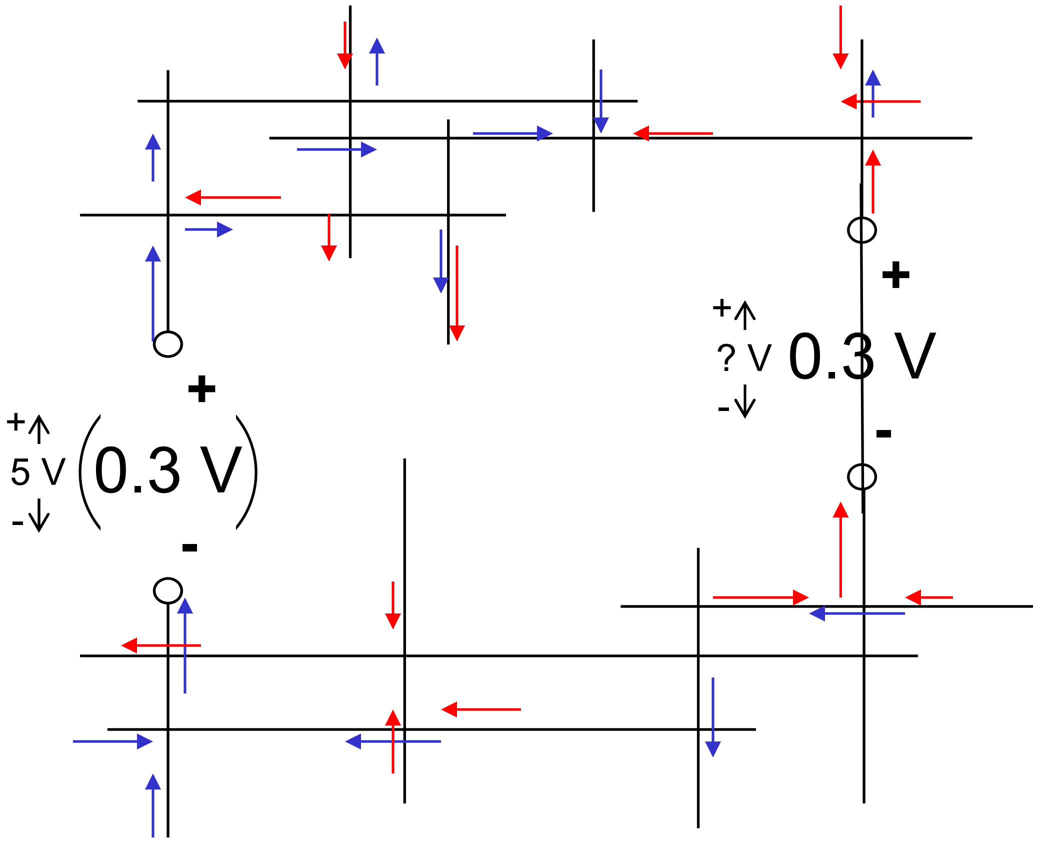
The reciprocity theorem

- What is it?
- When does it *not* apply?

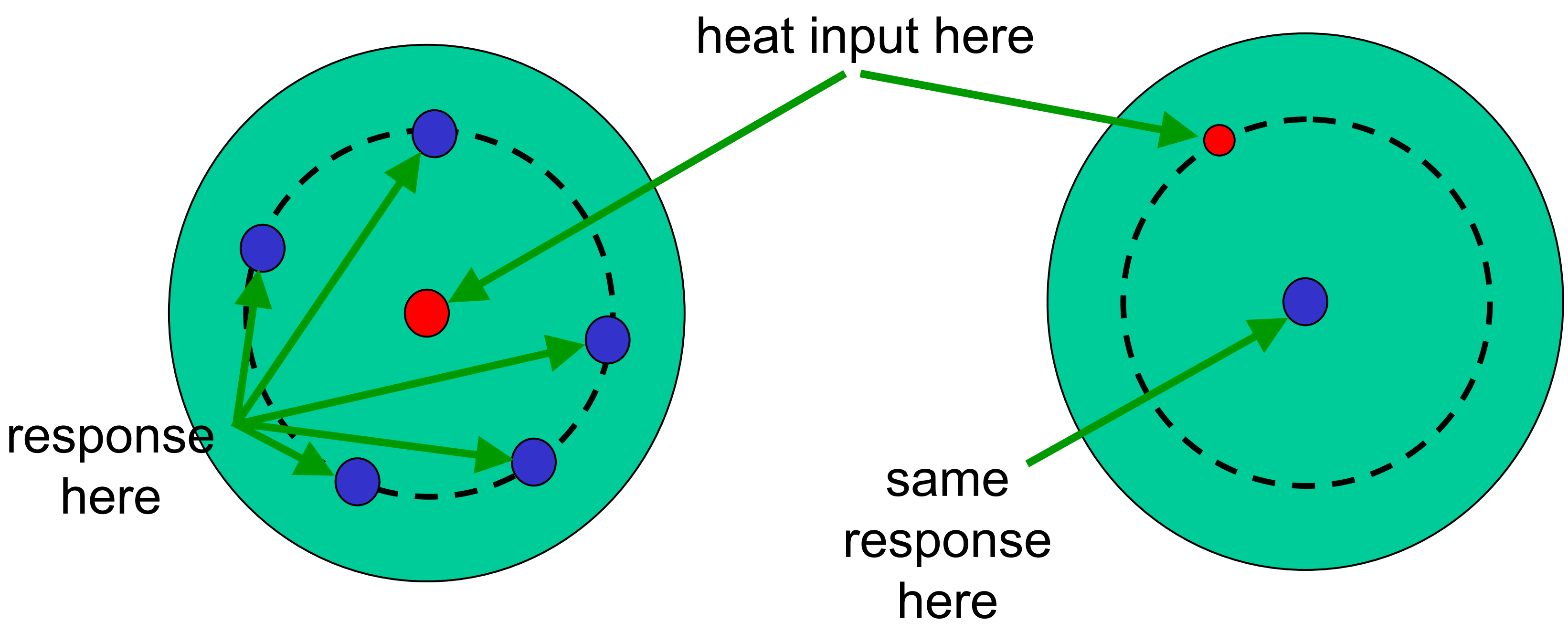
Electrical reciprocity



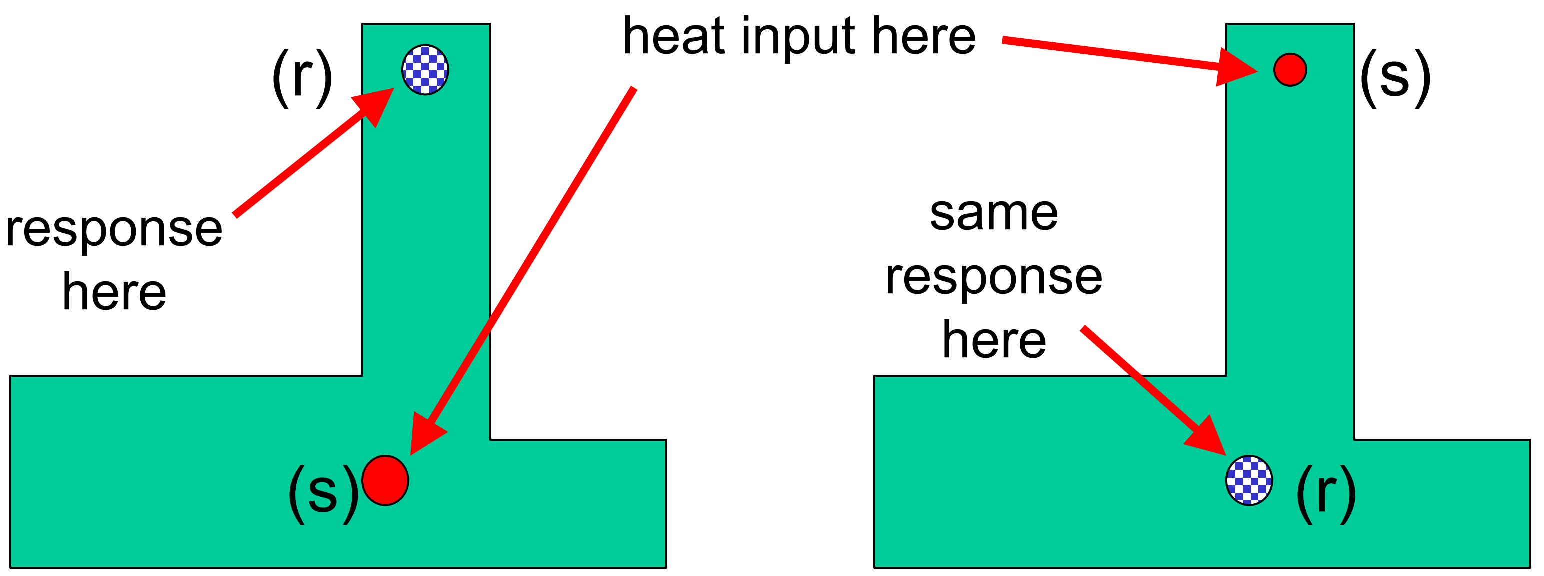
Electrical reciprocity



Thermal reciprocity



Another thermal reciprocity example



(square part of) matrix is symmetric

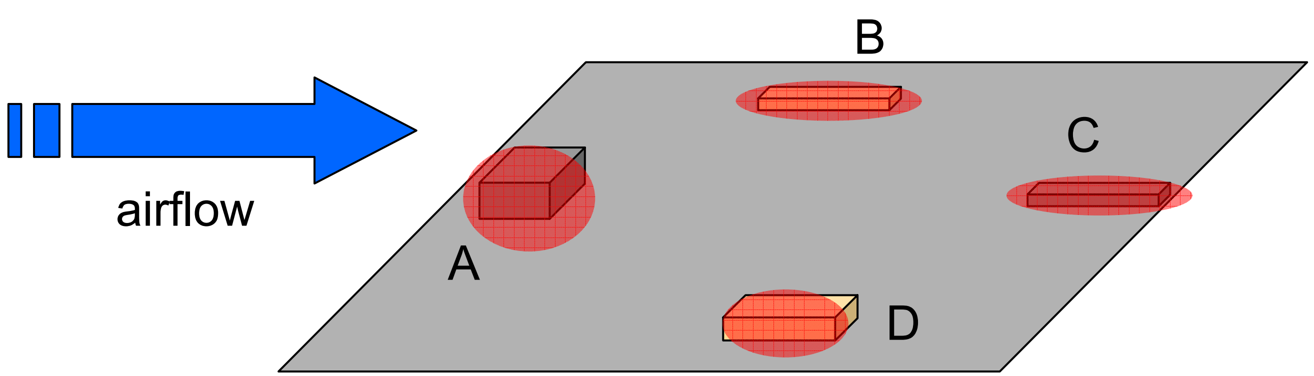
columns are the “x” heat sources

rows are the “y” response locations

J1	75	65	55	60	22	10
J2	65	71	60	55	25	11
J3	55	60	65	61	21	15
J4	60	55	61	73	18	11
J5	22	25	21	18	125	14
J6	10	11	15	11	14	180
R1	73	65	55	59	22	10
R3	55	60	63	61	21	15
R5	20	24	14	19	95	15
B	65	63	62	63	21	12

When does reciprocity *NOT* Apply?

- Upwind and downwind in forced-convection dominated applications



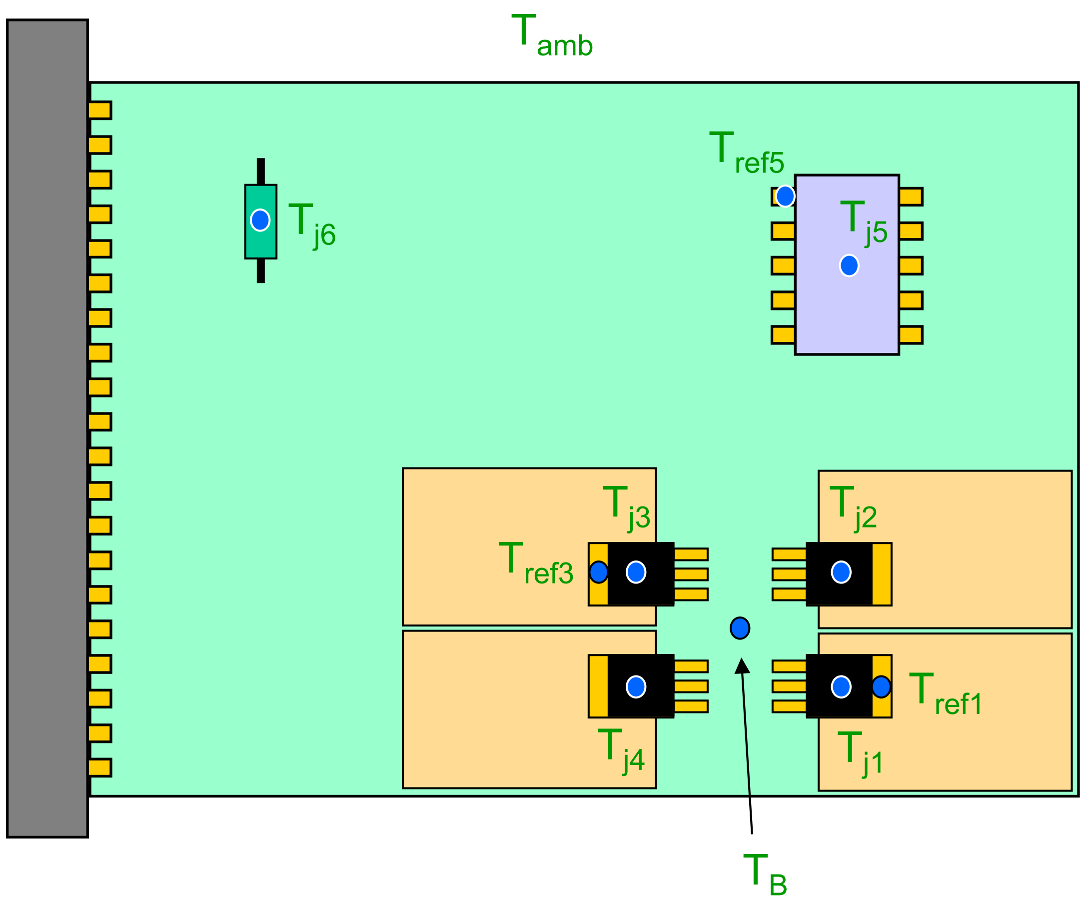
Heat in at "A" will raise temperature of "C" more than heat in at "C" will raise temperature of "A"

"B" and "D" may still be roughly reciprocal

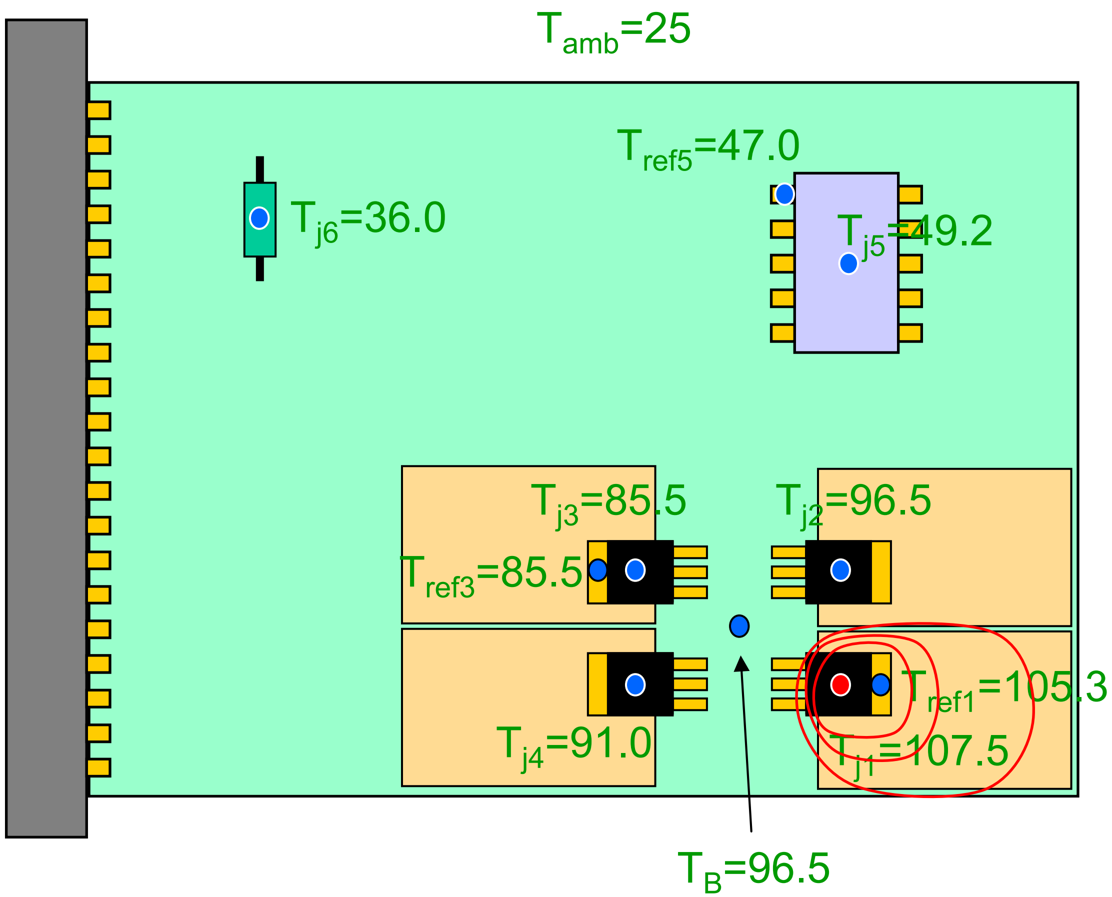
A linear superposition example

(unequivocal proof that a published theta-JA is virtually meaningless)

Superposition example



Device 1 heated, 1.1 W



Reduce the data

$$\theta_{j1A} = \frac{T_{j1} - T_{amb}}{q_1} = \frac{107.5 - 25}{1.1} = 75$$

$$\Psi_{j2A} = \frac{T_{j2} - T_{amb}}{q_1} = \frac{96.5 - 25}{1.1} = 65$$

$$\vdots$$

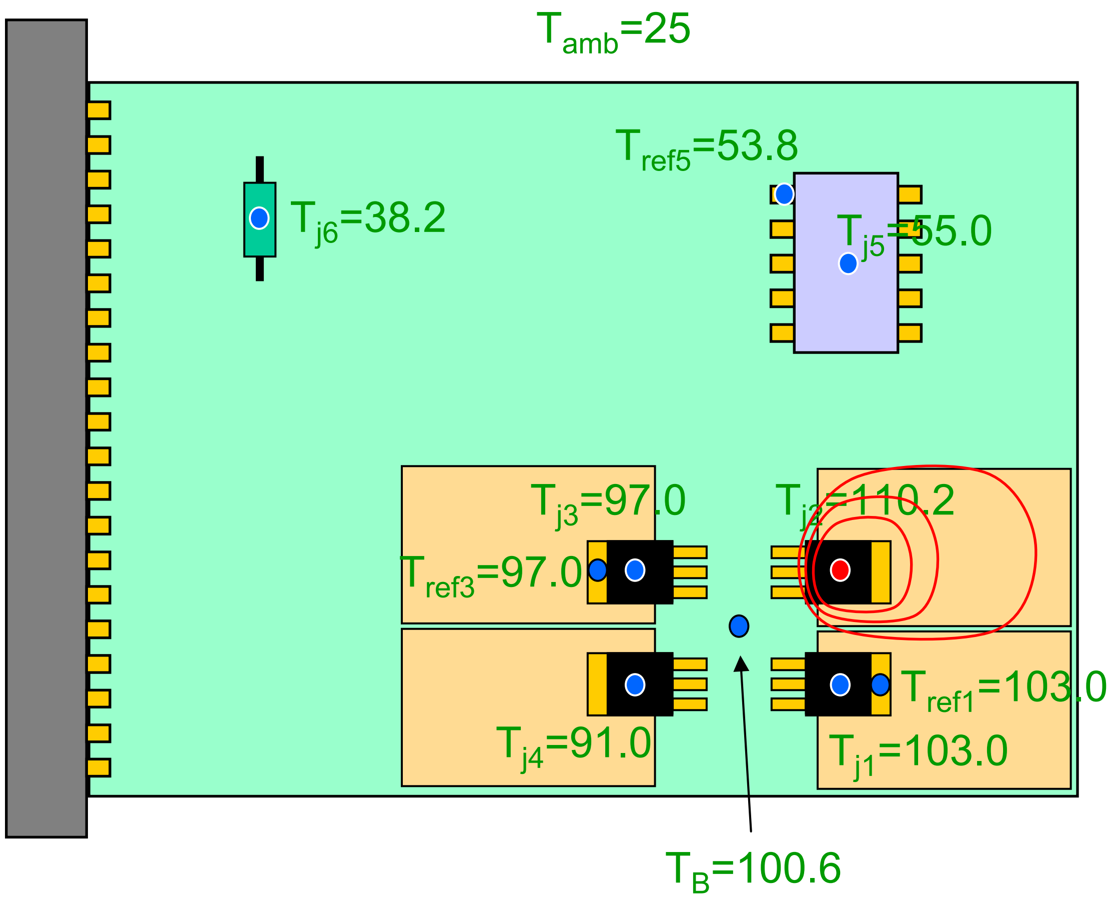
$$\Psi_{BA} = \frac{T_{B} - T_{amb}}{q_1} = \frac{96.5 - 25}{1.1} = 65$$

θ_{j1A}	75
Ψ_{j2A}	65
Ψ_{j3A}	55
Ψ_{j4A}	60
Ψ_{j5A}	22
Ψ_{j6A}	10
Ψ_{r1A}	73
Ψ_{r3A}	55
Ψ_{r5A}	20
Ψ_{BA}	65

Collect the θ/Ψ values in the matrix

J1	75					
J2	65					
J3	55					
J4	60					
J5	22					
J6	10					
R1	73					
R3	55					
R5	20					
B	65					

Device 2 heated, 1.2 W

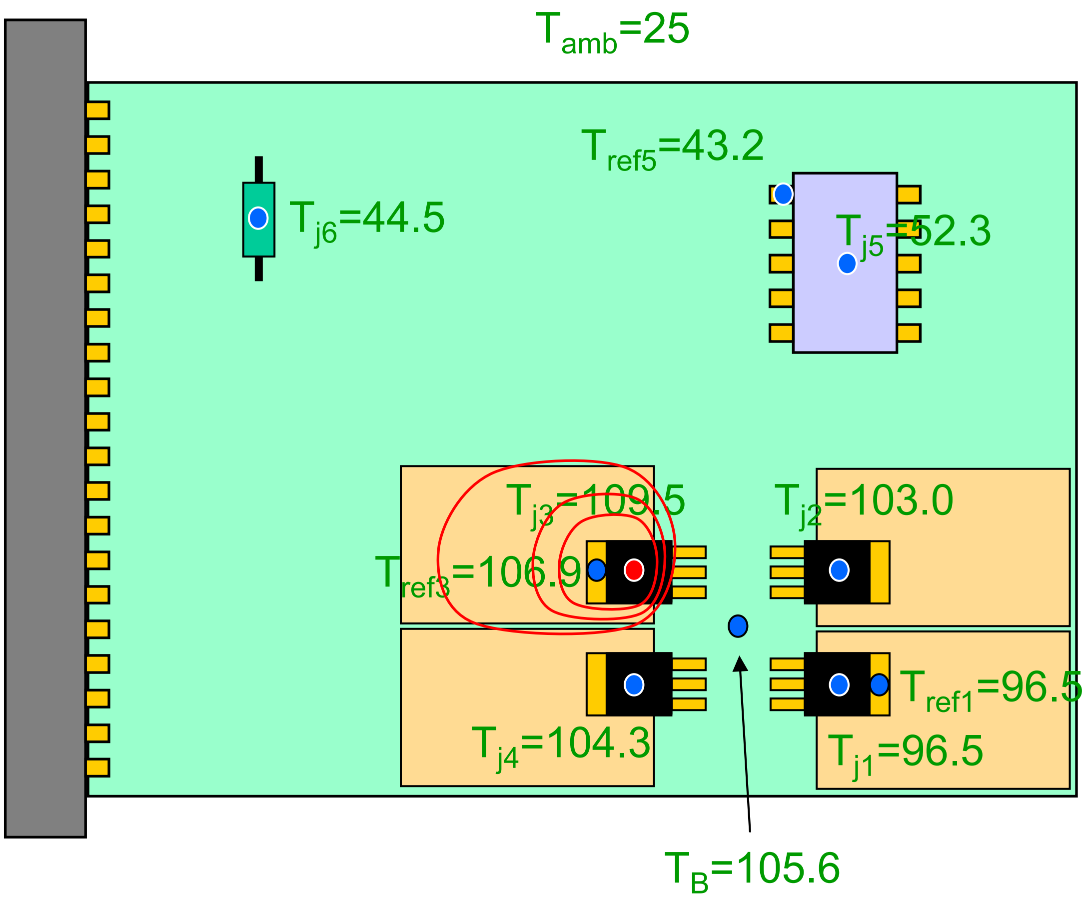


Ψ_{j1A}	65
θ_{j2A}	71
Ψ_{j3A}	60
Ψ_{j4A}	55
Ψ_{j5A}	25
Ψ_{j6A}	11
Ψ_{r1A}	65
Ψ_{r3A}	60
Ψ_{r5A}	24
Ψ_{BA}	63

Collect the θ/Ψ values

J1	75	65					
J2	65	71					
J3	55	60					
J4	60	55					
J5	22	25					
J6	10	11					
R1	73	65					
R3	55	60					
R5	20	24					
B	65	63					

Device 3 heated, 1.3 W

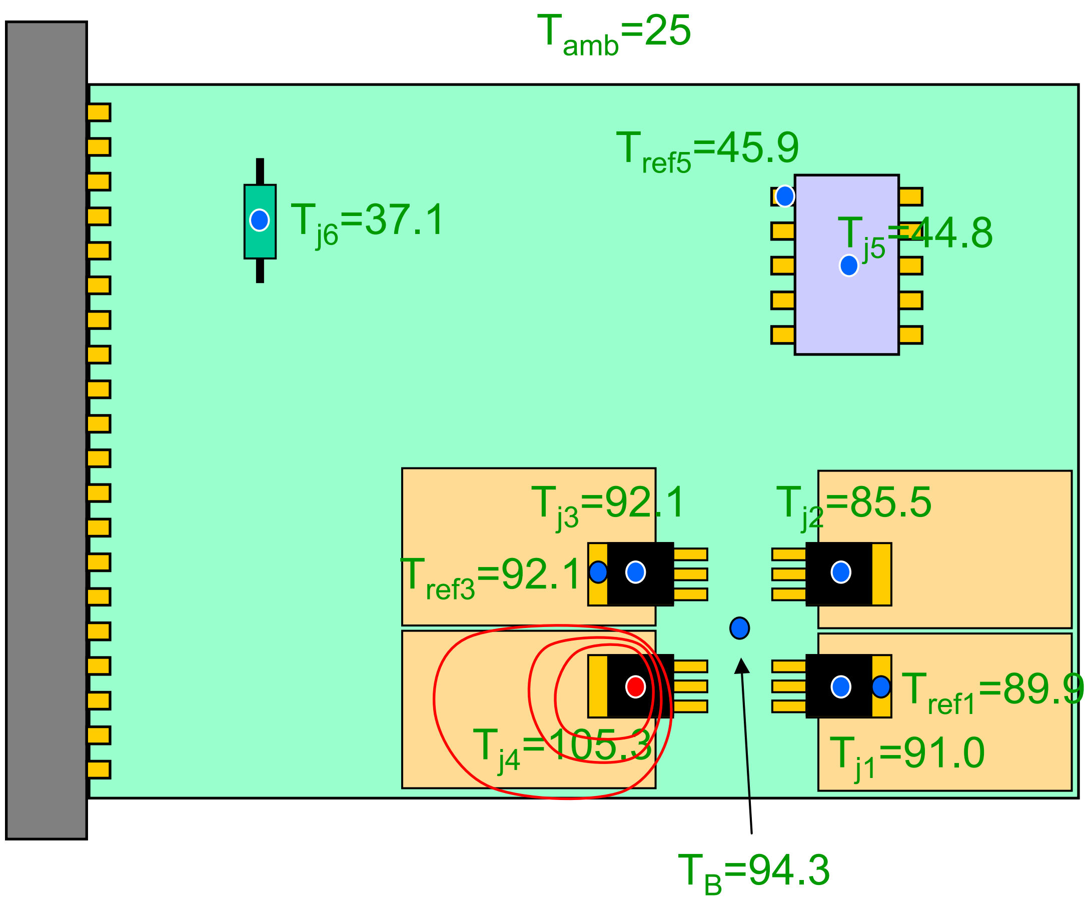


Ψ_{j1A}	55
Ψ_{j2A}	60
θ_{j3A}	65
Ψ_{j4A}	61
Ψ_{j5A}	21
Ψ_{j6A}	15
Ψ_{r1A}	55
Ψ_{r3A}	63
Ψ_{r5A}	14
Ψ_{BA}	62

Collect the θ/Ψ values

J1	75	65	**55**			
J2	65	71	**60**			
J3	55	60	**65**			
J4	60	55	**61**			
J5	22	25	**21**			
J6	10	11	**15**			
R1	73	65	**55**			
R3	55	60	**63**			
R5	20	24	**14**			
B	65	63	**62**			

Device 4 heated, 1.1 W

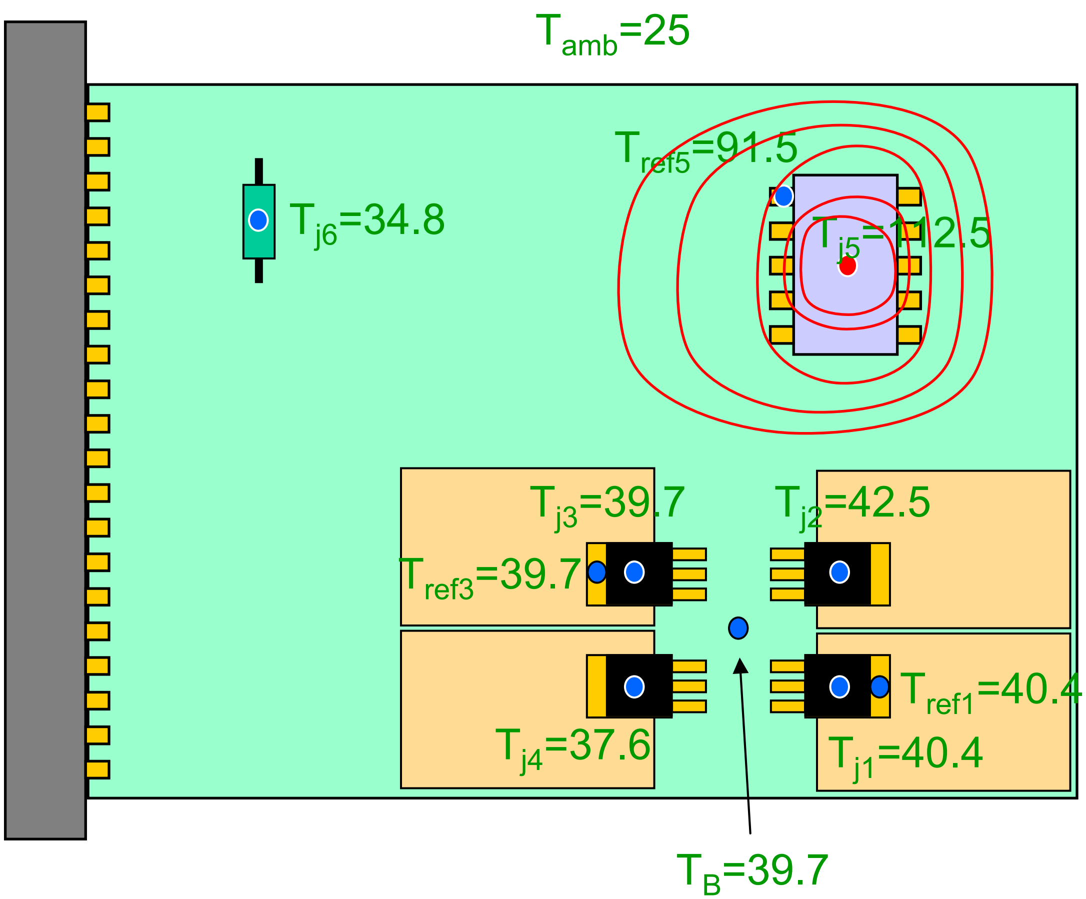


Ψ_{j1A}	60
Ψ_{j2A}	55
Ψ_{j3A}	61
θ_{j4A}	73
Ψ_{j5A}	18
Ψ_{j6A}	11
Ψ_{r1A}	59
Ψ_{r3A}	61
Ψ_{r5A}	19
Ψ_{BA}	63

Collect the θ/Ψ values

J1	75	65	55	**60**		
J2	65	71	60	**55**		
J3	55	60	65	**61**		
J4	60	55	61	**73**		
J5	22	25	21	**18**		
J6	10	11	15	**11**		
R1	73	65	55	**59**		
R3	55	60	63	**61**		
R5	20	24	14	**19**		
B	65	63	62	**63**		

Device 5 heated, 0.7 W

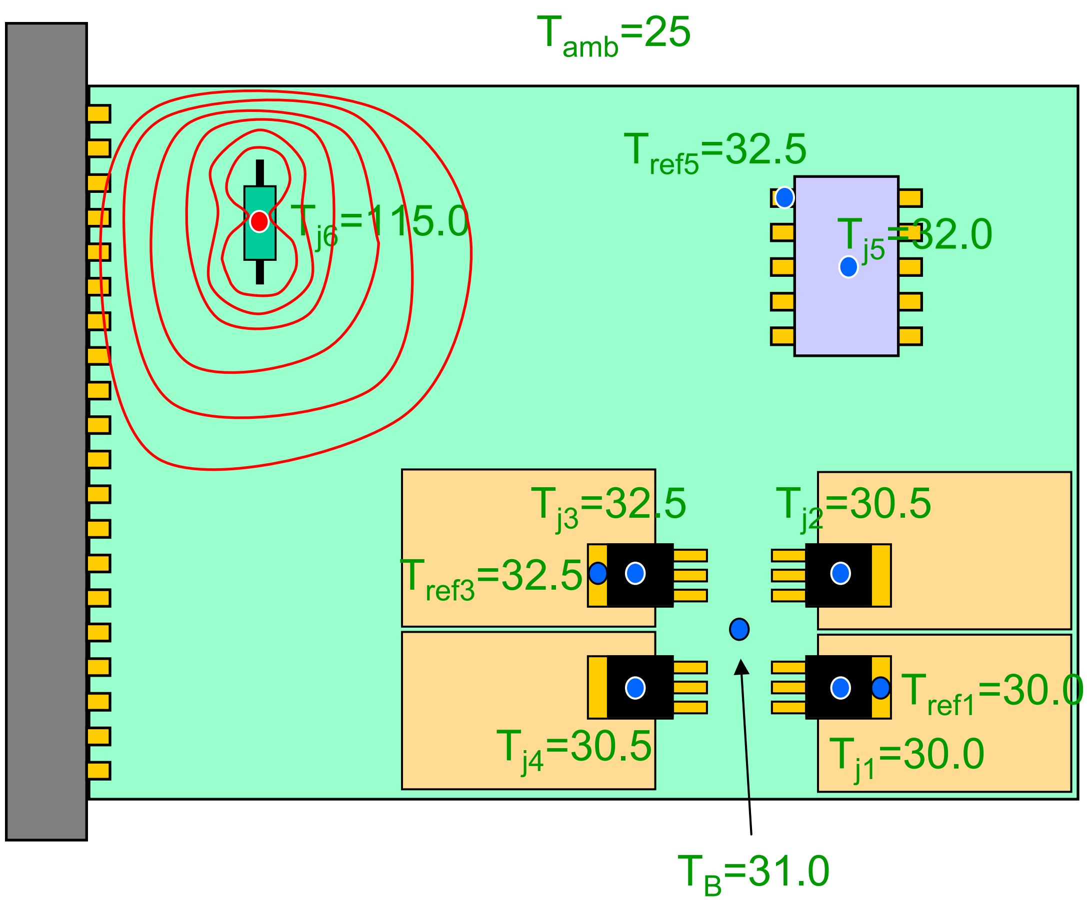


Ψ_{j1A}	22
Ψ_{j2A}	25
Ψ_{j3A}	21
Ψ_{j4A}	18
θ_{j5A}	125
Ψ_{j6A}	14
Ψ_{r1A}	22
Ψ_{r3A}	21
Ψ_{r5A}	95
Ψ_{BA}	21

Collect the θ/Ψ values

J1	75	65	55	60	**22**	
J2	65	71	60	55	**25**	
J3	55	60	65	61	**21**	
J4	60	55	61	73	**18**	
J5	22	25	21	18	**125**	
J6	10	11	15	11	**14**	
R1	73	65	55	59	**22**	
R3	55	60	63	61	**21**	
R5	20	24	14	19	**95**	
B	65	63	62	63	**21**	

Device 6 heated, 0.5 W

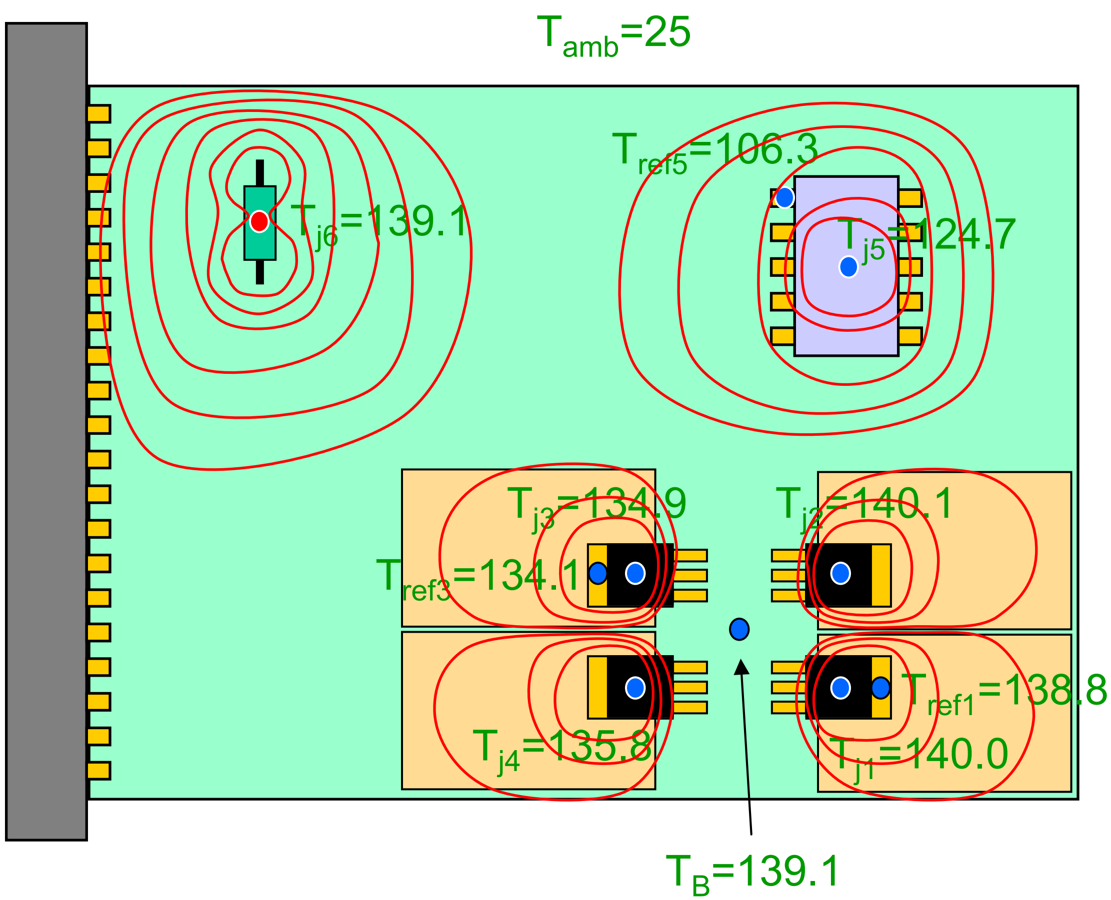


Ψ_{j1A}	10
Ψ_{j2A}	11
Ψ_{j3A}	15
Ψ_{j4A}	11
Ψ_{j5A}	14
θ_{j6A}	180
Ψ_{r1A}	10
Ψ_{r3A}	15
Ψ_{r5A}	15
Ψ_{BA}	12

Collect the θ/Ψ values

J1	75	65	55	60	22	**10**
J2	65	71	60	55	25	**11**
J3	55	60	65	61	21	**15**
J4	60	55	61	73	18	**11**
J5	22	25	21	18	125	**14**
J6	10	11	15	11	14	**180**
R1	73	65	55	59	22	**10**
R3	55	60	63	61	21	**15**
R5	20	24	14	19	95	**15**
B	65	63	62	63	21	**12**

Now apply actual power



Actual power in application

q_{j1}	.4
q_{j2}	.4
q_{j3}	.4
q_{j4}	.4
q_{j5}	.5
q_{j6}	.2

Compute some effective θ/Ψ values

Take T_{j1}, for instance. Remember when it was heated all alone, we calculated its self-heating theta-JA like this:

$$\theta_{j1A} = \frac{T_{j1} - T_{amb}}{q_1}$$

Now let's see:

$$\theta_{j1A} = \frac{T_{j1} - T_{amb}}{q_1} = \frac{140 - 25}{0.4} = 288$$

$\neq$

And that's not just a single aberration!

Self heating			
θ_{j1A}	288	← 3.8x -	75
θ_{j2A}	288	← 4.1x -	71
θ_{j3A}	274	← 4.2x -	65
θ_{j4A}	277	← 3.8x -	73
θ_{j5A}	199	← 1.6x -	125
θ_{j6A}	309	← 1.7x -	180

Junction to Reference			
$\Psi_{j1\text{-}R1}$	3.0	← 1.5x –	2.0
$\Psi_{j3\text{-}R3}$	2.0	← 1.0x –	2.0
$\Psi_{j5\text{-}R5}$	36.8	← 1.2x –	30.0

Junction to Board			
$\Psi_{j1\text{-}B}$	2.2	← 0.2x –	10.0
$\Psi_{j2\text{-}B}$	2.5	← 0.3x –	8.0
$\Psi_{j3\text{-}B}$	-10.5	← -3.5x -	3.0
$\Psi_{j4\text{-}B}$	-8.3	← -0.8x -	10.0

Is the moral clear?

- You simply *cannot* use published theta-JA values for devices in your real system, even if those values are perfectly accurate and correct as reported on the datasheet and you know the exact specifications of the test conditions.
- Not unless your actual application is identical to the manufacturer's test board – and uses just that one device *all by itself*.

So is it *really* this bad?

Only sort-of. Let's revisit the math for one device …

$$\begin{Bmatrix} T_{j1} \\ T_{j2} \\ \vdots \\ T_{jn} \end{Bmatrix} = \begin{bmatrix} \theta_{J1A} & \Psi_{12} & \cdots & \Psi_{1n} \\ \Psi_{12} & \theta_{J2A} & & \Psi_{2n} \\ \vdots & & \ddots & \vdots \\ \Psi_{1n} & \Psi_{2n} & \cdots & \theta_{JnA} \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ \vdots \\ q_n \end{Bmatrix} + T_a$$

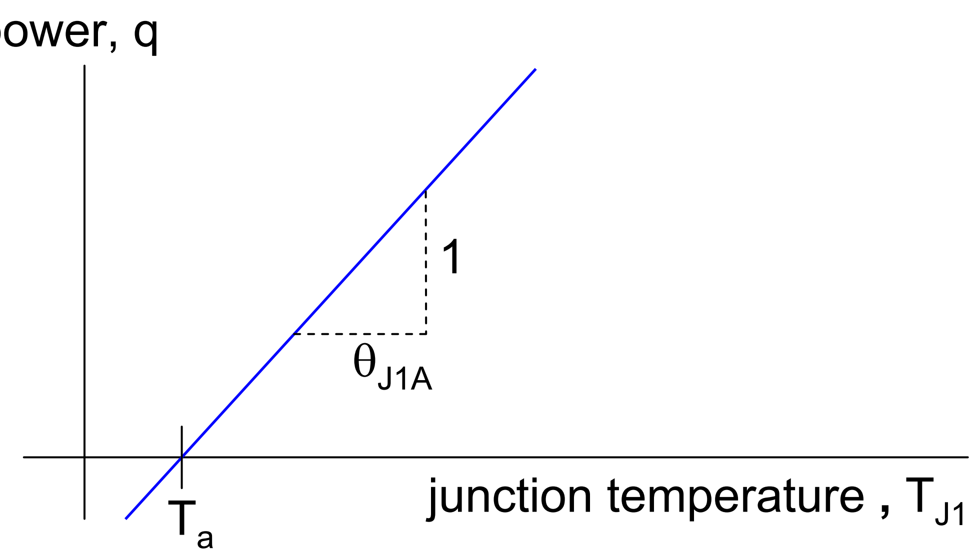
$$T_{j1} = \theta_{J1A} q_1 + \Psi_{12} q_2 + \ldots \Psi_{1n} q_n + T_a$$

0 0

$$T_{j1} = \theta_{J1A} q_1 + \sum_{2}^{n} \Psi_{1n} q_n + T_a$$

"effective" ambient

A graphical view



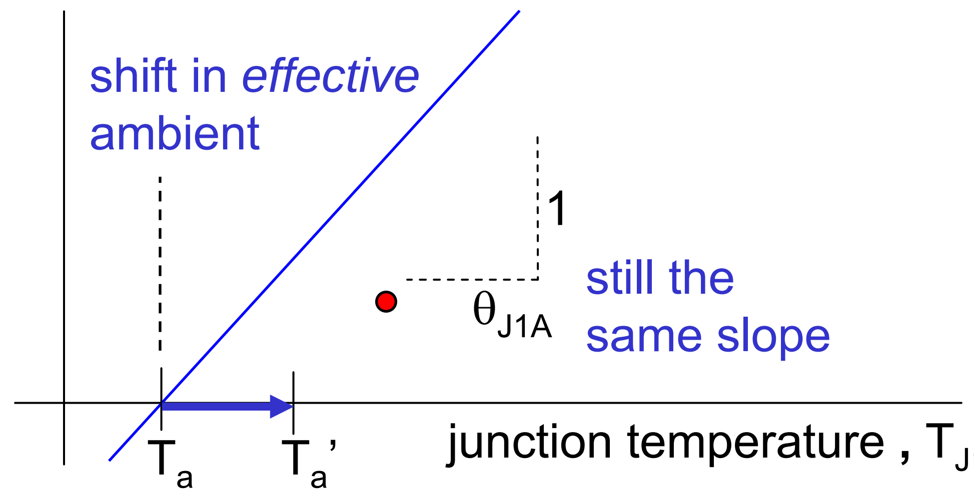
Isolated device

$$T_{j1} = \theta_{J1A} q_1 + T_a$$

Device in a system

$$T_{j1} = \theta_{J1A} q_1 + \underbrace{\sum_{2}^{n} \Psi_{1n} q_n + T_a}_{T_a'}$$

$$= \theta_{J1A} q_1 + T_a'$$



How does *effective ambient* relate to board temperature?

"system" slope for isolated device

if any of *these* are non-zero, T'_a will be higher than T_a

$$T_{j1} = \theta_{j1a} \cdot Q_1 + \sum_{i=2}^{n} \left(\Psi_{i1} \cdot Q_i \right) + T_a$$

$$= \left(\theta_{j1B} + \theta_{B1a} \right) \cdot Q_1 + T'_a$$

effective ambient

$$= \theta_{j1B} \cdot Q_1 + \theta_{B1a} \cdot Q_1 +$$

$$= \Delta T_{j1B} + \Delta T_{B1a} +$$

when Q_1 is zero, *not* both of these will be zero

zero, both of these will be non-zero

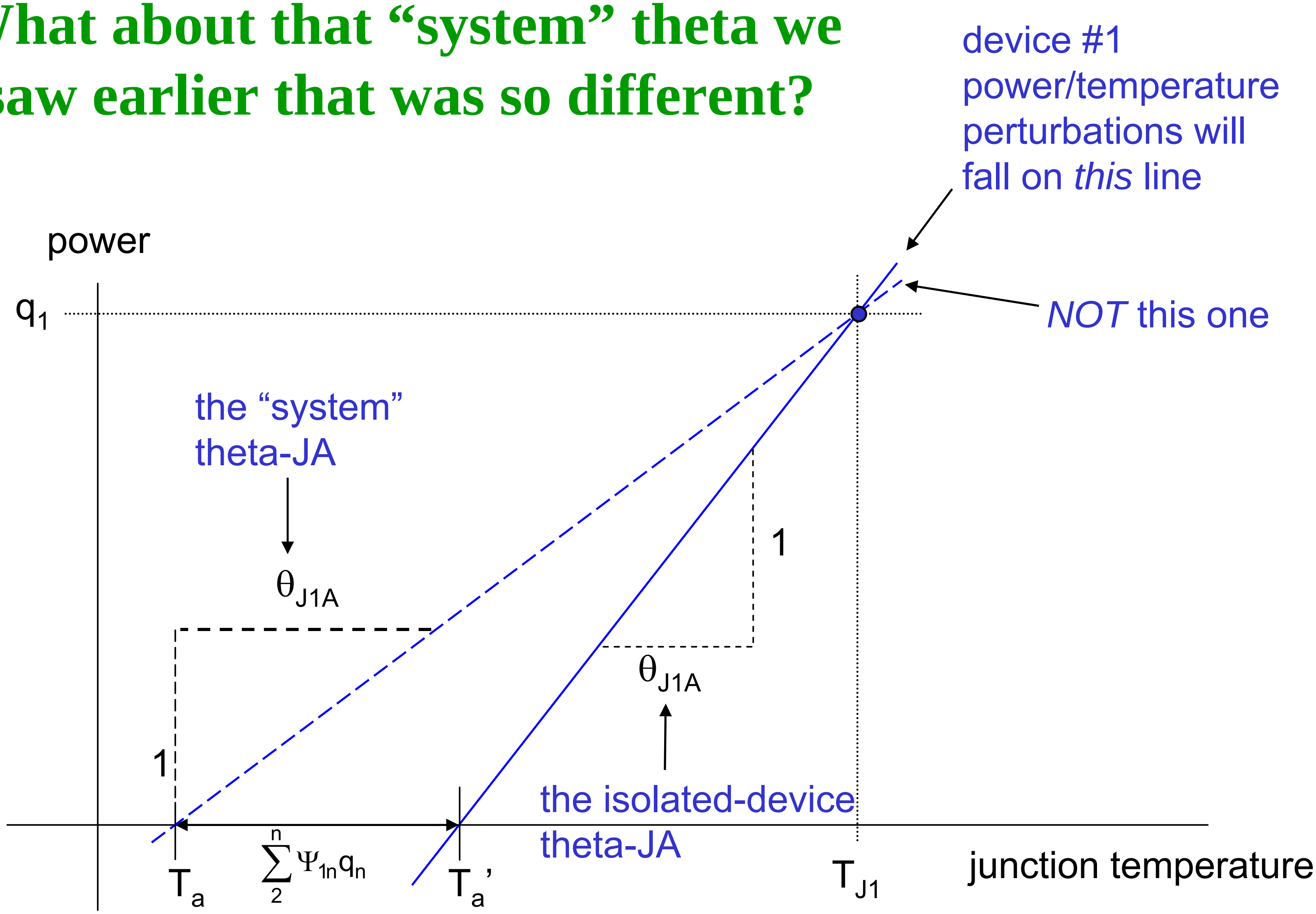
temperature rise, board to J1

temperature rise, ambient to board

How does *effective ambient* relate to local air temperature?

NOT.

What about that "system" theta we saw earlier that was so different?



System modeling

Filling in the theta-matrix

- Handy formulas for quick estimates
- Utilizing symmetry

Conduction resistance

basic heat transfer relationship for 1-D conduction

$$q = k \cdot A \cdot \frac{dT}{dx} \approx k \cdot A \cdot \frac{\Delta T}{L}$$

if we define

$$R = \frac{\Delta T}{q}$$

then

$$R = \frac{L}{k \cdot A}$$

Convection resistance

basic heat transfer relationship for surface cooling

$$q = h \cdot A \cdot \Delta T$$

if we define

$$R = \frac{\Delta T}{q}$$

then

$$R = \frac{1}{hA}$$

Radiation resistance

basic heat transfer relationship for surface radiation

$$\begin{aligned} q &= \sigma \cdot \varepsilon \cdot F \cdot A \cdot \left(T^4 - T_a^4\right) \\ &= \sigma \cdot \varepsilon \cdot F \cdot A \cdot \left(T^2 + T_a^2\right)\left(T + T_a\right)\left(T - T_a\right) \\ &= \sigma \cdot \varepsilon \cdot F \cdot A \cdot \left(T^2 + T_a^2\right)\left(T + T_a\right)\Delta T \end{aligned}$$

if we define

$$R = \frac{\Delta T}{q}$$

then

$$R = \frac{1}{\sigma \varepsilon F A \left(T^2 + T_a^2\right)\left(T + T_a\right)}$$

temperatures *must* be expressed in degrees “absolute”!

Thermal capacitance and time constant

capacitance is ability to store energy
specific heat is energy storage/mass

$$C = \rho c_p V$$

so if

$$R = \frac{L}{k \cdot A} \quad \text{and} \quad C = \rho c_p (L \cdot A)$$

then

$$\tau = \frac{\rho c_p L^2}{k} = \frac{L^2}{\alpha}$$

based on simple RC concept, relate rate of storage to rate of flux result is

$$\tau = RC$$

and if

$$R = \frac{1}{h \cdot A} \quad \text{and} \quad C = \rho c_p (L \cdot A)$$

then

$$\tau = \frac{\rho c_p L}{h}$$

Some useful formulas

- conduction resistance…………………… $R = \dfrac{L}{k \cdot A}$
- convection resistance…………………… $R = \dfrac{1}{h \cdot A}$
- thermal capacitance…………………….. $C = \rho c_p V$
- characteristic time……………………… $\tau = \dfrac{L^2}{\alpha}$
  – (dominated by 1-D conduction)
- characteristic time……………………... $\tau = \dfrac{\rho c_p L}{h}$
  – (dominated by 1-D convection)
- short-time 1-D transient response…….. $\Delta T = \dfrac{2}{\sqrt{\pi}} \dfrac{Q}{A \eta} \sqrt{t}$

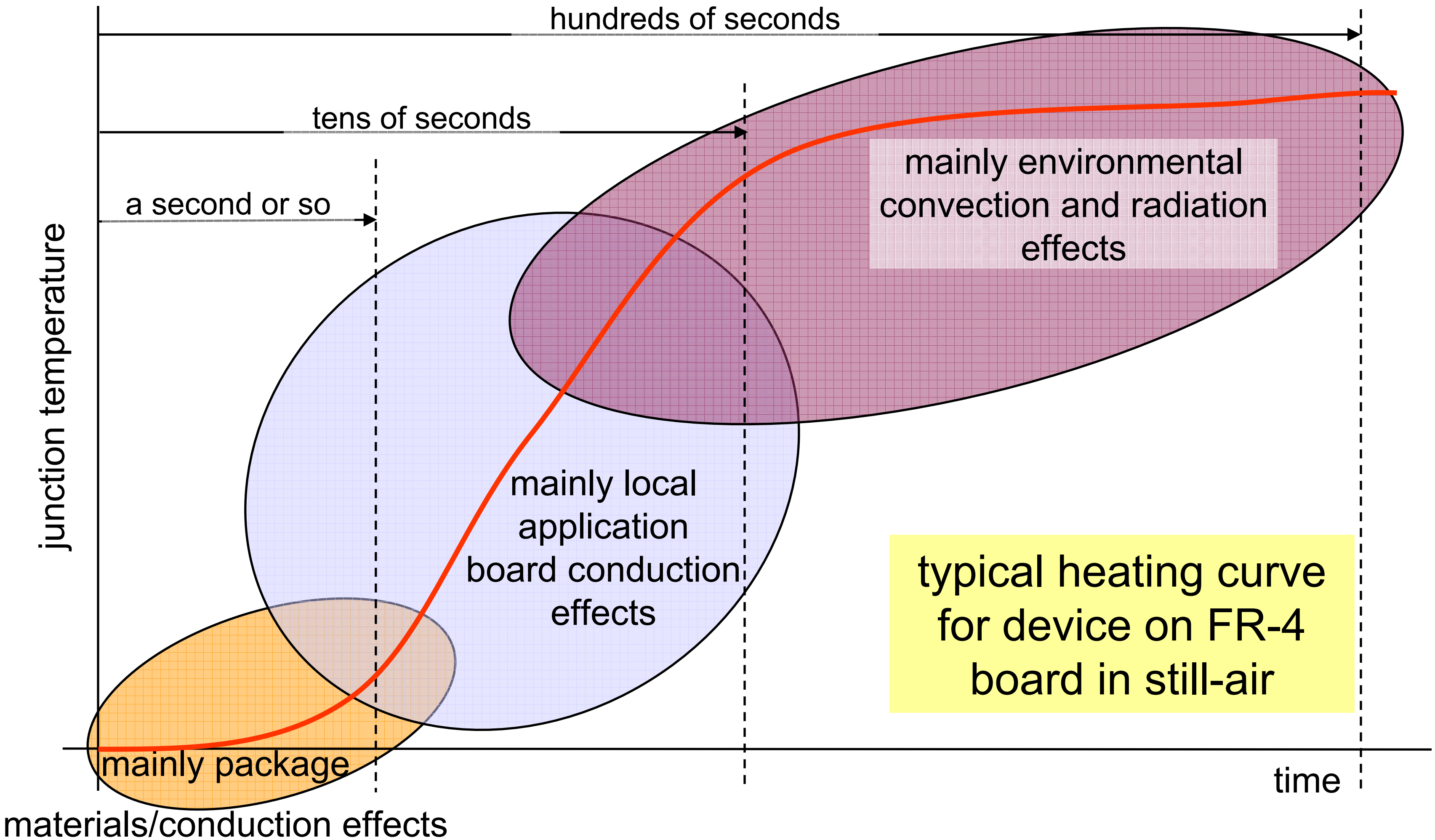
Terms used in preceding formulas

- L - thermal path length
- A - thermal path cross-sectional area
- k - thermal conductivity
- ρ - density
- c_p - heat capacity
- V – volume of material (L·A)
- α - thermal diffusivity
- η - thermal effusivity
- h - convection heat-transfer “film coefficient”)
- ΔT - junction temperature rise
- Q - heating power
- t - time since heat was first applied

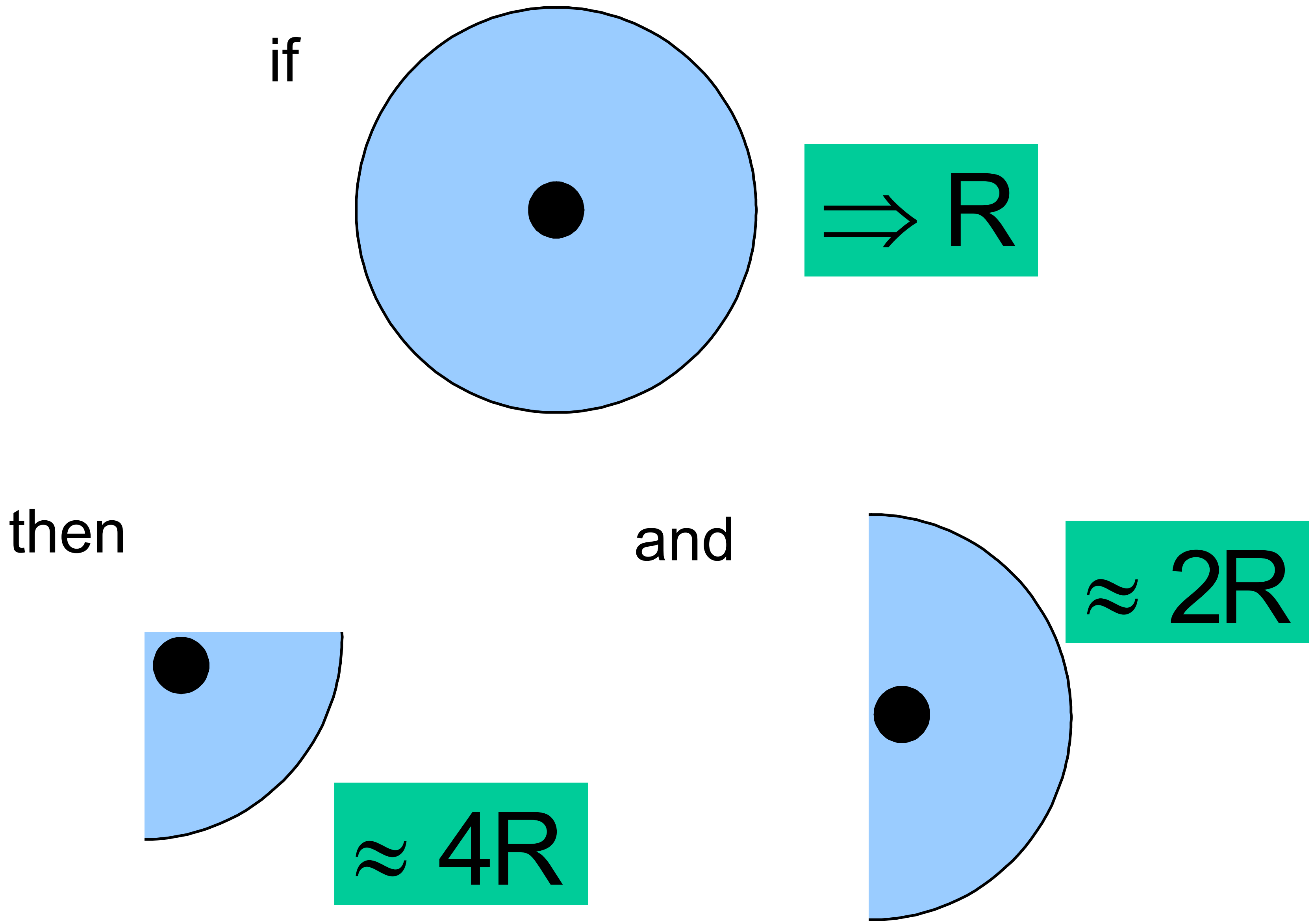
$$\alpha = \frac{k}{\rho c_p}$$

$$\eta = \sqrt{\rho c_p k}$$

When do these effects enter?



Utilize symmetry whenever possible


if
⇒ R
then
and
≈ 2R
≈ 4R

Cylindrical and spherical conduction (through radial thickness) resistance formulas

Half-cylinder

$$R = \frac{ln\left(\frac{r_o}{r_i}\right)}{\pi \cdot k \cdot L}$$

Full cylinder

$$R = \frac{ln\left(\frac{r_o}{r_i}\right)}{2\pi \cdot k \cdot L}$$

[included angle]

Hemisphere

$$R = \frac{\frac{1}{r_i} - \frac{1}{r_o}}{2\pi \cdot k}$$

Full sphere

$$R = \frac{\frac{1}{r_i} - \frac{1}{r_o}}{4\pi \cdot k}$$

[solid angle]

where

- L – cylinder length
- r_i – inner radius
- r_o – outer radius

Predicting the temperature of high power components

- The device and system are equally important to get right

Using the previous board example …

theta array

J1	75	65	55	60	22	10
J2	65	71	60	55	25	11
J3	55	60	65	61	21	15
J4	60	55	61	73	18	11
J5	22	25	21	18	125	14
J6	10	11	15	11	14	180
R1	73	65	55	59	22	10
R3	55	60	63	61	21	15
R5	20	24	14	19	95	15
B	65	63	62	63	21	12

power vector

q_{j1}	0.5
q_{j2}	0.5
q_{j3}	0.5
q_{j4}	0.5
q_{j5}	0.2
q_{j6}	0.02

Observe the relative contributions

For junction 1 (a high power component) we have:

the device itself …

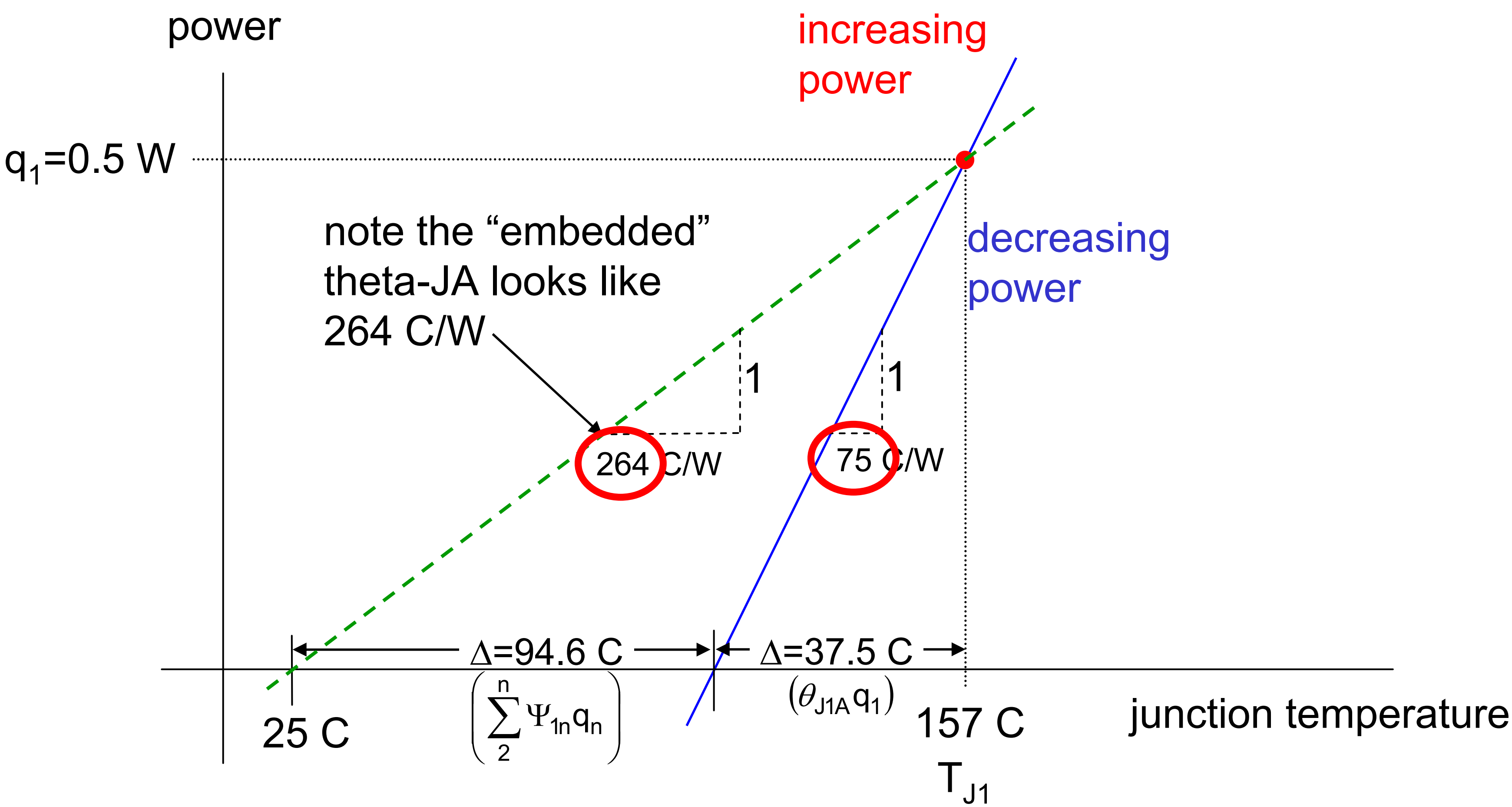
the other devices …

= (75 x 0.5) +
(65 x 0.5) + (55 x 0.5) + (60 x 0.5) + (22 x 0.2) + (10 x 0.02)
+ 25

= 37.5 + 32.5 + 27.5 + 30 + 4.4 + 0.2 + 25

= 37.5 + 94.6 + 25

Graphically, it looks like this:



Predicting the temperature of low power components

- The system is probably more important than the device

Using the previous board example …

theta array

J1	75	65	55	60	22	10
J2	65	71	60	55	25	11
J3	55	60	65	61	21	15
J4	60	55	61	73	18	11
J5	22	25	21	18	125	14
J6	10	11	15	11	14	180
R1	73	65	55	59	22	10
R3	55	60	63	61	21	15
R5	20	24	14	19	95	15
B	65	63	62	63	21	12

power vector

q_{j1}	0.5
q_{j2}	0.5
q_{j3}	0.5
q_{j4}	0.5
q_{j5}	0.2
q_{j6}	0.02

Relative contributions to ΔT_{J6}

the other devices …

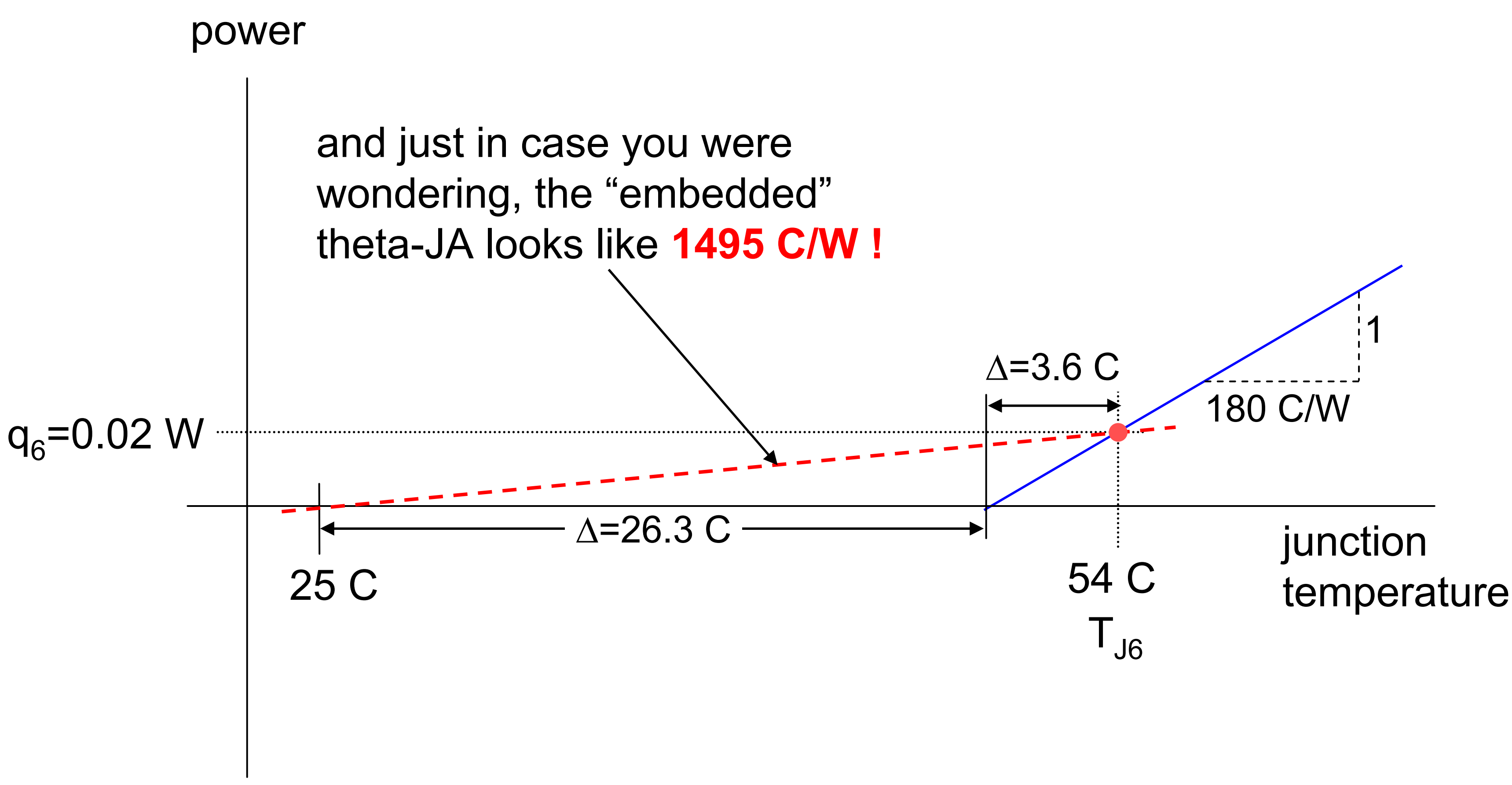
$$= (10 \times 0.5) + (11 \times 0.5) + (15 \times 0.5) + (11 \times 0.5) + (14 \times 0.2) + (180 \times 0.02) + 25$$

the device itself …

$$= 5.0 + 5.5 + 7.5 + 5.5 + 2.8 + 3.6 + 25$$

$$= 26.3 + 3.6 + 25$$

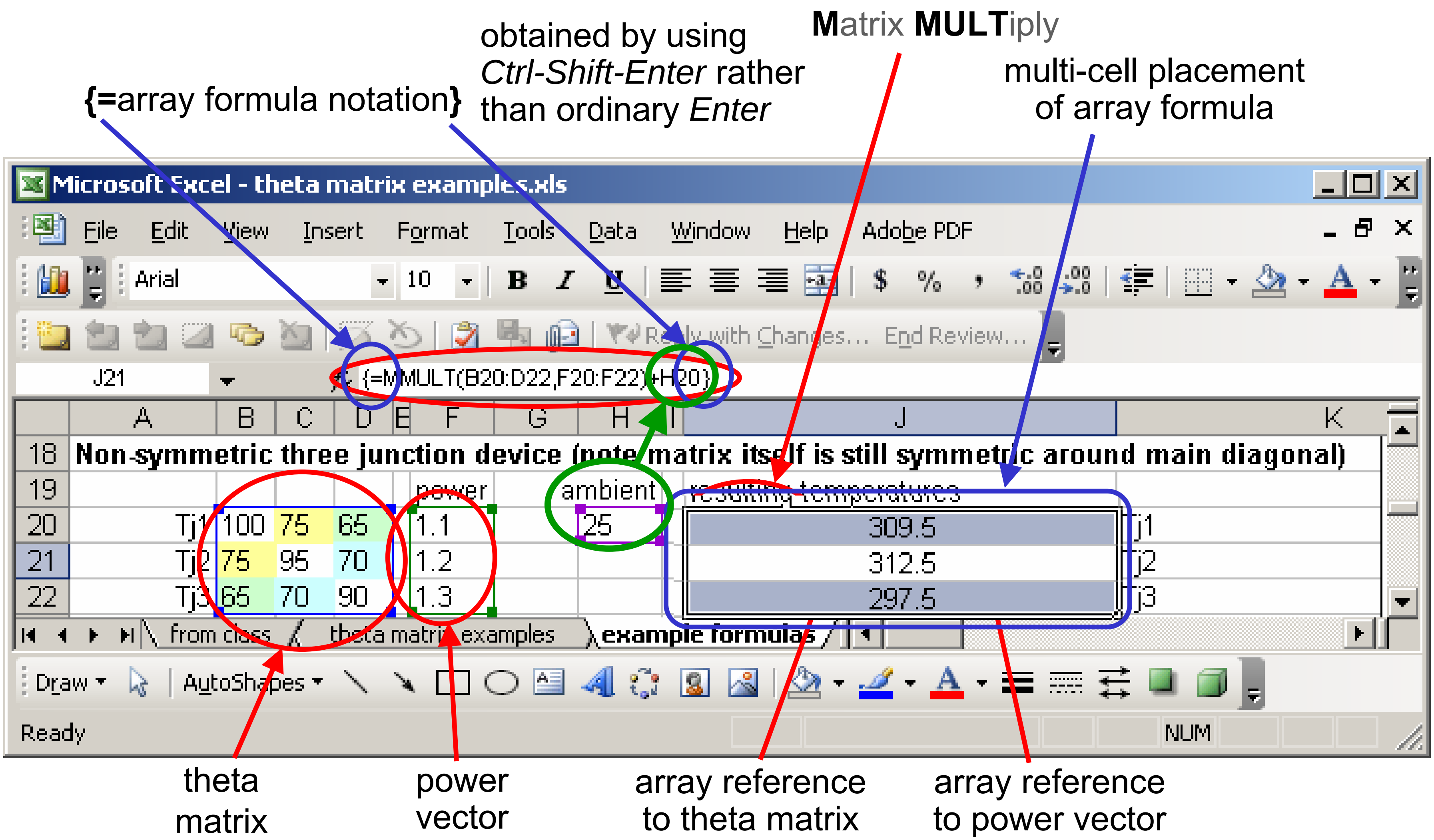
Graphically, low-power device #6 looks like this:



Controlling the matrix

How to harness this math in Excel®

3x3 theta matrix, 3x1 power vector Excel® math

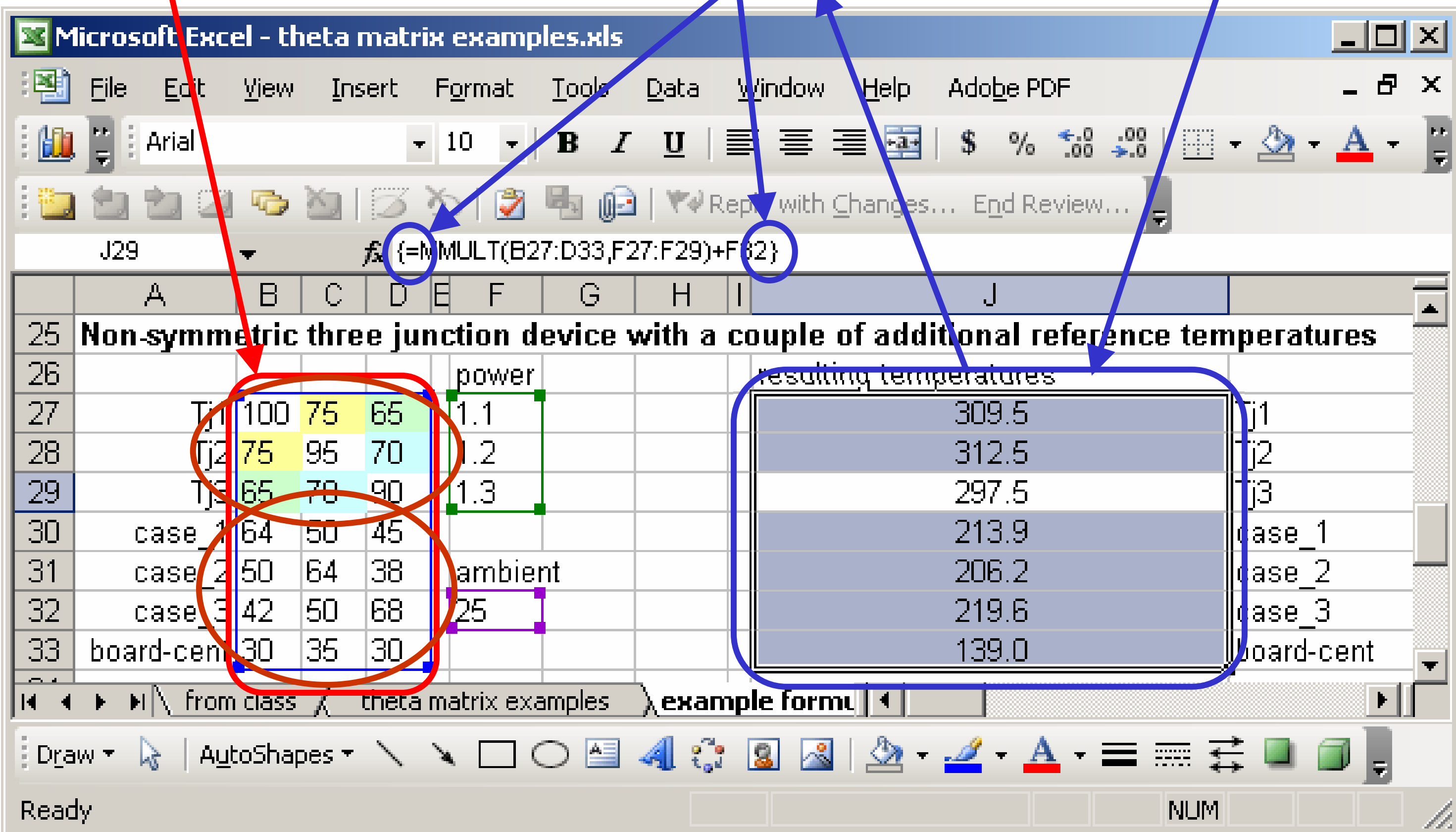


7x3 theta matrix, 3x1 power vector Excel® math

theta matrix is no longer square –
# of columns still must equal
# of rows of power vector

don't forget to use
Ctrl-Shift-Enter
to invoke array formula notation

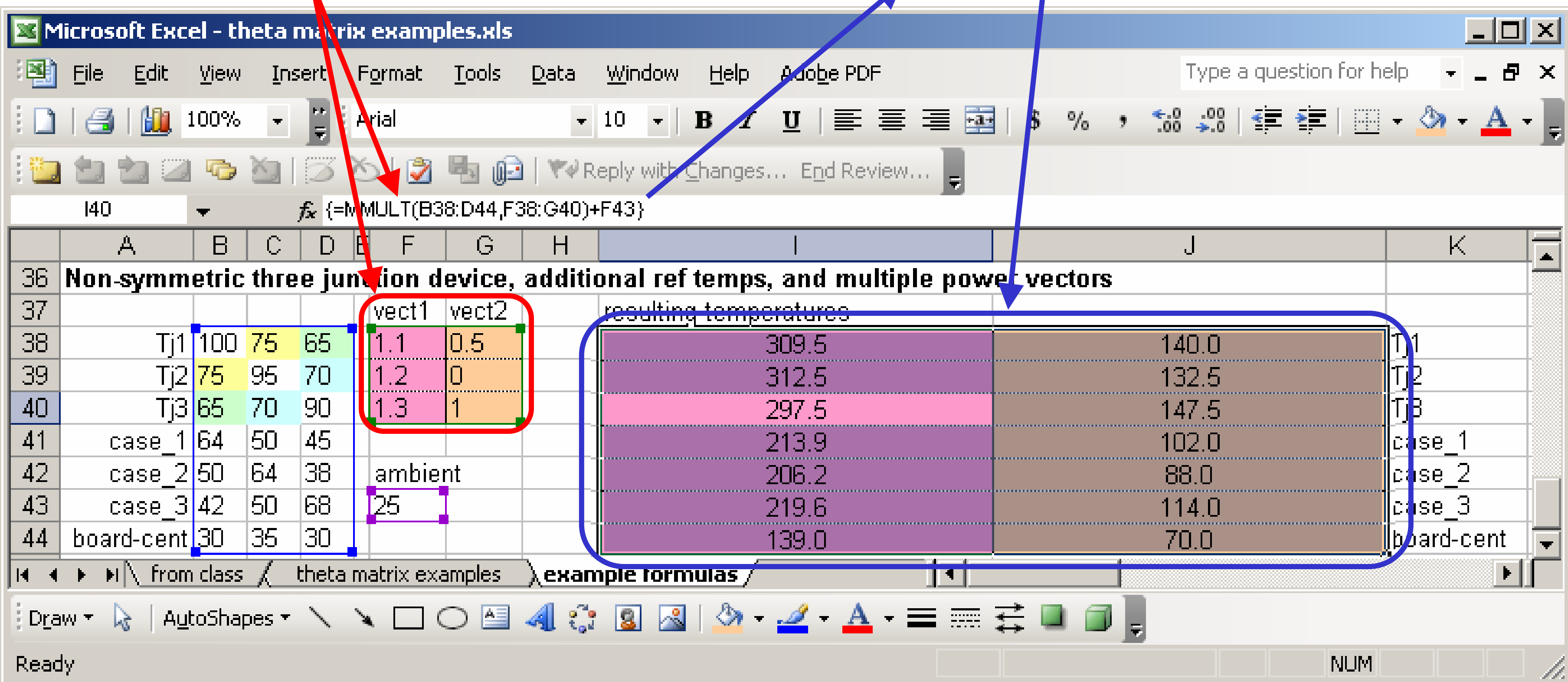
array formula now
occupies 7 cells



7x3 theta matrix, 3x2 power vector Excel® math

power "vector" is now a 3x***2*** array – each column is a different power scenario, yet both are still processed using a single array (MMULT) formula

the single MMULT array formula now occupies 7 rows and ***2*** columns (one column for each independent power scenario result)



	A	B	C	D	F	G	I	J	K
36	Non-symmetric three junction device, additional ref temps, and multiple power vectors								
37					vect1	vect2	resulting temperatures		
38	Tj1	100	75	65	1.1	0.5	309.5	140.0	Tj1
39	Tj2	75	95	70	1.2	0	312.5	132.5	Tj2
40	Tj3	65	70	90	1.3	1	297.5	147.5	Tj3
41	case_1	64	50	45			213.9	102.0	case_1
42	case_2	50	64	38	ambient		206.2	88.0	case_2
43	case_3	42	50	68	25		219.6	114.0	case_3
44	board-cent	30	35	30			139.0	70.0	board-cent

Package-shrink "gotcha"

Often, much or even *most* of theta-JA depends on what *isn't* the package?

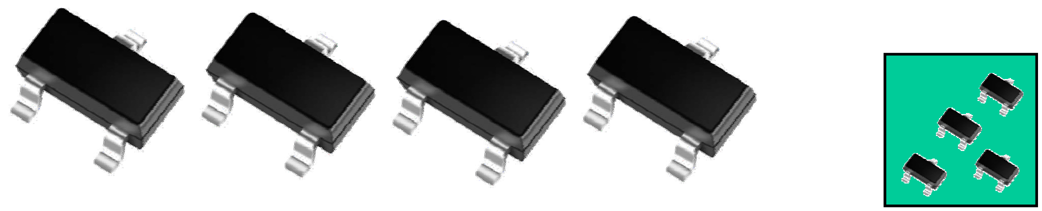
For instance, what if your cooling depends significantly on convection from the board surface (whether free or forced air)?

$$q = h \cdot A \cdot \Delta T \qquad \Leftrightarrow \qquad A = \frac{q}{h \cdot \Delta T}$$

So never mind the *package* resistance, the *board* can only transfer a certain amount of heat to the air:

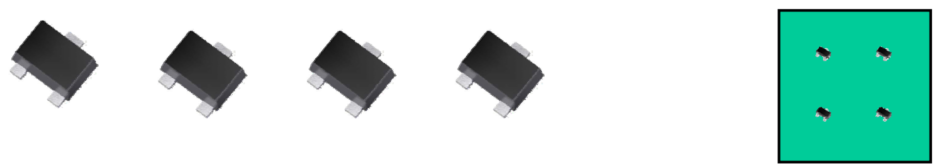
Heat transfer 101

SOT23



Decrease size but not power dissipation

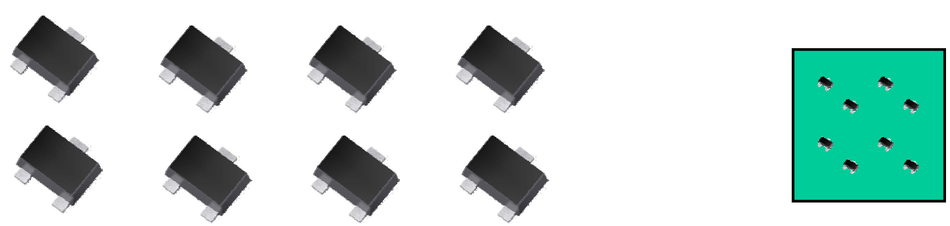
SOT723



Decrease size **and** reduce power dissipation

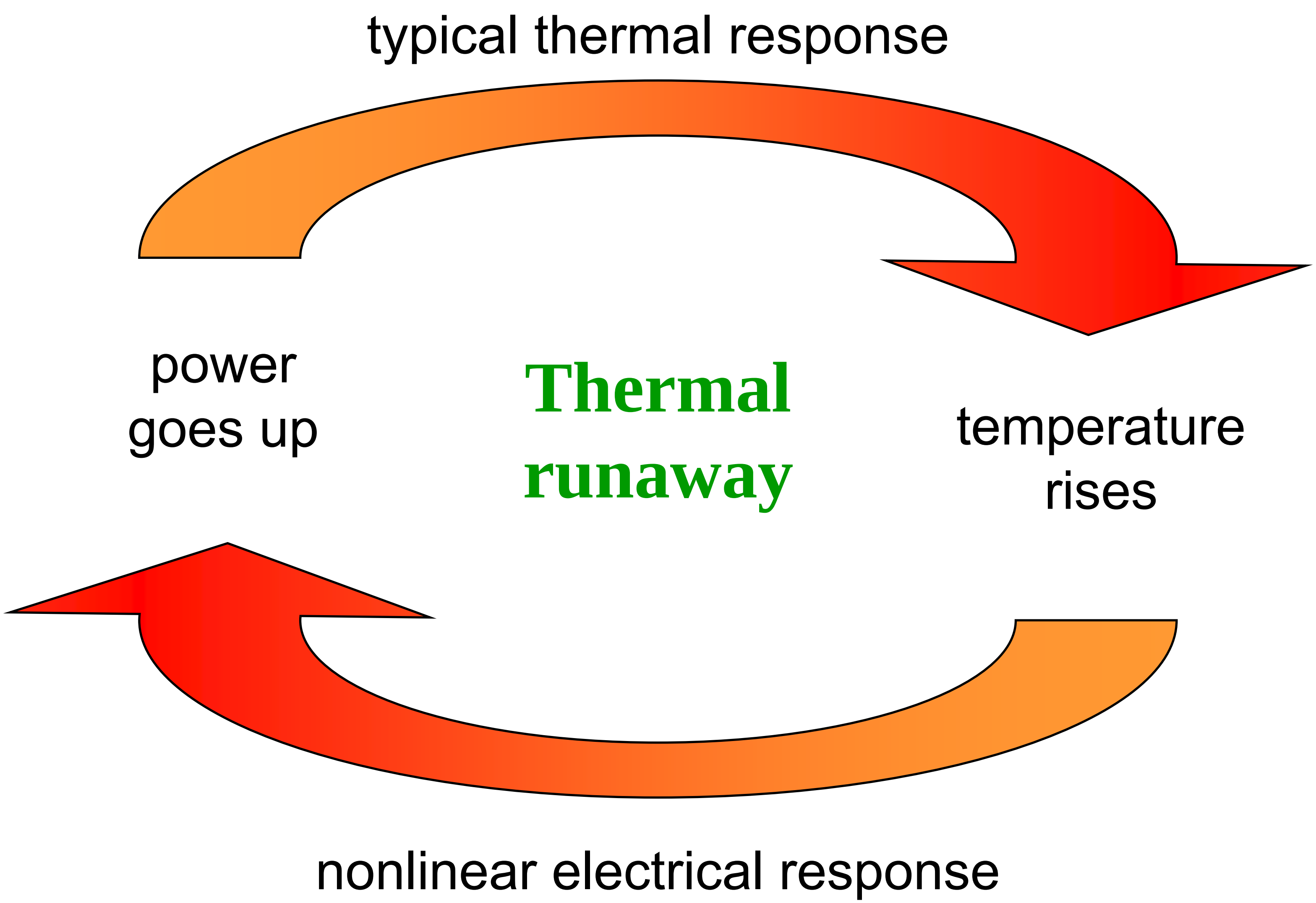
(RDSON or other electrical performance)

SOT723 @ **0.125 W**, ΔT = 100°C, **8** packages per 1000 mm^2



Thermal runaway

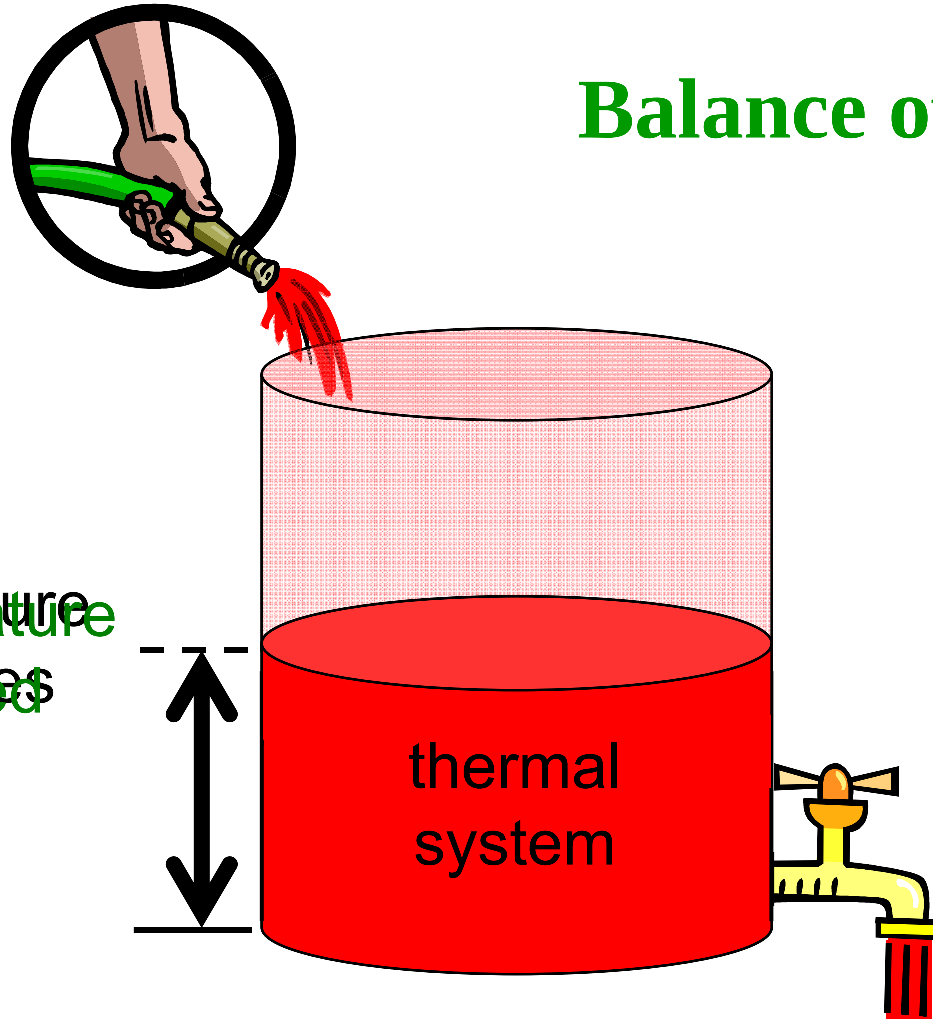
- Theory
  - What is it?
  - When can it happen?
  - A mathematical model of power-law runaway
- An actual device example
- The surrounding system
  - A paradox and its resolution
  - how other components in a complete system affect runaway in a susceptible device
- Review


typical thermal response
power
goes up
Thermal
runaway
temperature
rises
nonlinear electrical response

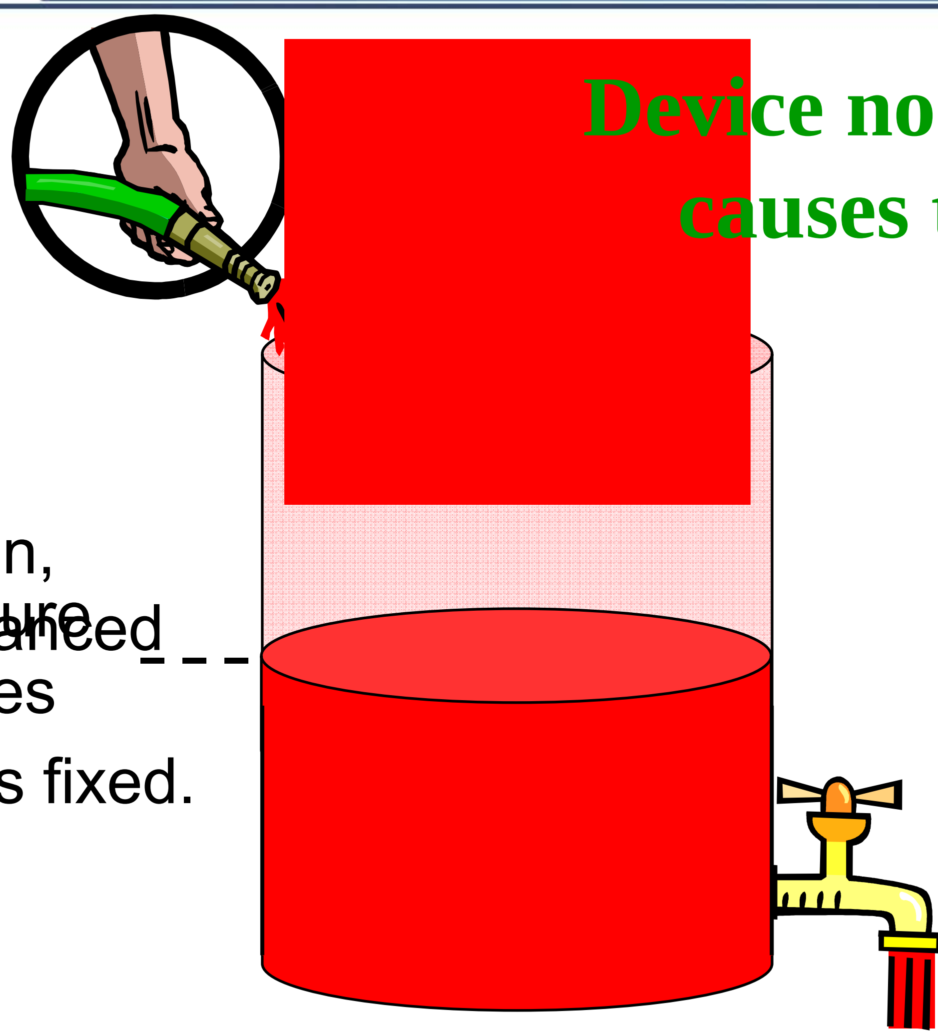
Thermal runaway

- System thermal resistance isn't low enough to shed small perturbations of power
- Nonlinear power vs. junction temperature device characteristic

Balance of power



Device nonlinearity causes trouble



By design,
power is balanced and
temperature is fixed.

temperature
increases

power
dissipation
rises

A linear thermal cooling system

$$T_J = Q \cdot \theta_{Jx} + T_x$$

junction temperature as function of power, theta, and ground

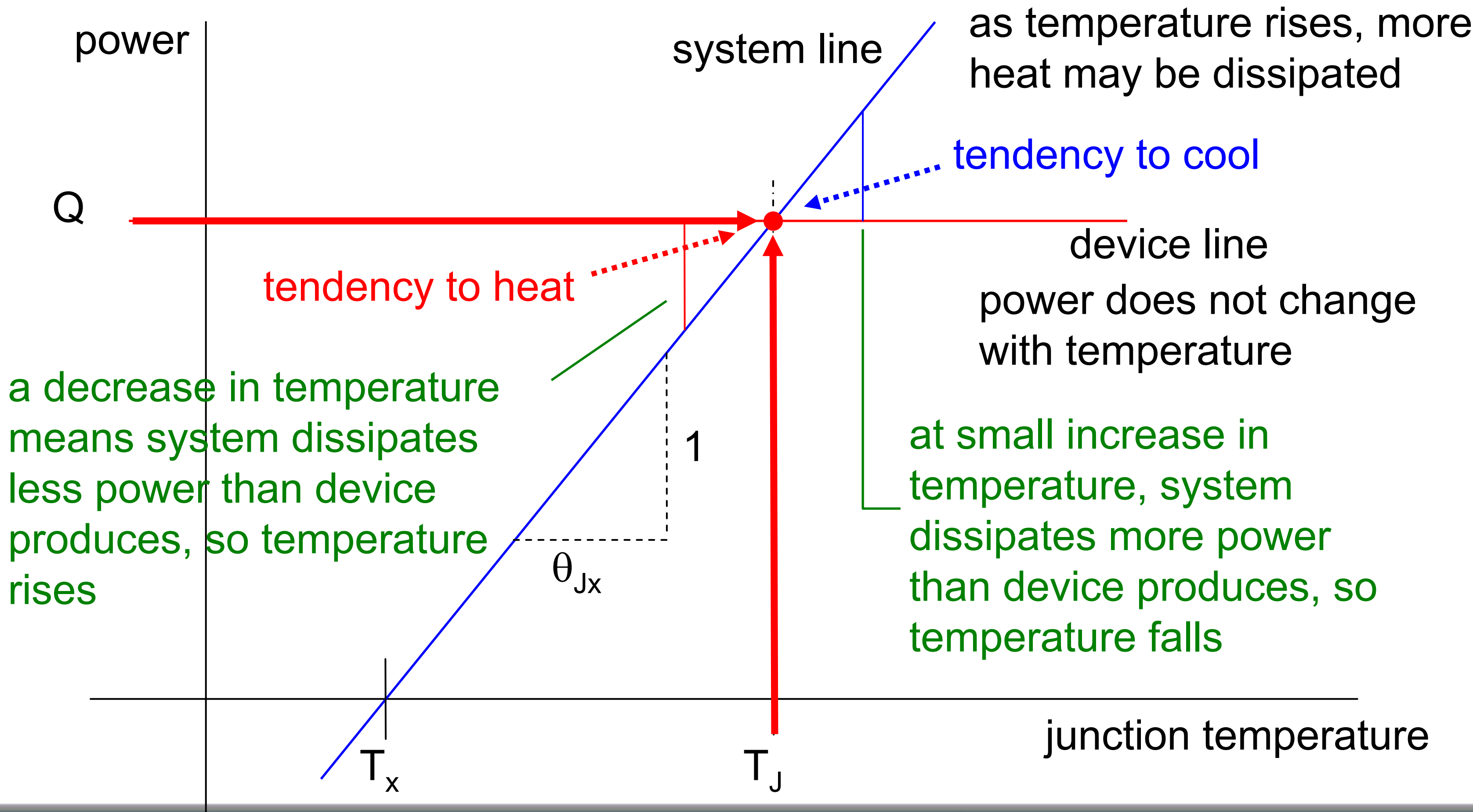
$$Q = \frac{T_J - T_x}{\theta_{Jx}}$$

… solving for power

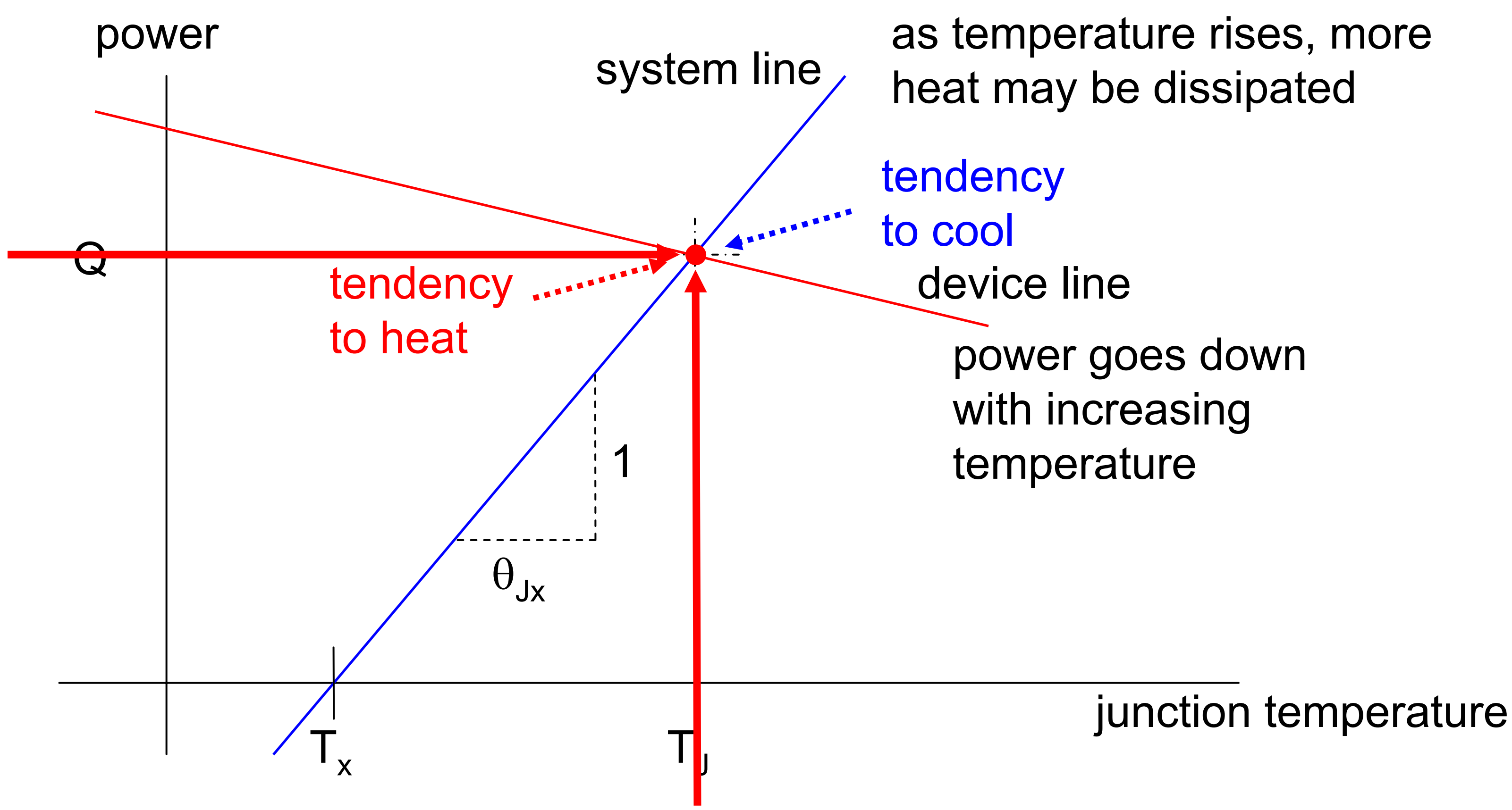
$$\frac{dQ}{dT} = \frac{1}{\theta_{Jx}}$$

sensitivity (slope) of power with respect to temperature

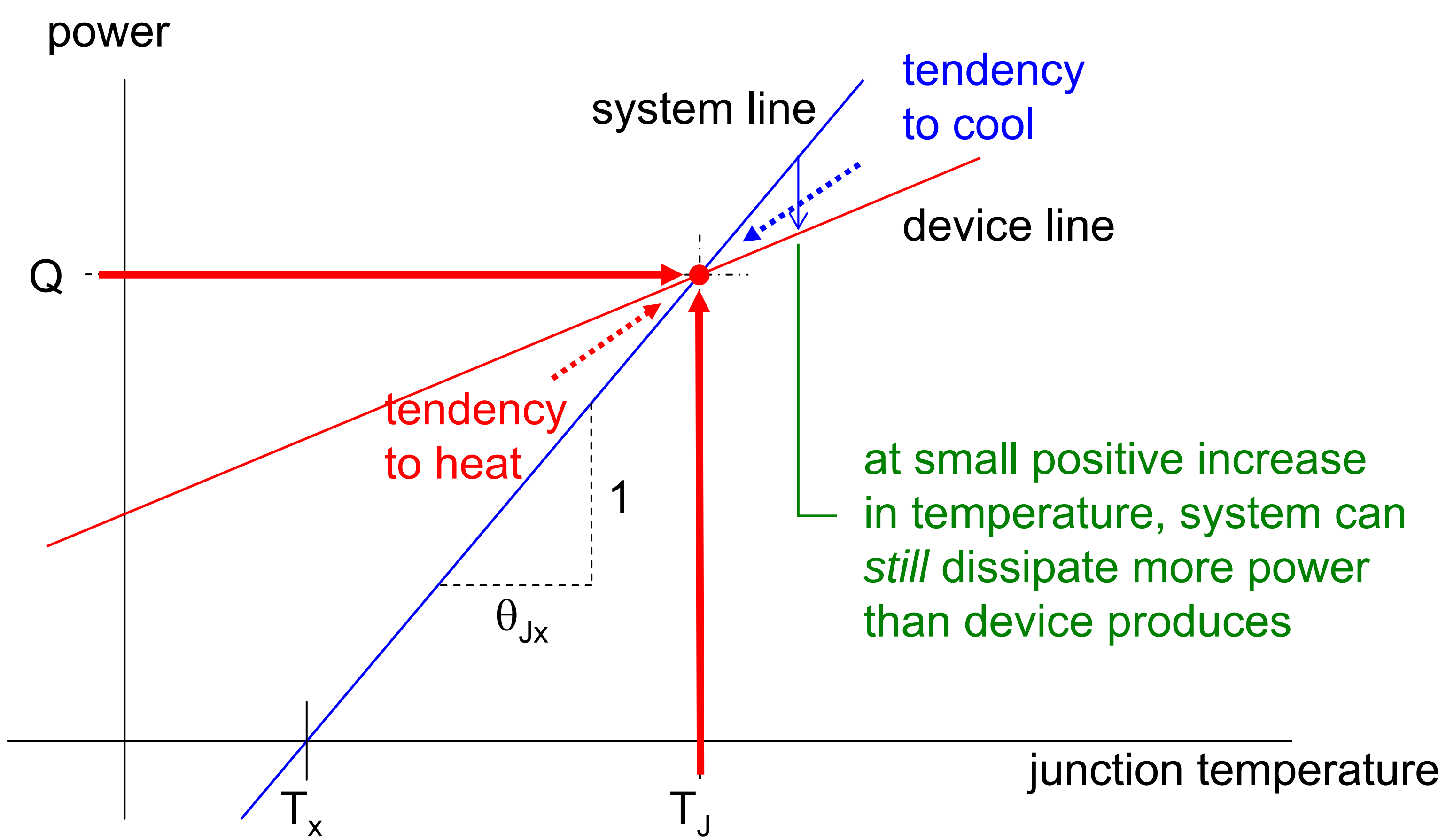
Operating point of thermal system with temperature-independent power



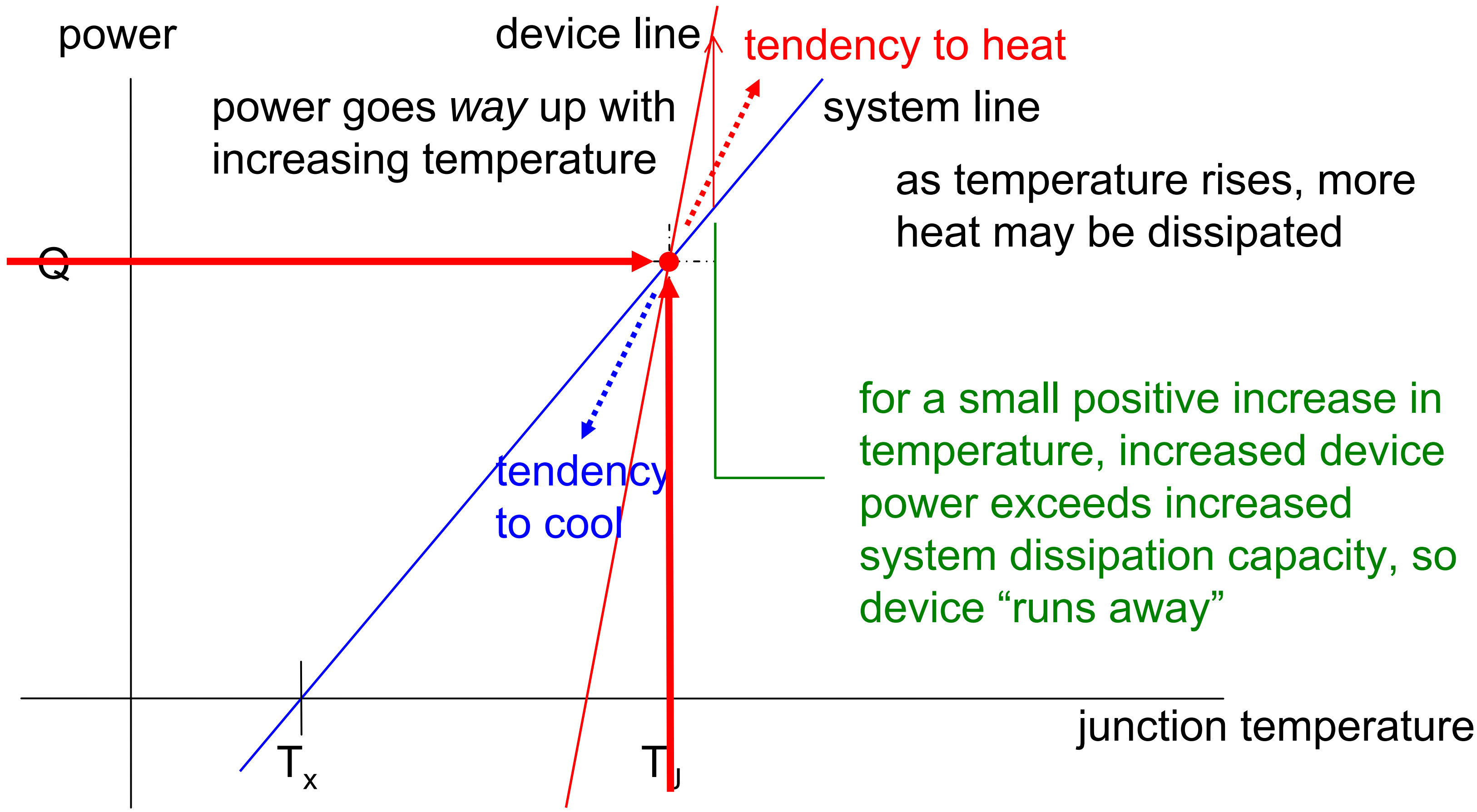
Operating point of thermal system where power *decreases* with temperature



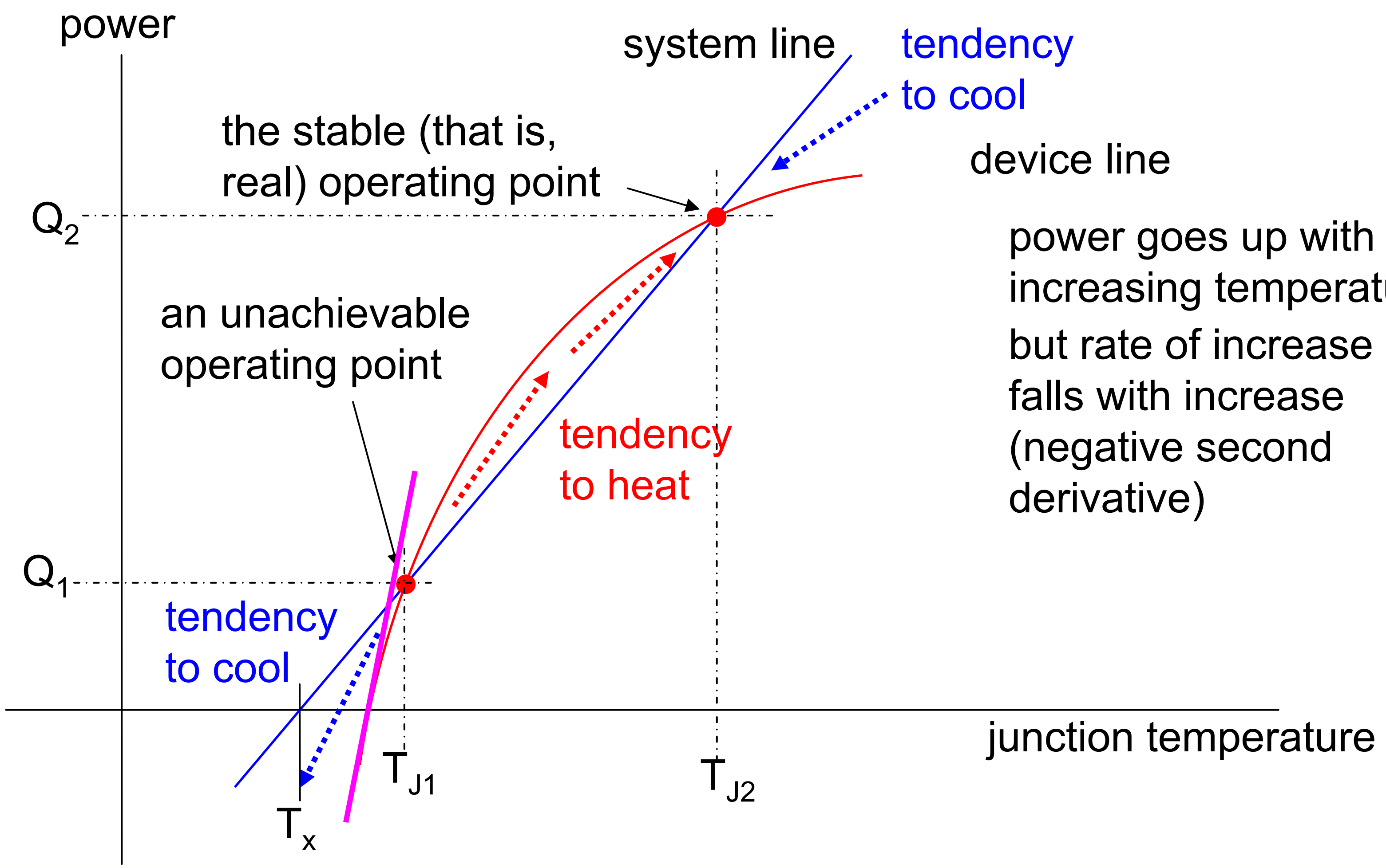
Operating point of thermal system where power *increases* with temperature, slopes favorable



Operating point of thermal system where power *increases* with temperature, *slopes unfavorable*

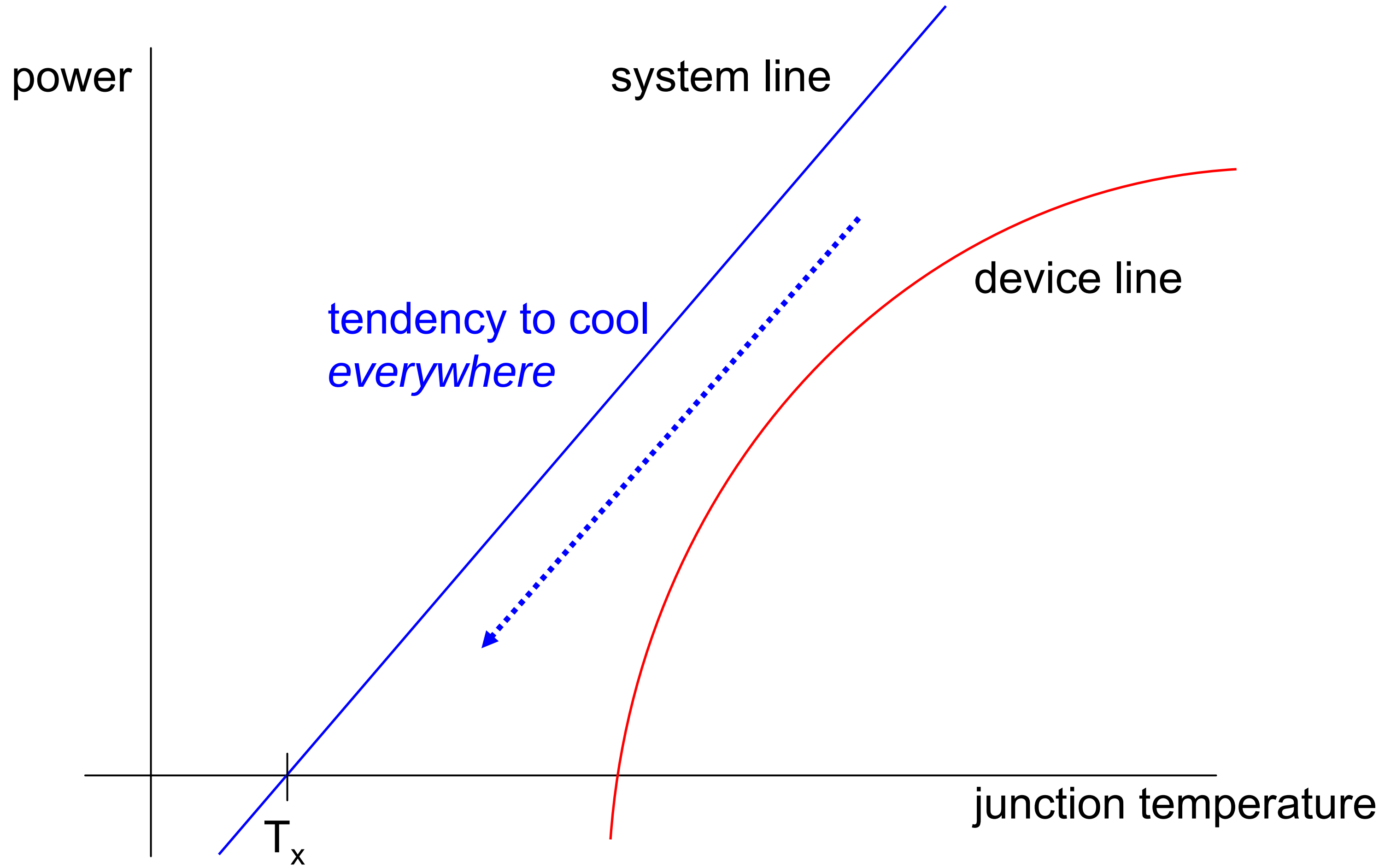


Operating points of thermal system when device line has negative second derivative

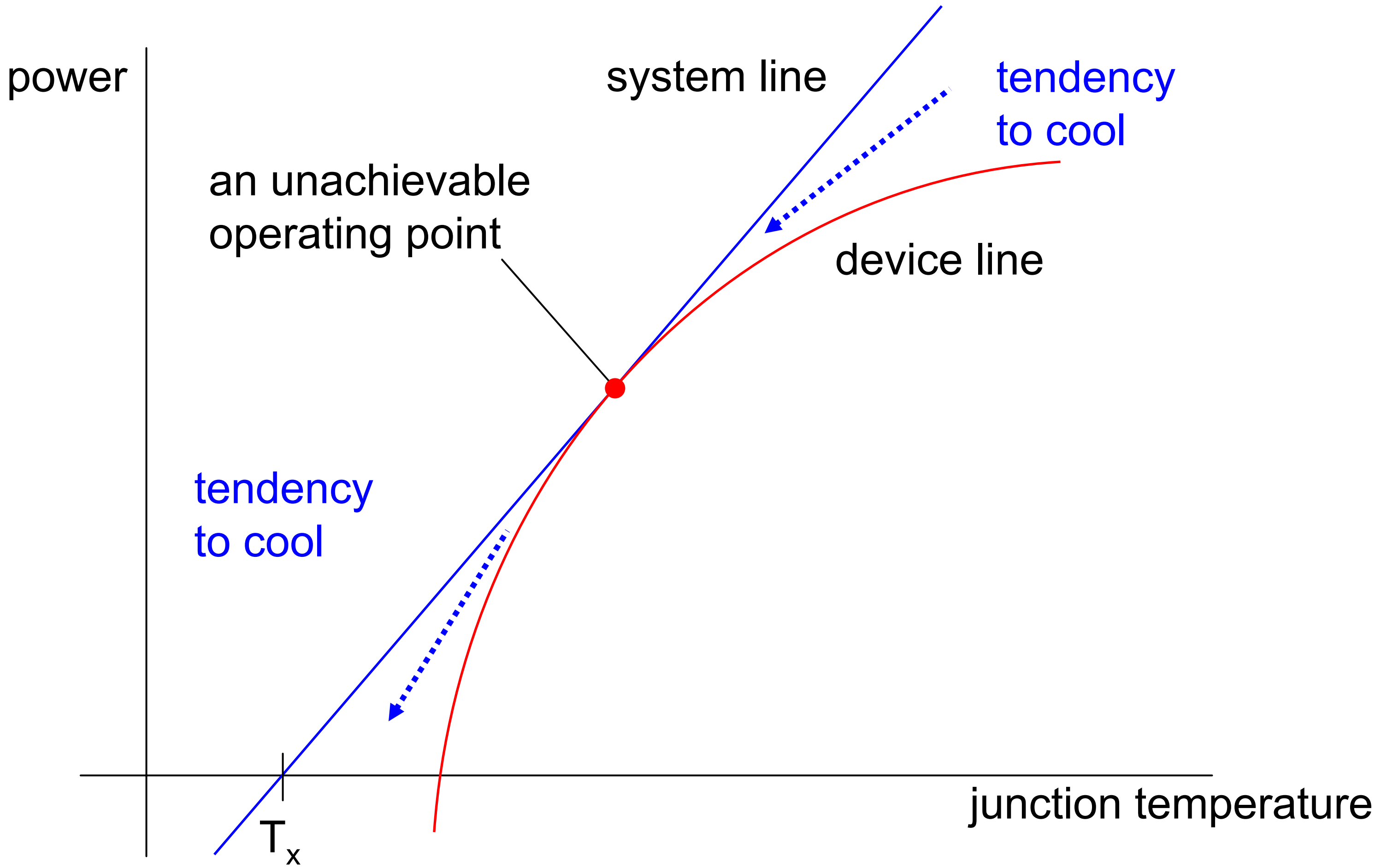


power goes up with increasing temperature but rate of increase falls with increase (negative second derivative)

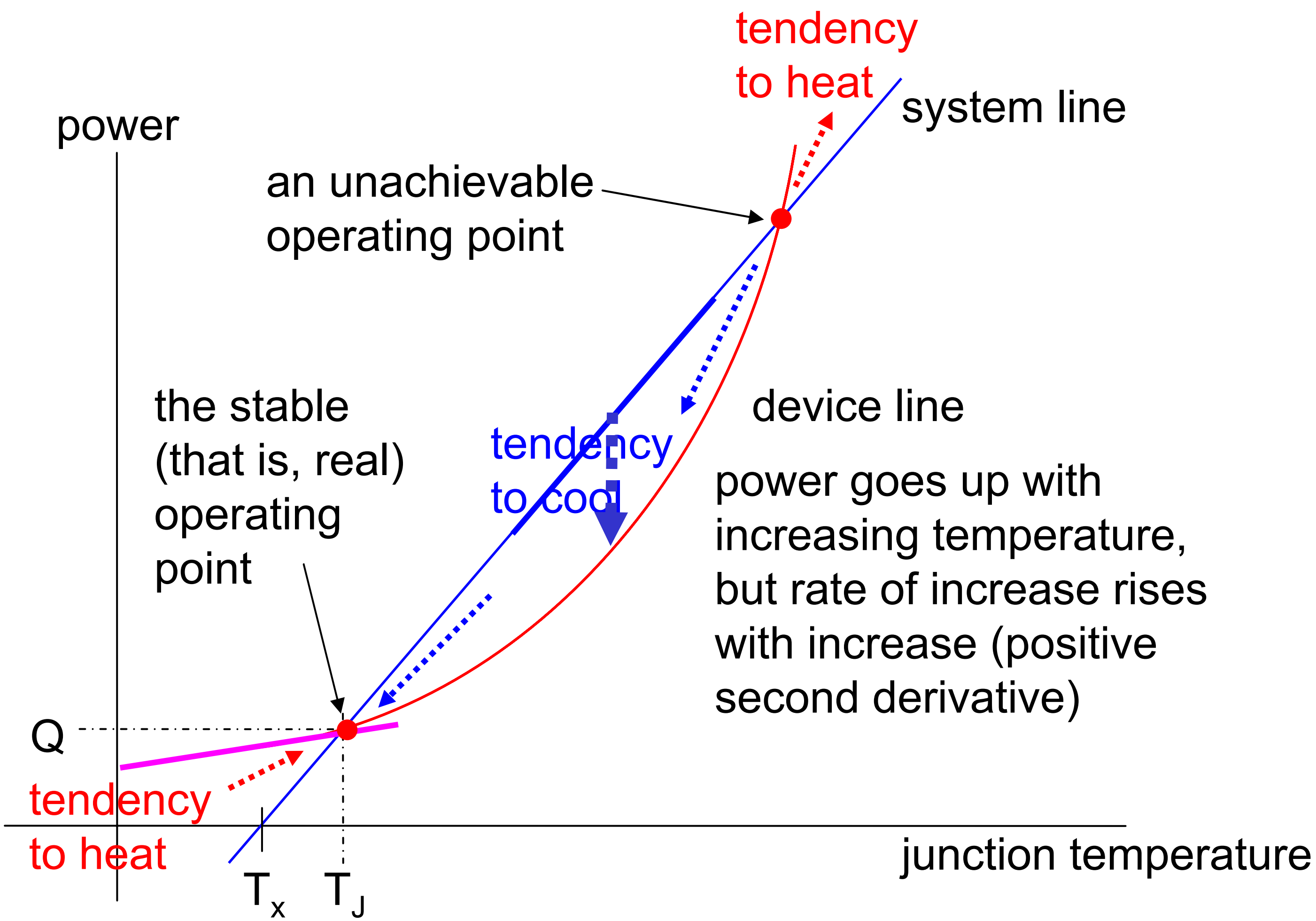
System with no operating point, negative second derivative, cannot be powered up



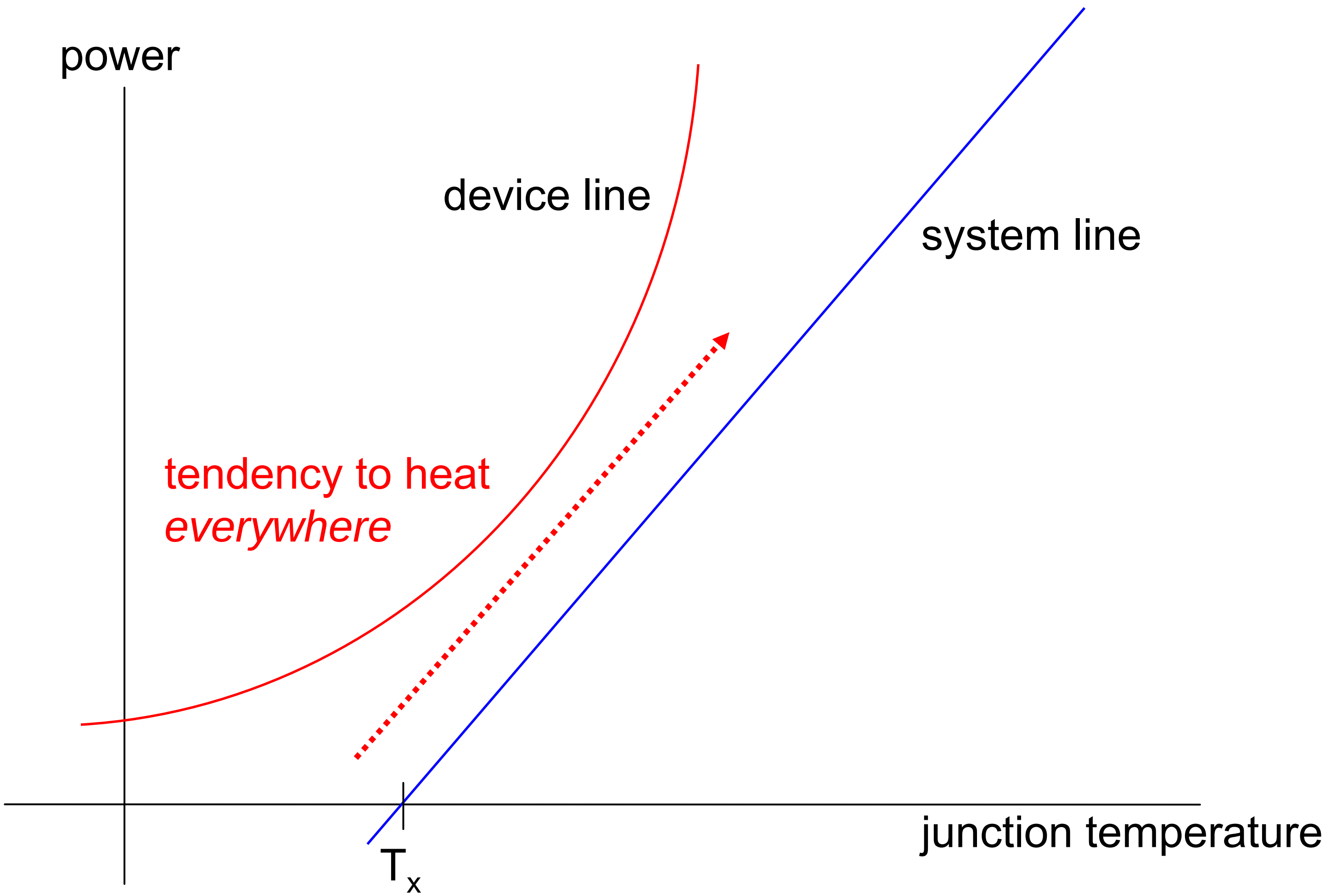
Device with negative second derivative, system has unrealizable operating point,



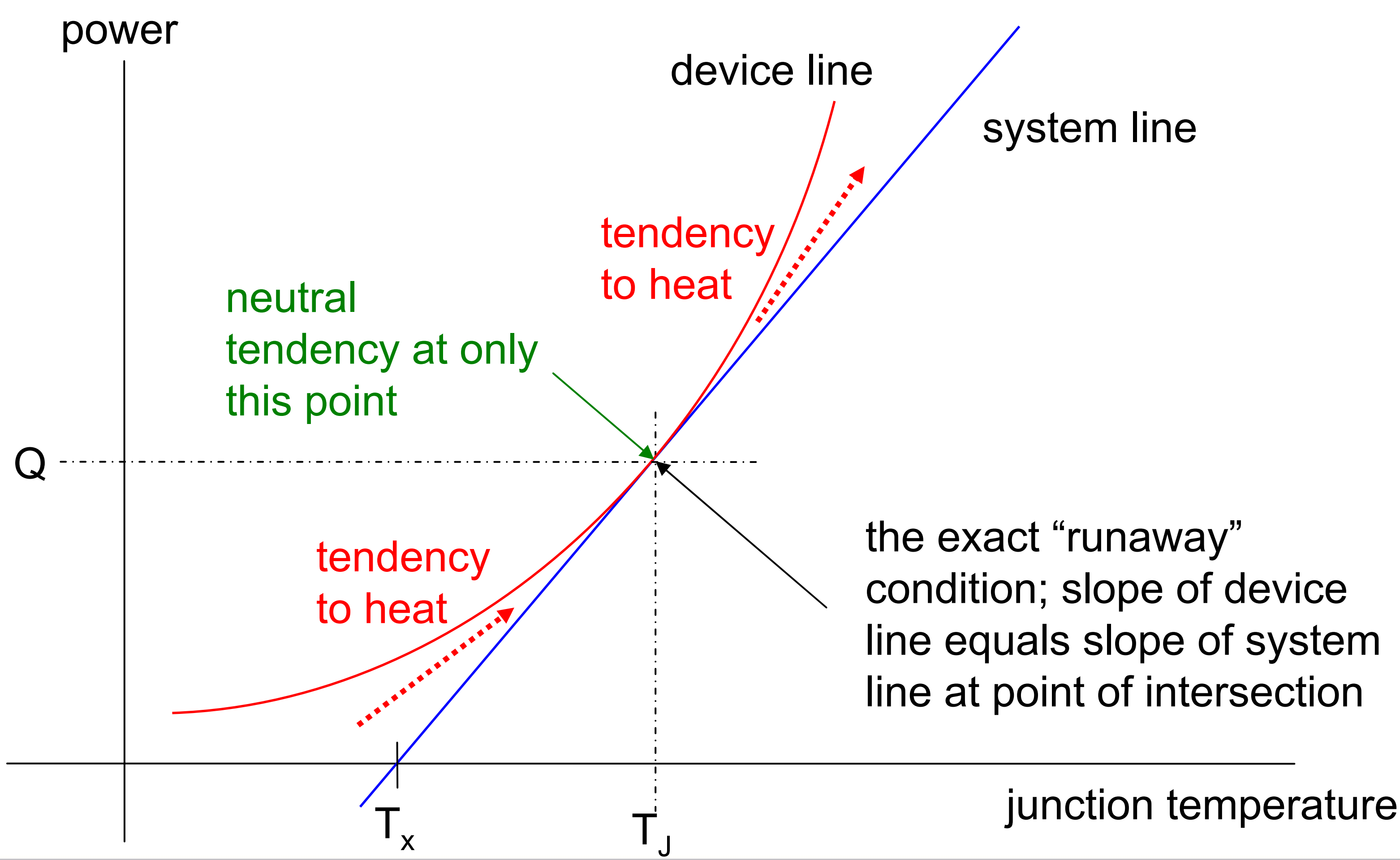
Operating points of thermal system when device line has *positive* second derivative



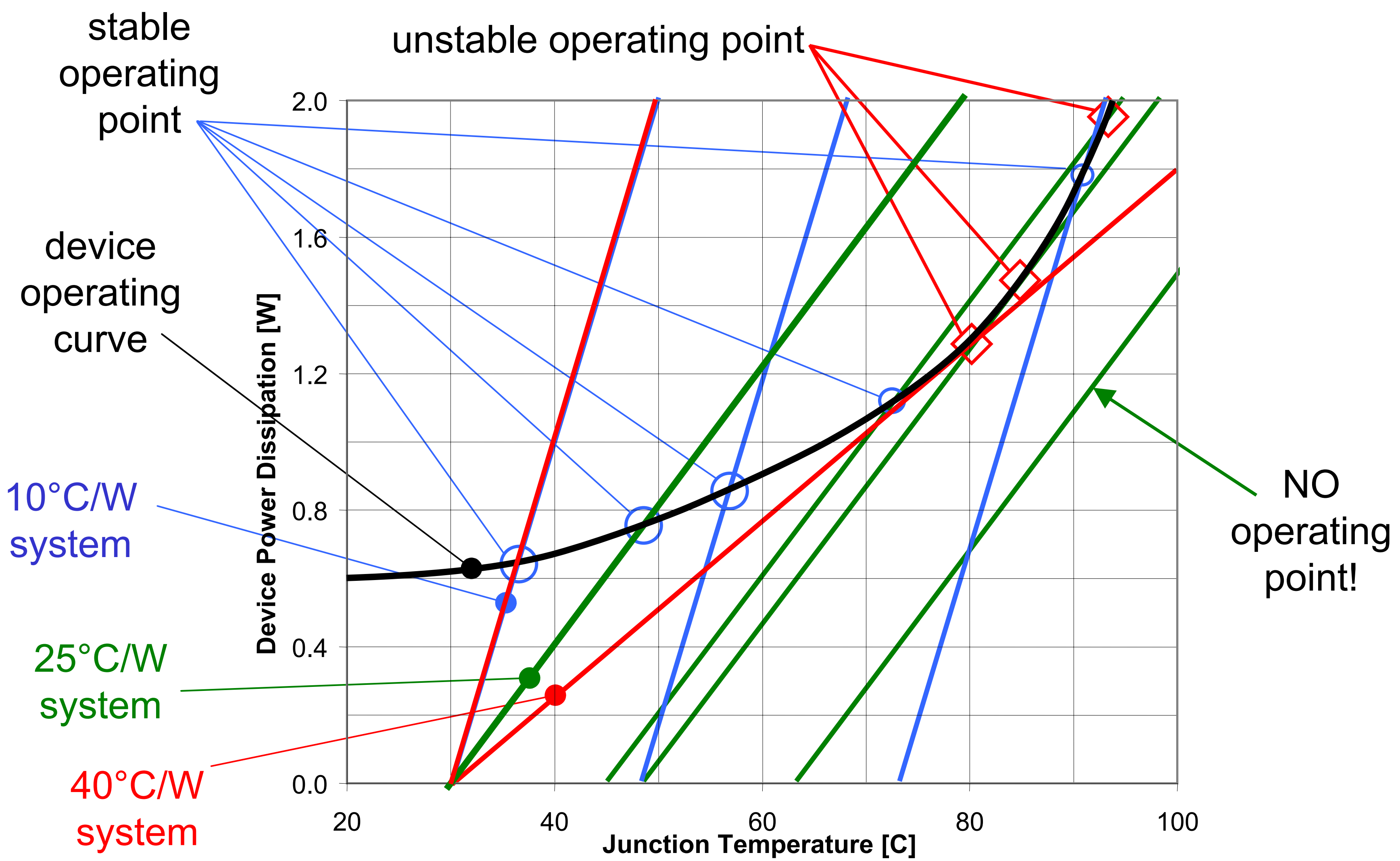
System with NO operating point, overheats as soon as powered up



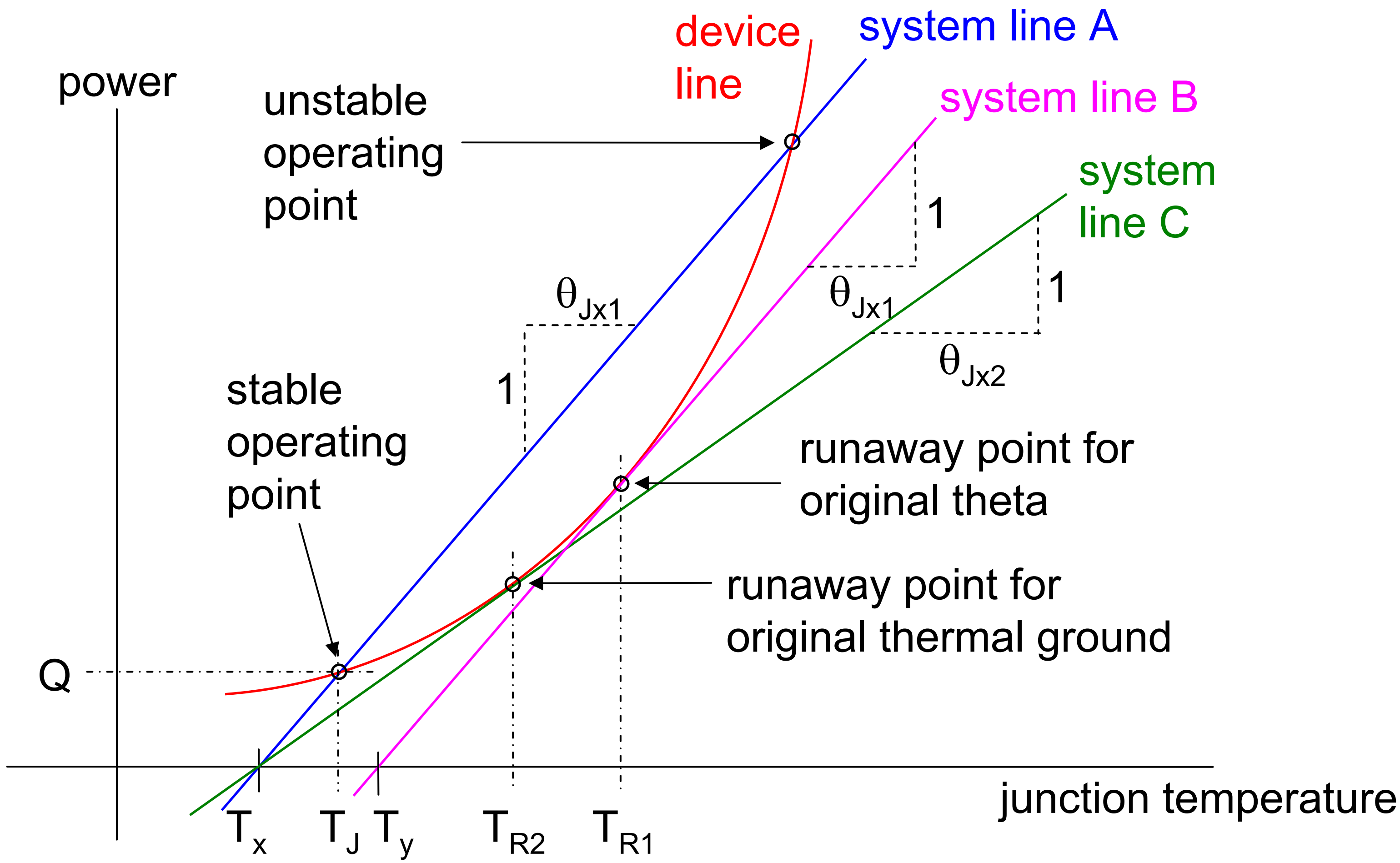
System with exactly one “runaway” operating point, device has positive second derivative



Let's see how it works



Generic power law device and generic linear cooling system



Don’t get confused by the terms!

device <u>power</u>

$$Q = V \cdot I$$

a mathematical
“power law”

$$y = a^x$$

an “exponential”
power law (base is e)

$$y = e^x$$

Definition of power law device

rule of thumb for leakage;
2x increase for every 10°C

$$I = I_o 2^{\frac{T}{10}}$$

$$I = I_o e^{(\ln 2)\frac{T}{10}} = I_o e^{\frac{T}{\left(\frac{10}{\ln 2}\right)}}$$

$$I = I_o e^{\frac{T}{\lambda}}$$

defining: $$\lambda = \frac{T_1 - T_2}{\ln\left(I_1 / I_2\right)}$$

for constant voltage, power does the same

$$Q = V_R I_o e^{\frac{T}{\lambda}} = Q_o e^{\frac{T}{\lambda}}$$

1st and 2nd derivatives

$$\frac{dQ}{dT} = \frac{Q_o}{\lambda} e^{\frac{T}{\lambda}} \qquad \frac{d^2Q}{dT^2} = \frac{Q_o}{\lambda^2} e^{\frac{T}{\lambda}}$$

both always positive

The mathematical essence

System line

$$Q = \frac{T - T_x}{\theta_{Jx}}$$

Power law device line

$$Q = Q_o e^{\frac{T}{\lambda}}$$

Non-dimensionalizing

$$z = \frac{T - T_x}{\lambda} \quad \textbf{temperature}$$

$$q = \left(\frac{1}{Q_o} e^{\frac{-T_x}{\lambda}} \right) Q \quad \textbf{power}$$

Leads to:

(system)

$$q = kz$$

where:

$$k = \frac{\lambda}{\theta_{Jx} Q_o} e^{\frac{-T_x}{\lambda}}$$

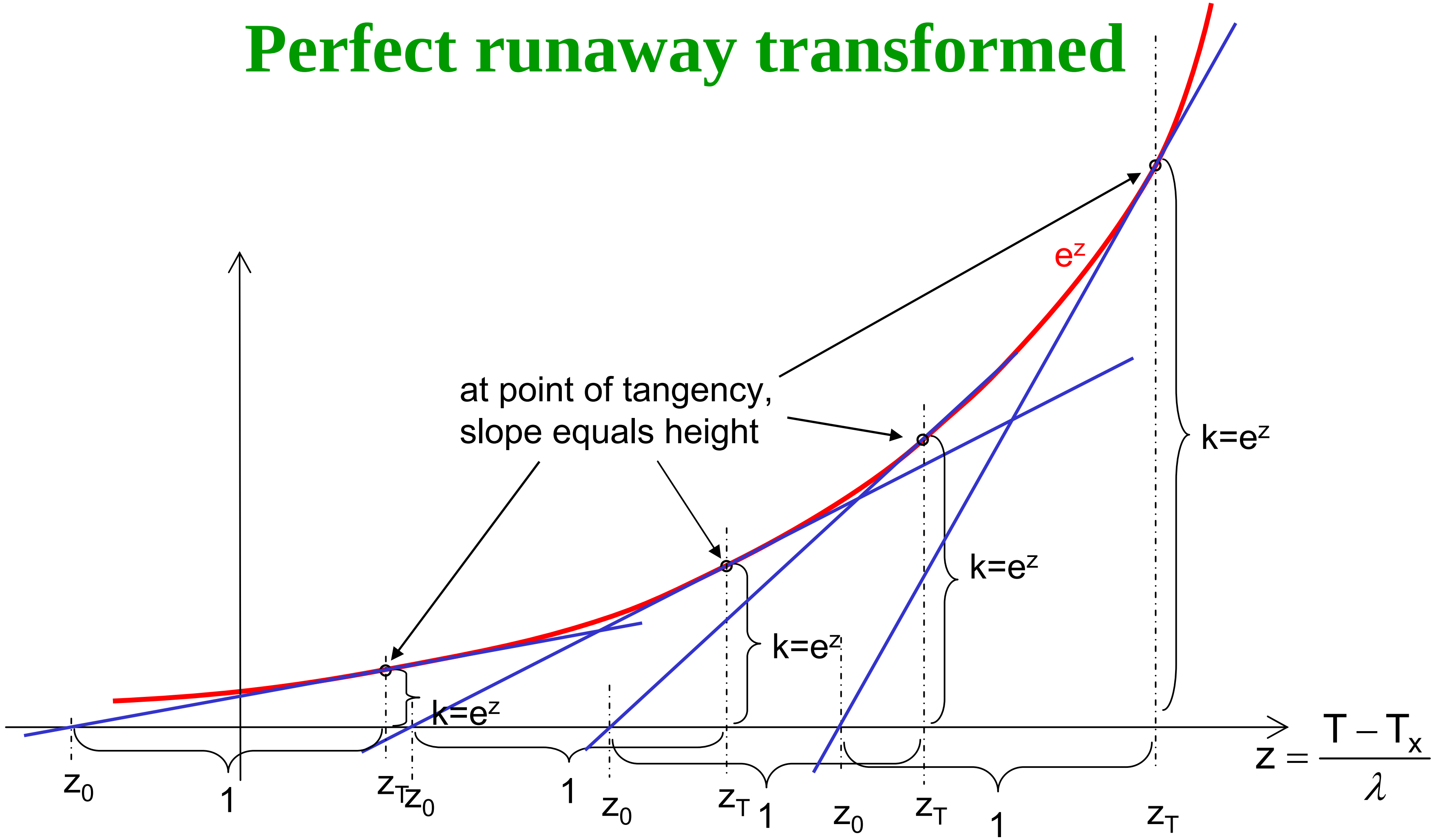
(power law device)

$$q = e^z$$

Eliminating q:

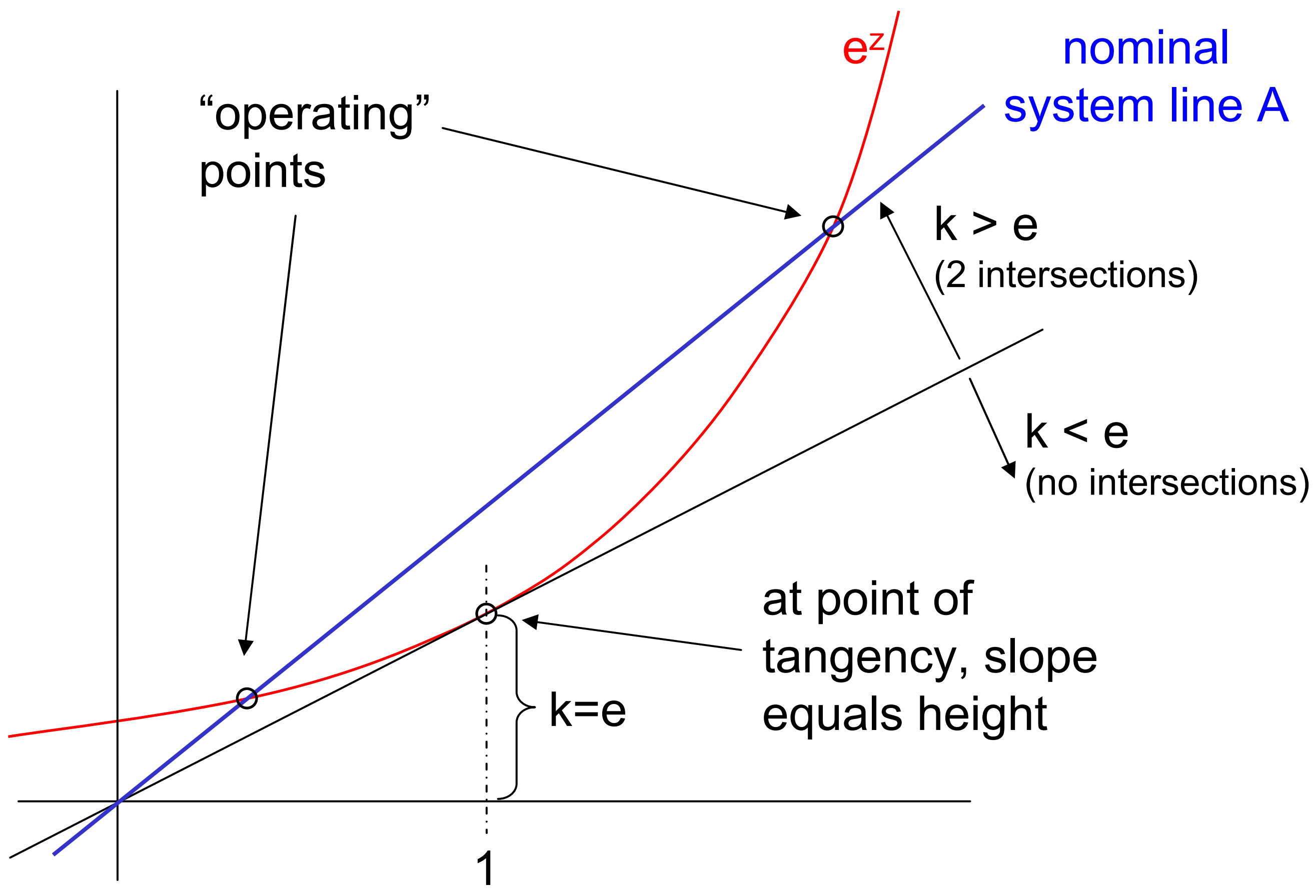
$$kz = e^z$$

Perfect runaway transformed

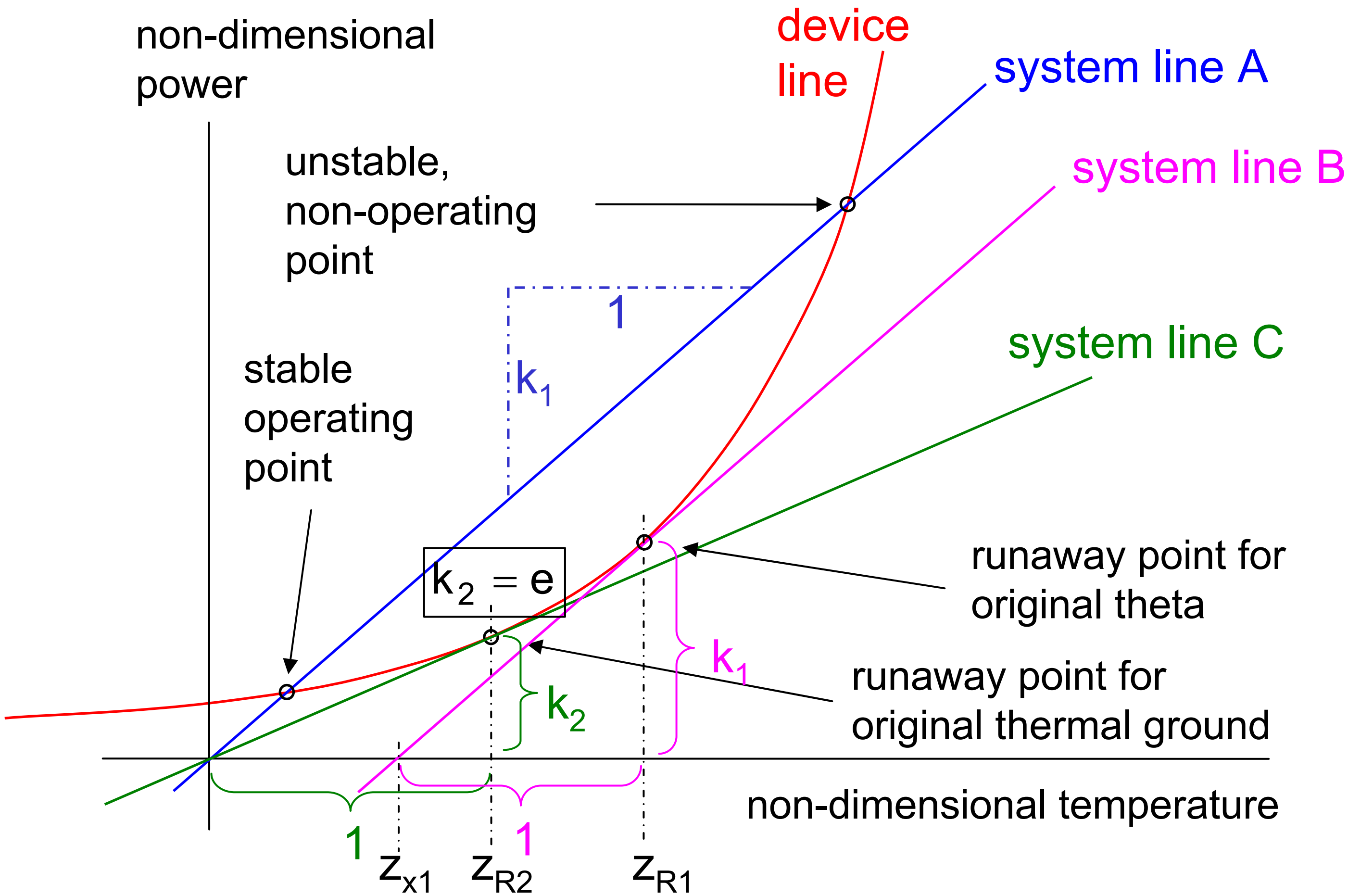


$$z_T - z_0 = 1$$

Transforming the nominal system



Everything transformed



$z_{x1} = ln(k_1) - 1$ | $z_{R2} = 1$ | $z_{R1} = ln(k_1)$

"Perfect runaway" results in original terms

runaway temperature based on original slope

$$T_{R1} = \lambda \, ln\left(\frac{\lambda}{\theta_{Jx1} Q_o}\right)$$

runaway temperature based on original ambient

$$T_{R2} = T_x + \lambda$$

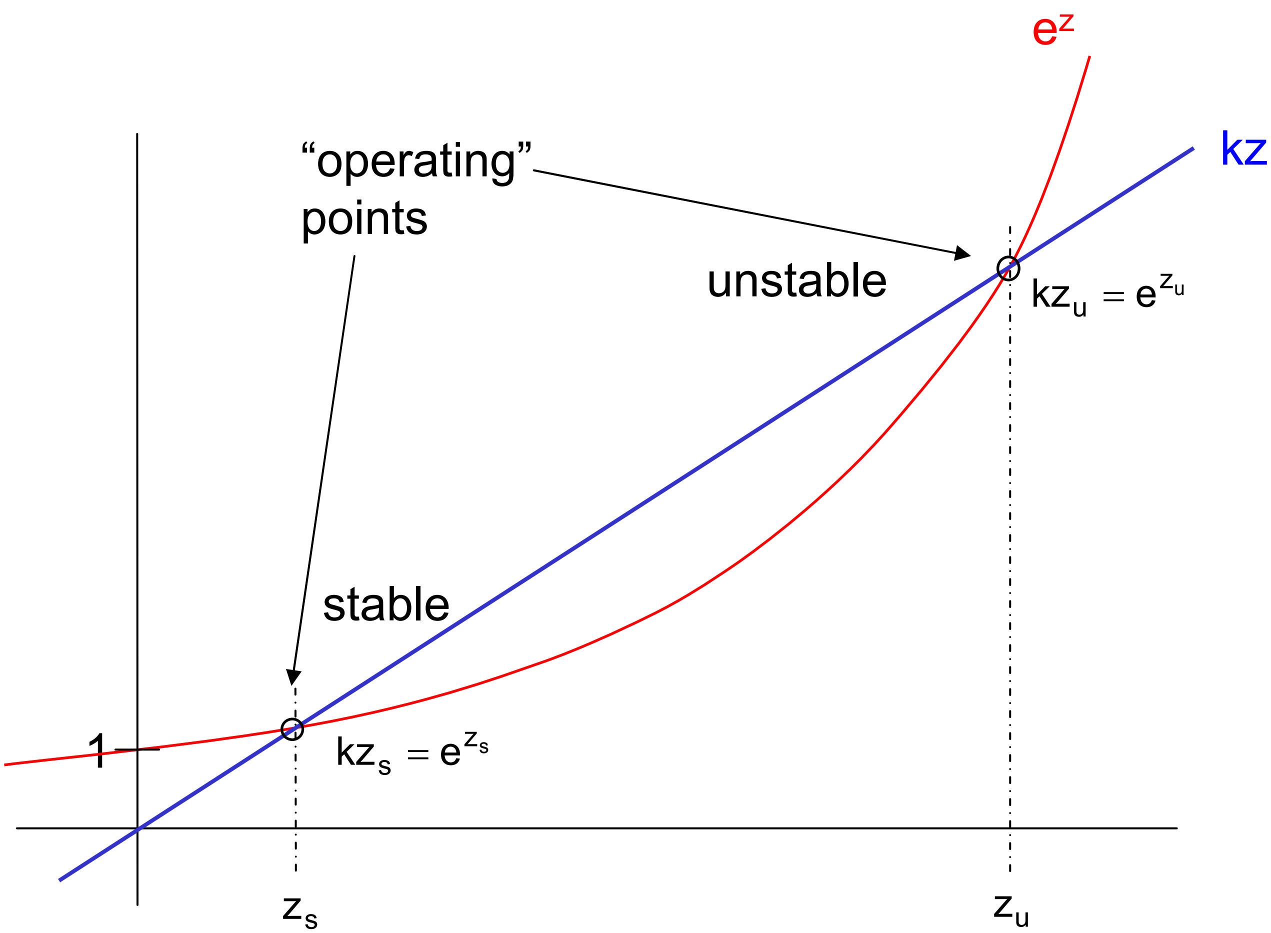
max ambient that goes with it

$$T_{x1} = \lambda \, ln\left(\frac{\lambda}{\theta_{Jx1} Q_o}\right) - \lambda$$

system resistance that goes with it

$$\theta_{Jx2} = \frac{\lambda}{Q_o} e^{-\left(\frac{T_x}{\lambda} + 1\right)}$$

The "operating" points



Newton's method for the intersections

$$z_{i+1} = z_i - \frac{-F(z_i)}{F'(z_i)}$$

$$kz = e^z$$

$$\ln kz = z$$

$$F(z) = z - \ln kz$$

$$F'(z) = 1 - \frac{1}{z}$$

$$z_{i+1} = \frac{\ln\left(\frac{k}{e} z_i\right)}{1 - \frac{1}{z_i}}$$

For k/e ranging between 1.01 and 1000, convergence is to a dozen significant digits in fewer than 10 iterations.

$$z_o = \frac{1}{k} = \frac{1}{e \cdot \frac{k}{e}}$$

this initial guess converges to lower, stable point

this initial guess converges to upper, unstable point

$$z_o = \ln k = 1 + \ln\left(\frac{k}{e}\right)$$

Excel® implementation of Newton's method

	A	B	C
1	number of iterations required		
2	k	# of iterations	
3	2.72	9	
4	2.8	7	
5	3	6	
6	10	4	
7	100	3	
8	1000	2	
9			
10	k/e	1.609210697	
11			
12			
13			
14			
15		Newton's method	
16	i	lower, stable	upper, unstable
17	0	0.228608622744	1.475743808544
18	1	0.296368799805	2.682913734495
19	2	0.311857924364	2.331763211138
20	3	0.312456894855	2.316314217143
21	4	0.312457732003	2.315270211468
22	5	0.312457732004	2.315270211150
29	12	0.312457732004	2.315270211150
30	13	0.312457732004	2.315270211150
31			
32	z	0.312457732004	2.315270211150
33	T	80.58	116.32
34	Q	0.09294	0.68868

$$z_{i+1} = \frac{\ln\left(\frac{k}{e} z_i\right)}{1 - \frac{1}{z_i}}$$

	B	C
	='runaway graphic'!B29	
	Newton's method	
i	lower, stable	upper, unstable
	=EXP(-1)/B10	=1+LN(B10)
	=LN(B10*B17)/(1-1/B17)	=LN(B10*C17)/(1-1/C17)
	=LN(B10*B18)/(1-1/B18)	=LN(B10*C18)/(1-1/C18)
	=LN(B10*B19)/(1-1/B19)	=LN(B10*C19)/(1-1/C19)
	=LN(B10*B20)/(1-1/B20)	=LN(B10*C20)/(1-1/C20)
	=LN(B10*B21)/(1-1/B21)	=LN(B10*C21)/(1-1/C21)
	=LN(B10*B28)/(1-1/B28)	=LN(B10*C28)/(1-1/C28)
	=LN(B10*B29)/(1-1/B29)	=LN(B10*C29)/(1-1/C29)
	=B30	=C30
	=Tamb_given+B32*Thermal Runaway	=Tamb_given+C32*Thermal Runaway
	=(B33-Tamb_given)/theta_given	=(C33-Tamb_given)/theta_given

$$z_{i+1} = \frac{\ln\left(\frac{k}{e} z_i\right)}{1 - \frac{1}{z_i}}$$

And the intersection points come from …

find the non-dimensional intersections first, then

$$T_{stable} = T_x + \lambda \cdot z_{stable}$$

$$T_{unstable} = T_x + \lambda \cdot z_{unstable}$$

Real datasheet example

raw device data†

V_r [V]	12	40
T_{max} [°C]	125	125
T_{ref} [°C]	75	75
I_{tmax} [A]	8.50E-3	2.80E-2
I_{tref} [A]	5.20E-4	1.70E-3

$$I = I_0 e^{\frac{T}{\lambda}}$$

the device power curve parameters

	@12V	@40V
λ [°C]	17.9	17.8
Q_o [W]	9.4E-5	1.02E-3

$$\lambda = \frac{T_{max} - T_{ref}}{ln\left(I_{max}/I_{ref}\right)}$$

rule of thumb gave us: $= \dfrac{10}{ln(2)} = 14.4$

$$I_0 = I_{t\,max} e^{-\frac{T_{max}}{\lambda}} = I_{tref} e^{-\frac{T_{ref}}{\lambda}}$$

$$Q_0 = V_R I_o$$

† MBRS140T3

Runaway analysis in nominal system

raw device data†

V_r [V]	12	40
T_{max} [°C]	125	125
T_{ref} [°C]	75	75
I_{tmax} [A]	8.50E-3	2.80E-2
I_{tref} [A]	5.20E-4	1.70E-3

computed results

		@12V	@40V	@40V
λ [°C]		17.9	17.8	
Q_o [W]		9.4E-5	1.02E-3	
k/e (compare to unity)		10.6	0.97	1.609
given theta	T_x max [°C]	117.2	74.4	83.5
	T_{R1} [°C]	135.1	92.2	101.3
given ambient	θ_{Jx2} max [°C/W]	1055	96.6	
	T_{R2} [°C]	92.9	92.8	
		$\theta_{Jx1} = 100$		$\theta_{Jx1} = 60$

$$\frac{k}{e} = \frac{\lambda}{\theta_{Jx} Q_o} e^{\frac{-T_x}{\lambda} - 1} \qquad T_x = 75$$

These translate into:

a stable operating point at 80.6°C (and 0.09 W), ← $z = 0.312$

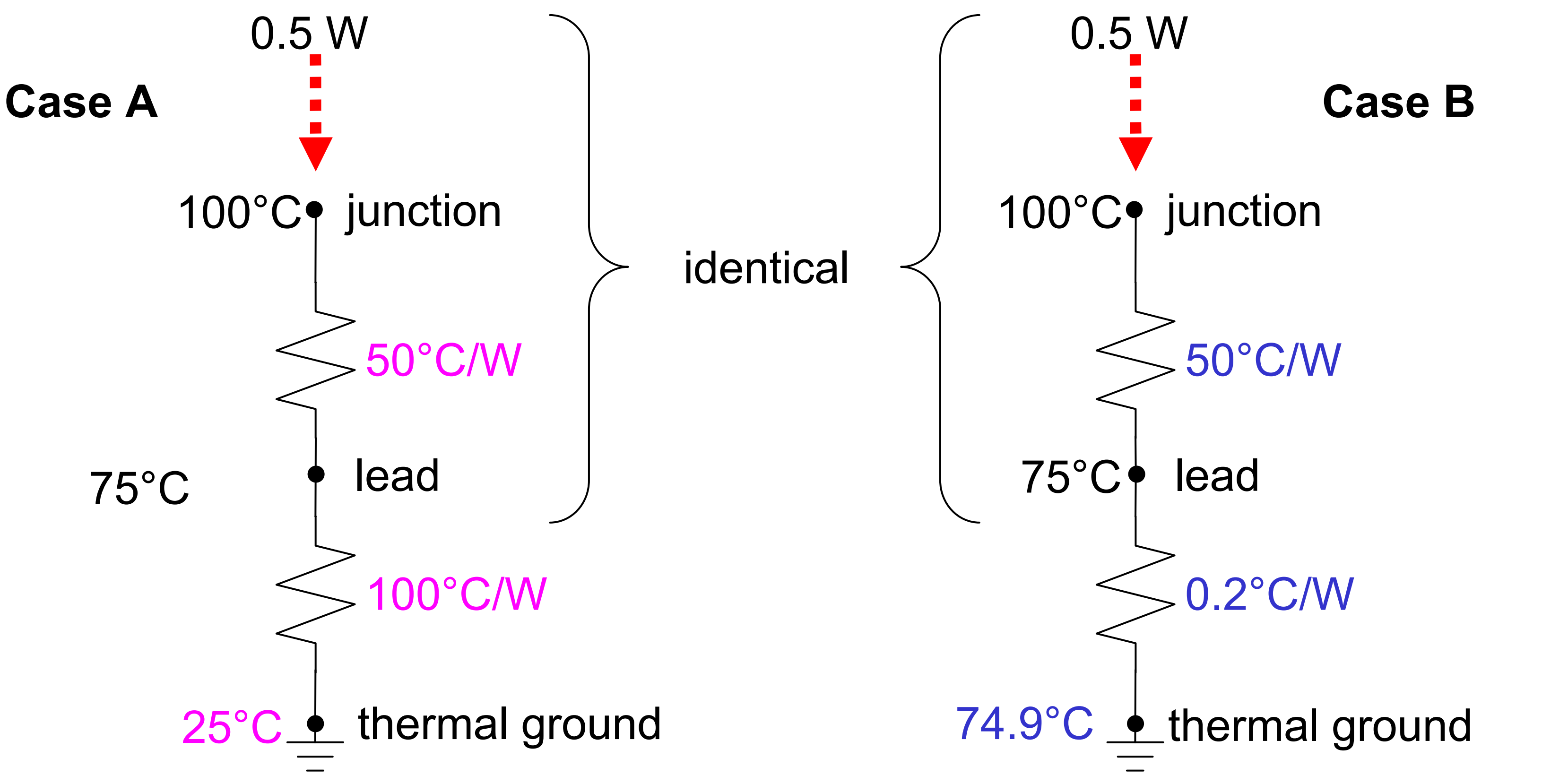
an unstable point at 116.3°C (0.69 W) ← $z = 2.315$

† MBRS140T3

How about the real thermal system?

- Is ambient really ambient?
- Is theta-JA what you think it is?

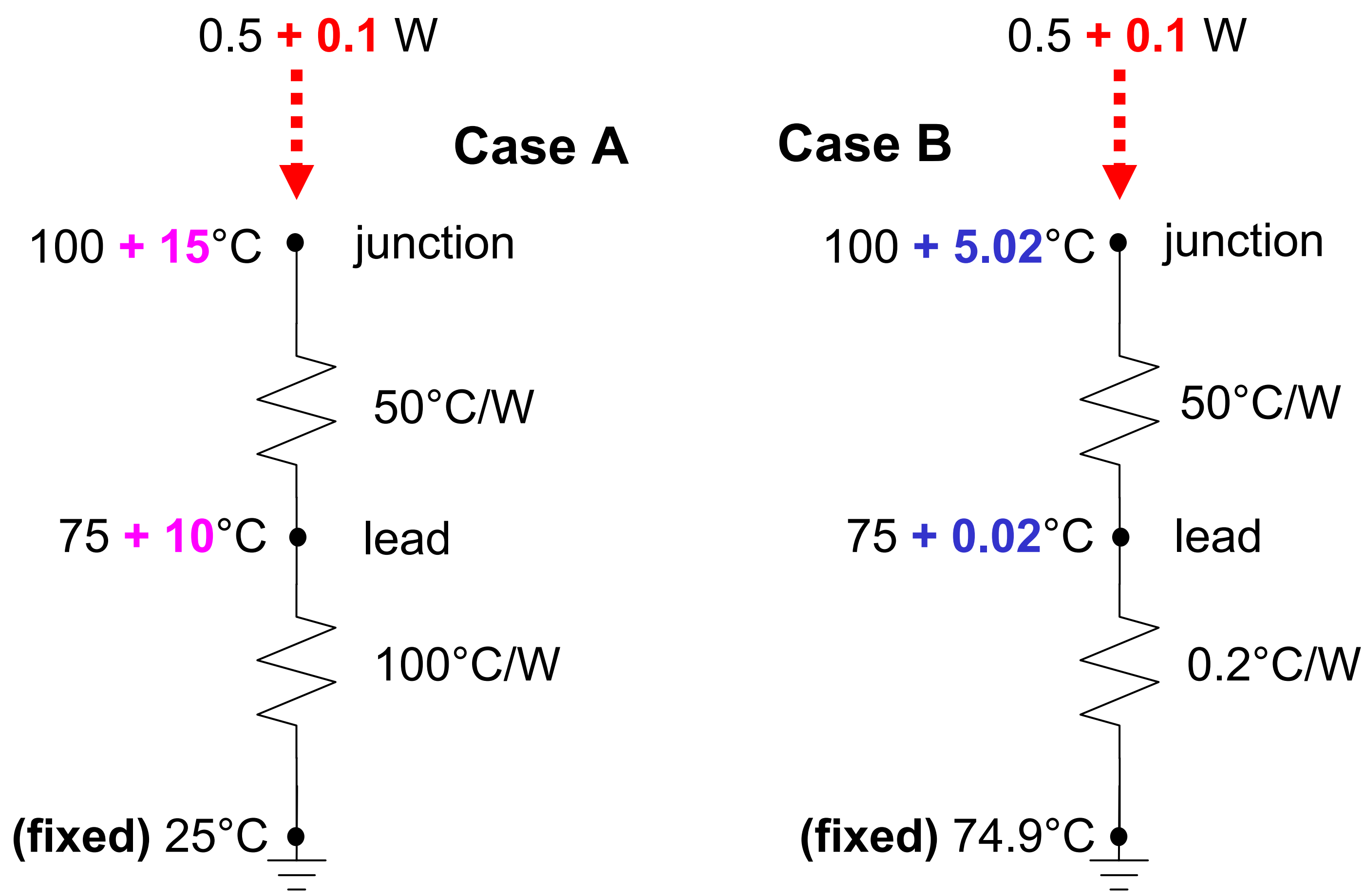
A paradox



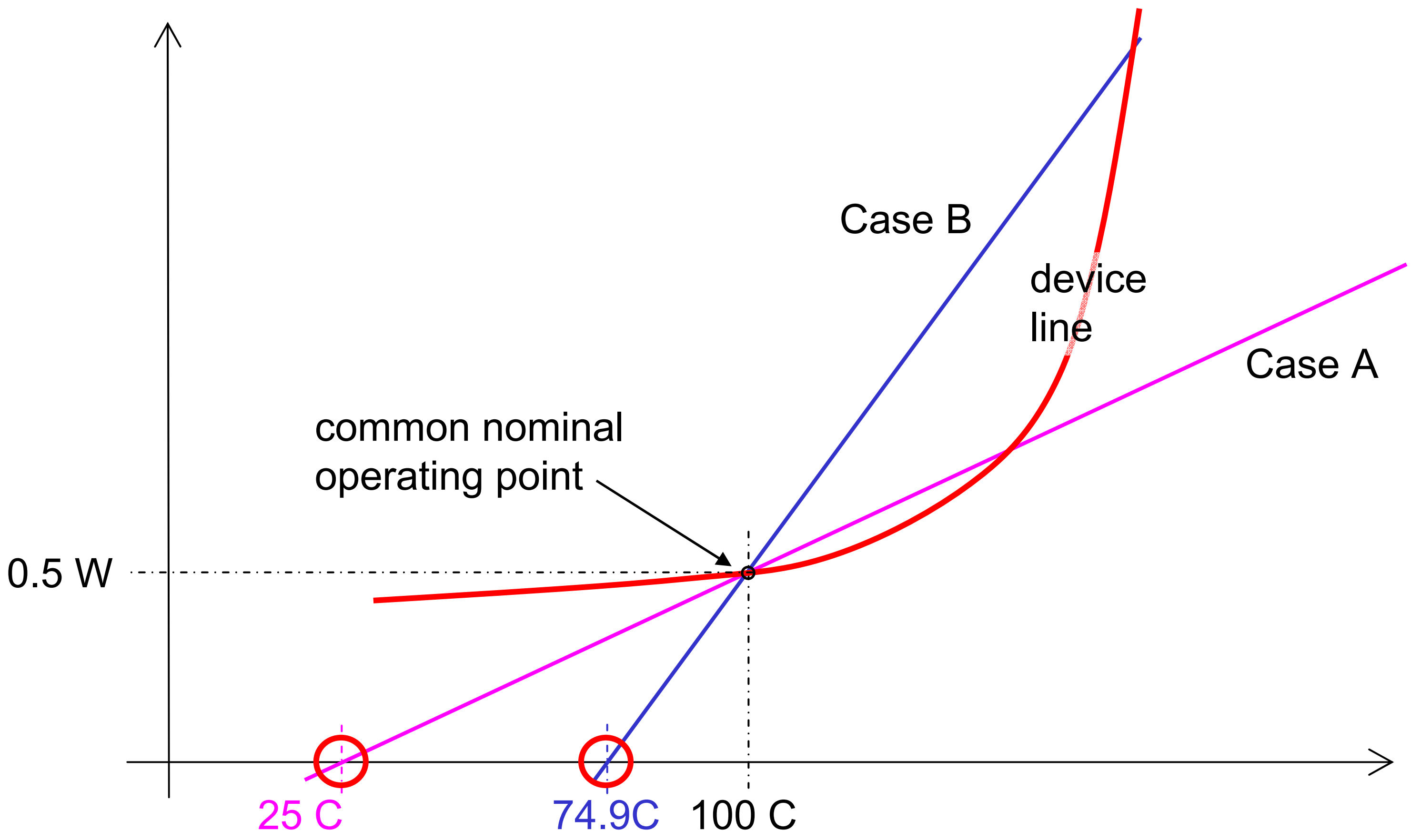
Case A	Case B
thermal runaway, based on θ_{Jx}=150°C/W, calculated to be at **125°C**	thermal runaway, based on θ_{Jx}=50.2°C/W, calculated to be at **150°C**

Paradox lost

raise the power by 0.1 W and see what happens

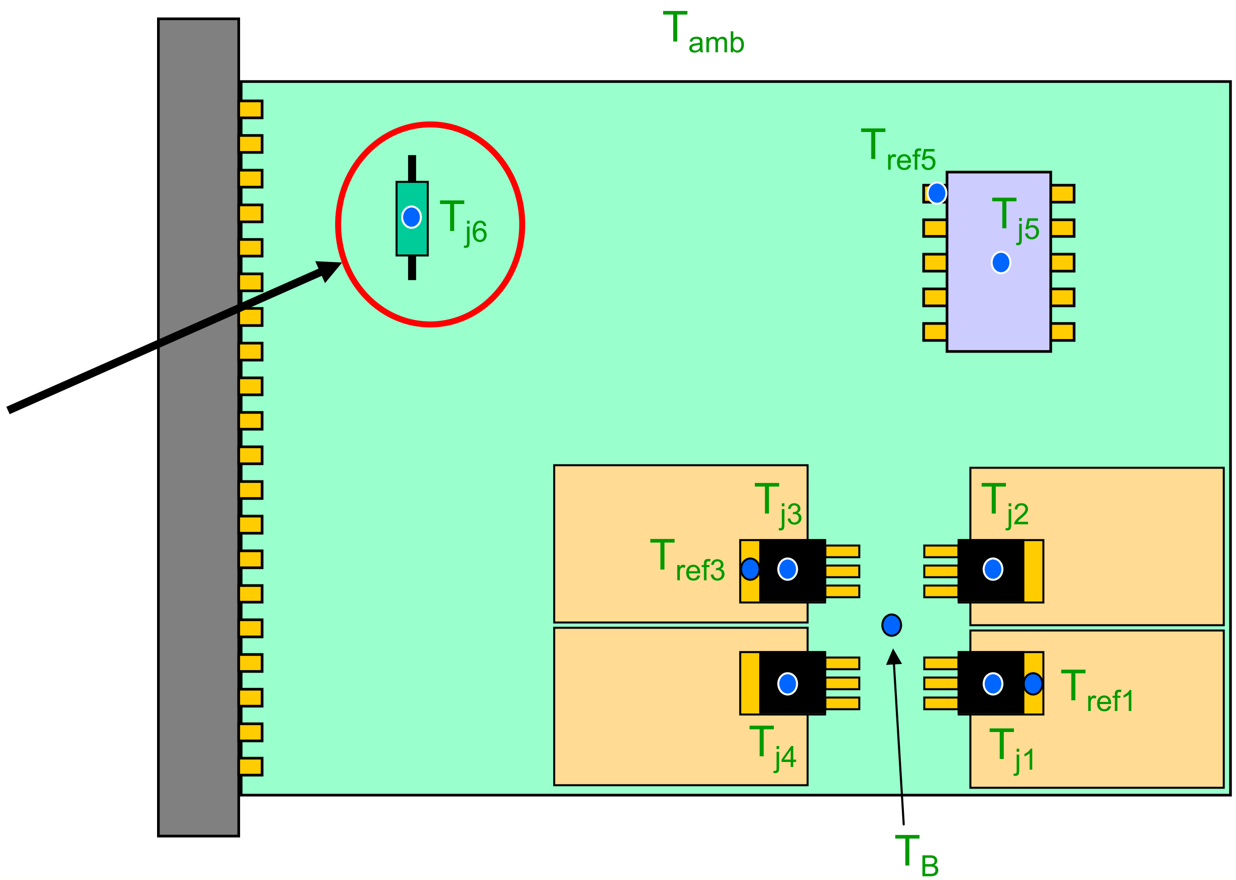


Illustrating the paradox



Consider the following 6-component example of a complete system, using linear superposition to describe the thermal behavior

This is the one we're interested in



Linear superposition math

matrix product

$$T_j = \boldsymbol{\theta} \cdot \mathbf{Q} + T_a$$

temperature (vector)

theta (matrix)

power (vector)

ambient (scalar)

Putting illustrative numbers on the problem:

theta array

J1	75	65	55	60	22	10
J2	65	71	60	55	25	11
J3	55	60	65	61	21	15
J4	60	55	61	73	18	11
J5	22	25	21	18	125	14
J6	10	11	15	11	14	180
R1	73	65	55	59	22	10
R3	55	60	63	61	21	15
R5	20	24	14	19	95	15
B	65	63	62	63	21	12

power vector

Q_{j1}	0.5
Q_{j2}	0.5
Q_{j3}	0.5
Q_{j4}	0.5
Q_{j5}	0.2
Q_{j6}	0.02

Observe the relative contributions

the other devices …

$$= (10 \times 0.5) + (11 \times 0.5) + (15 \times 0.5) + (11 \times 0.5) + (14 \times 0.2)$$

$$+ (180 \times 0.02)$$

the device itself …

$$+ 25$$

$$= 5.0 + 5.5 + 7.5 + 5.5 + 2.8 + 3.6 + 25$$

$$= 26.3 + 3.6 + 25$$

(ambient)

Symbolically, for just T_{j6}, we'd write this:

"system" slope

effective ambient

$$T_{j6} = \sum_{i=1}^{5}\left(\psi_{i6} \cdot Q_i\right) + \theta_{j6a} \cdot Q_6 + T_a$$

temperature of device #6

"interaction" terms from theta matrix (off-diagonal elements)

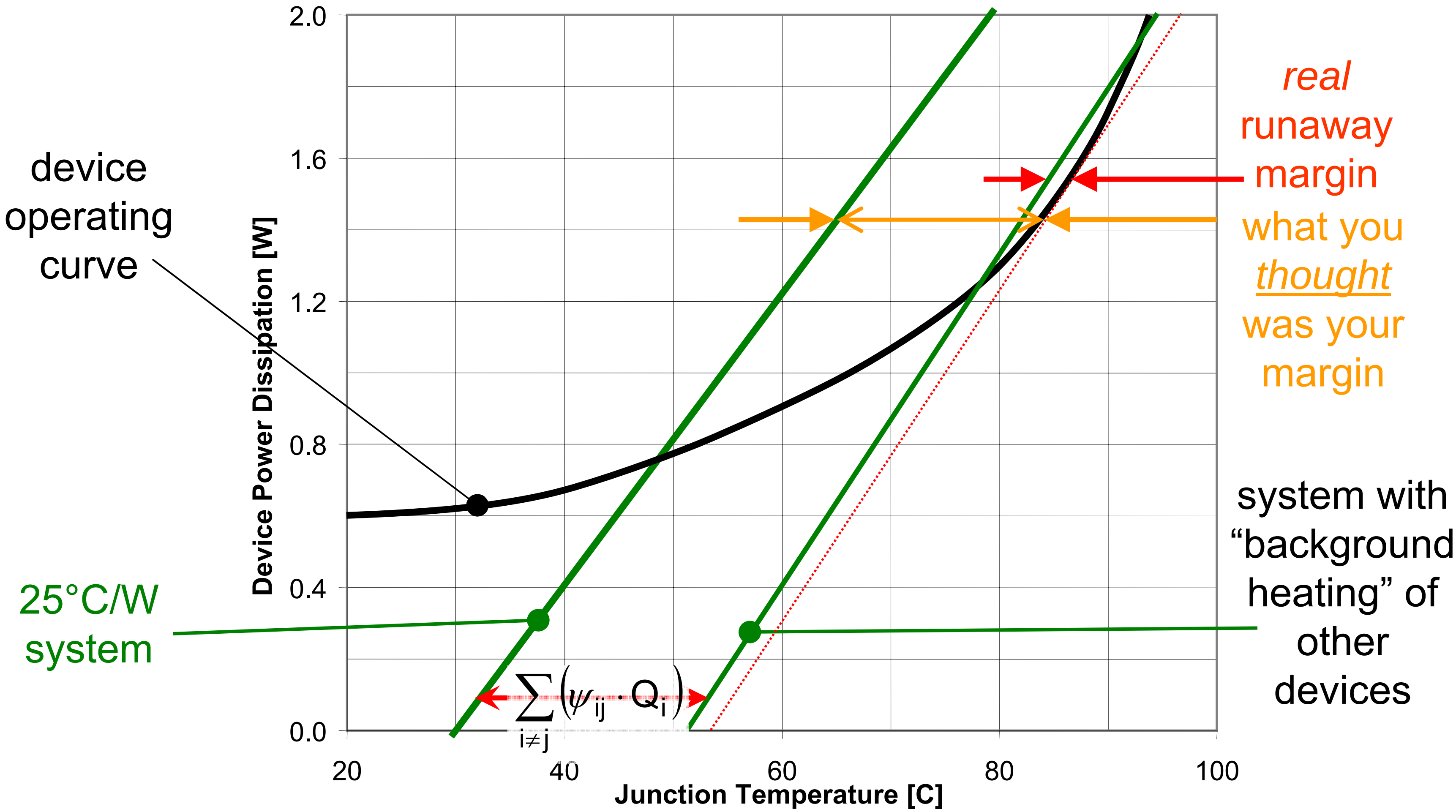
power of other devices

device #6 "self heating" term from theta matrix

power of device #6

ambient (scalar)

Graphically, it looks like this



How does *effective ambient* relate to board temperature?

"system" slope for isolated device

if any of *these* are non-zero, T'_a will be higher than T_a

$$T_{j6} = \theta_{j6a} \cdot Q_6 + \sum_{i=1}^{5} \left(\Psi_{i6} \cdot Q_i \right) + T_a$$

$$= \left(\theta_{j6B} + \theta_{B6a} \right) \cdot Q_6 + T'_a$$

effective ambient

$$= \theta_{j6B} \cdot Q_6 + \theta_{B6a} \cdot Q_6 +$$

$$= \Delta T_{j6B} + \Delta T_{B6a} +$$

temperature rise, board to J6

temperature rise, ambient to board

when Q_6 is zero, *not* both of these will be zero, both of these will be non-zero

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