IC Power Dissipation/Objectives

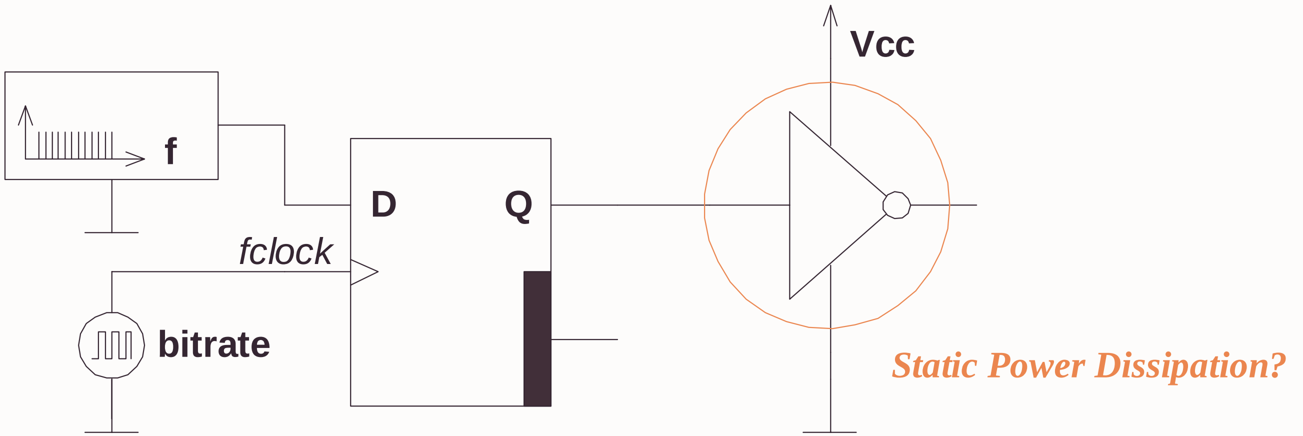
- Power Dissipation in Logic ICs
  - static and dynamic power dissipation
  - input power
  - internal power
  - drive power
  - output power
- Effective cycle frequency for bitstreams

IC Power Dissipation/General

- Power dissipation in a logic device is only indirectly related to the typical supply current specification on its data sheet (Pcc=Vcc*Icc)
- Datasheet specs often ignore additional power dissipation occuring at high speeds or high output loading
- Power dissipation categories of high-speed logic:
  - Input power
  - Internal dissipation
  - Drive circuit dissipation
  - Output power
- Each categorie has two sub-categories
  - static / quiescent (power used to hold a circuit in one logic state or the other)
  - dynamic (power used everytime a logic circuit changes state)

IC Power Dissipation/Static

- Static power dissipation
  - Power used to hold a circuit in one logic state or the other
  - Depending on situation use
    - » maximum (worst case) power dissipation
      Assumption that IC spends all its time in worst case state
    - » average power dissipation
      Assumption that IC spends equal time in either state
    - » weighted average power dissipation
      Useful if statistical information on states is available…

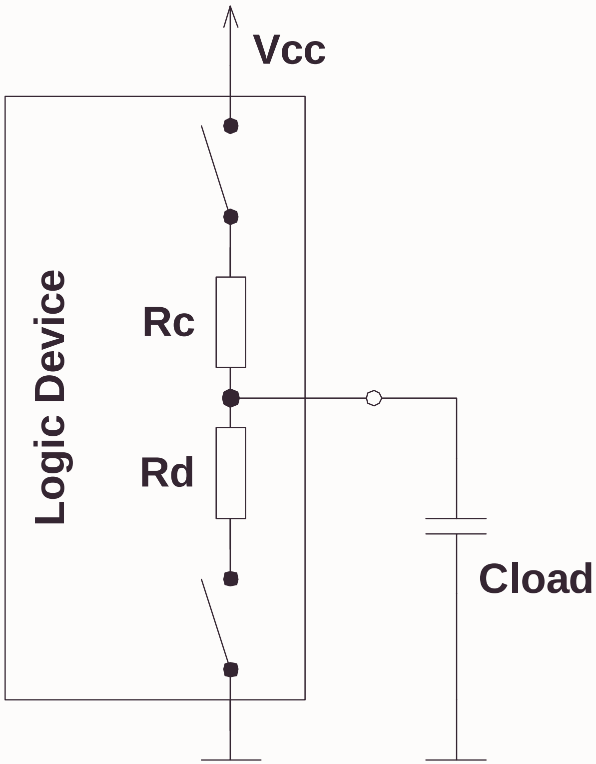


IC Power Dissipation/Dynamic

Charging/discharging capacitors: Energy budget and power dissipation considerations

Dissipated in Rc per cycle

$$E_{Rc_{charge}} = \frac{1}{2} C \cdot Vcc^2$$



Dissipated in Rd per cycle

$$E_{Rd_{discharge}} = \frac{1}{2} C \cdot Vcc^2$$

Note: Regardless of values of Rc and Rd !

Thermal energy in IC per cycle

$$E_{IC_{cycle}} = C \cdot Vcc^2$$

Average IC Power Dissipation

$$P_{diss} = E_{diss} \cdot f_{cycle} = C \cdot Vcc^2 \cdot f_{cycle}$$

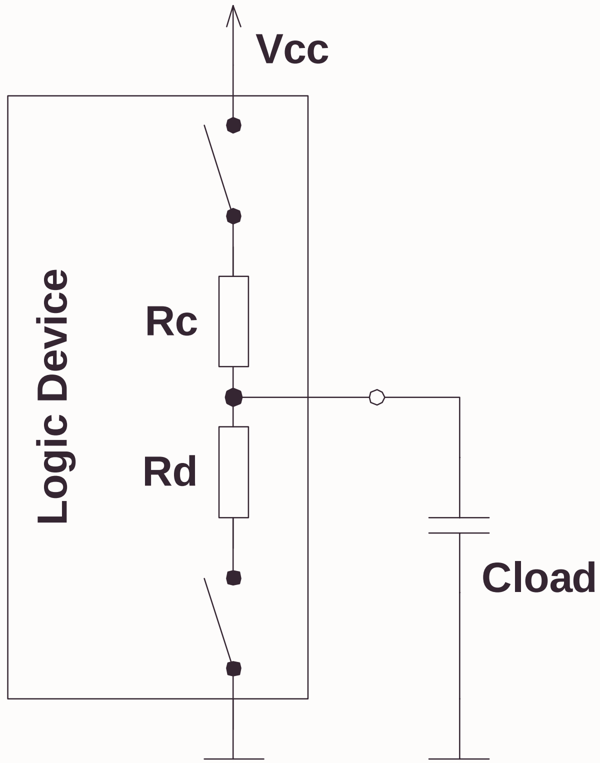
Equations valid only if

- Cload fully charged from 0V to Vcc
- Cload fully discharged from Vcc to 0V

IC Power Dissipation/Dynamic

Charging/discharging capacitors: Energy budget and power dissipation considerations

Watch out: Situation changes considerably if load capacitance is pre-charged…

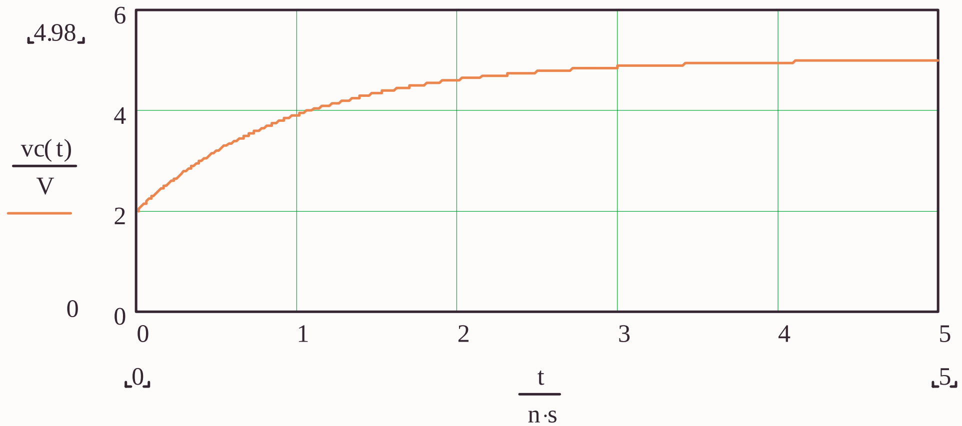


Dissipated in Rc per charge cycle

$$E_{Rc_{charge}} = \frac{1}{2} C \cdot \left(V_{end} - V_{start}\right)^2 = \frac{1}{2} C \cdot \Delta V^2$$

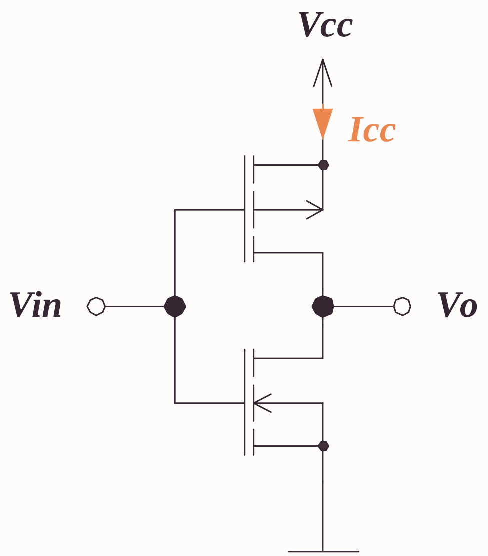
Energy transferred into Cload

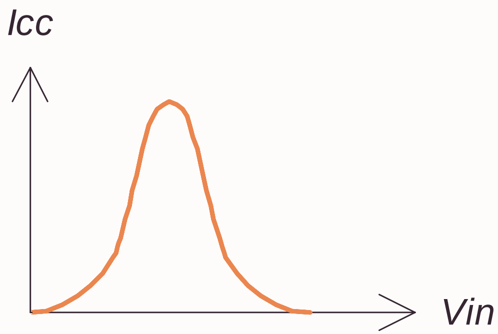
$$E_{Cload} = \frac{1}{2} C \cdot \left(V_{end}^{\ 2} - V_{start}^{\ 2}\right)$$



IC Power Dissipation/Dynamic/Cross-Conduction

- Cross-Conduction common for totem-pole output stages
- During input transitions high-side and low-side switch of totem-pole output conduct simultaneously
- Complex trade-off between speed, output impedance, supply voltage range, etc.
- Particularly pronounced in bipolar TTL (saturated low-side BJT)
- Adverse effect of slow rise and fall times





$$E_{cross-conduction} \propto Vcc$$

$$P_{cross-conduction} \propto \left(f_{cycle}, Vcc\right)$$

Modern logic devices featuring very low supply voltages can even suffer from static cross-conduction (significant sub-threshold conduction)

IC Power Dissipation/Dynamic

- Heat energy due to cross-conduction

$$E_{cross-conduction} \propto Vcc$$

- Heat energy due to charge/discharge of circuit capacitances

$$E_{capacitive} \propto Vcc^2$$

- Dependency of dynamic power dissipation

$$P_{dynamic} \propto \left(Vcc^{1..2}, f_{cycle}\right)$$

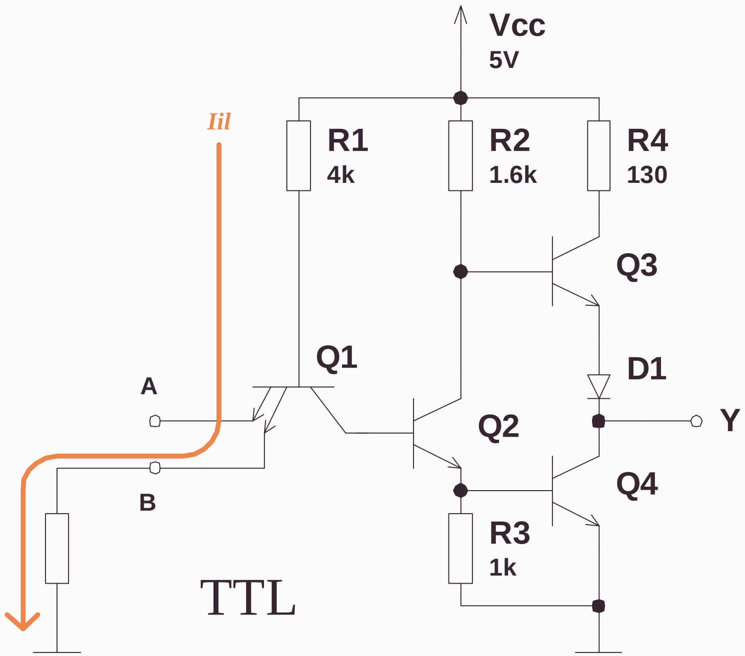
- more typically…

$$P_{dynamic} \propto \left(Vcc^{1.8}, f_{cycle}\right)$$

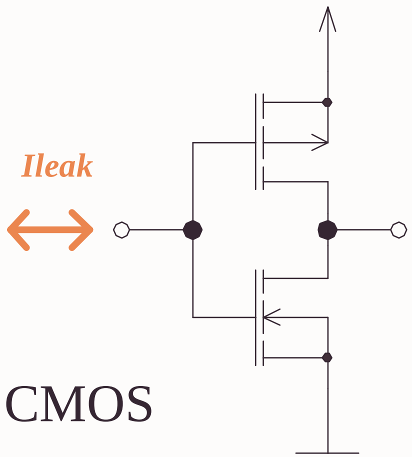
IC Power Dissipation/Input Power/Static

- Static Input Power
  - Required to bias and activate the input circuits
  - Often negligible (especially for CMOS)

Logic Family	I_{IH} (max)	I_{IL} (max)
74	40µA	-1.6mA
74LS	20µA	-0.4mA
74AS	20µA	-0.5mA
74ALS	20µA	-100µA
74F	20µA	-0.6mA
4000	±1µA	±1µA
74HC/HCT	±1µA	±1µA
74AC/ACT	±1µA	±1µA
74AHC/AHCT	±1µA	±1µA



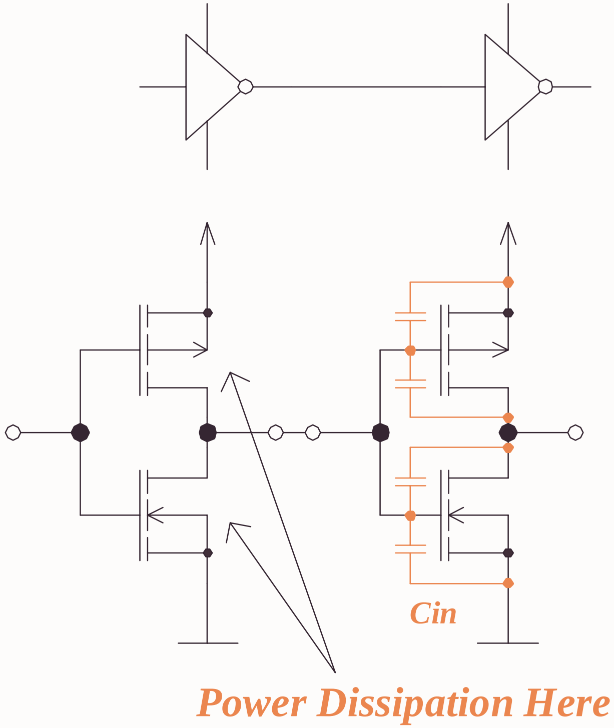
TTL



CMOS

IC Power Dissipation/Input Power/Dynamic

- Dynamic Input Power
  - Due to input capacitance
  - Causes only negligible power dissipation in input stage (i.e. causes power dissipation in output stage of driving circuit…)



Logic Family	C_{in} (typ)
74AS	3.0pF
ECL	3.0pF
4000	5pF
74HC/HCT	3.5pF
74AC/ACT	4.5pF
74LCX	7pF

IC Power Dissipation/Dissipation Constant

- Static and dynamic internal power dissipation
  - Used to bias and switch nodes internal to a logic device (static and dynamic)

Power dissipation constant

$$K_{dynamic} = \frac{P_{internal} - P_{static}}{f_{cycle}}$$

$$\{K_{dynamic}\} = W/Hz$$

- Knowning the power dissipation constant, the total internal power dissipation for an arbitrary operating frequency can be approximated
- Does not include extra energy dissipated in the driver caused by a connected load!

$$P_{internal} = P_{static} + K_{dynamic} \cdot f_{cycle}$$

IC Power Dissipation/Dissipation Constant

- Static and dynamic internal power dissipation
- Some CMOS circuits operate over a wide range of supply voltages. Many datasheets therefore rate their power dissipation in terms of an equivalent capacitance C_{PD}

$$P_{internal} = P_{static} + C_{PD} \cdot Vcc^2 \cdot f_{cycle} \qquad \{C_{PD}\} = \frac{As}{V}$$

-

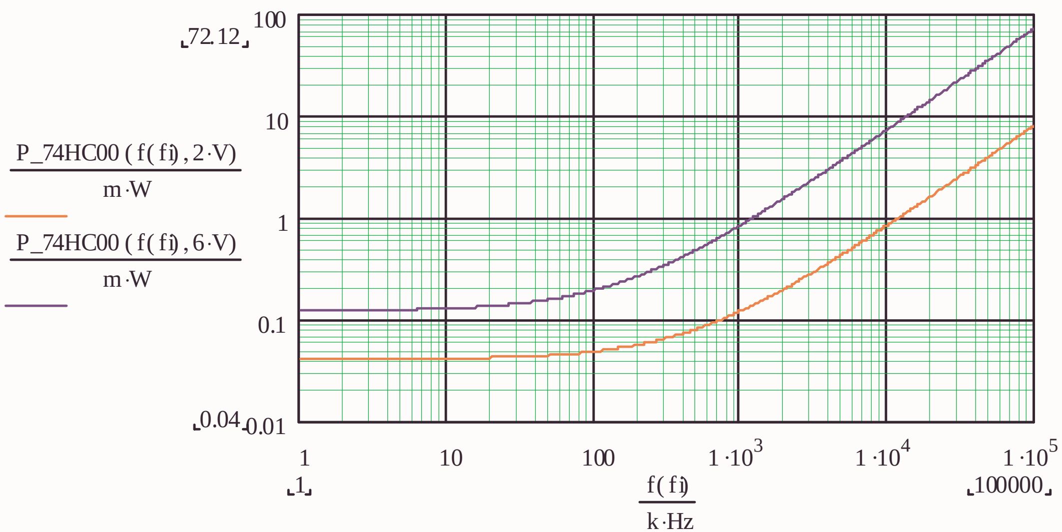
Example Parameter:

•Fairchild 74HC00

•Icc=20µA (static)

•Vcc=2V..6V

•C_{PD}=20pF

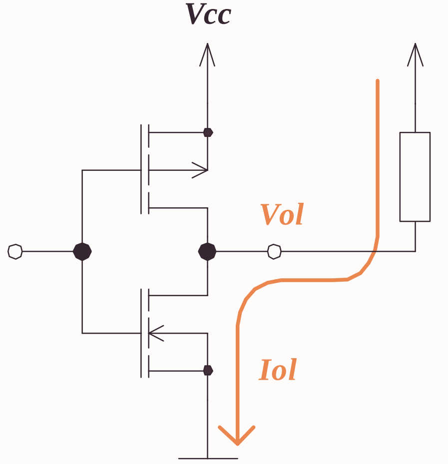


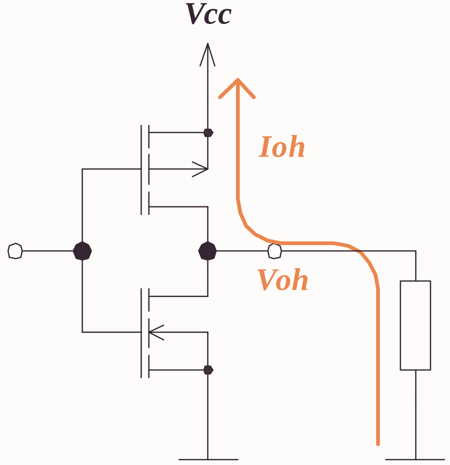
IC Power Dissipation/Driver Power/Static

- Static driver power dissipation
  - Power dissipation due to load (sink or source) current and the residual voltage across the conducting switch

$$P_{driver_{low}} = V_{ol} \cdot I_{ol}$$

$$P_{driver_{high}} = (Vcc - V_{oh}) \cdot |I_{oh}|$$





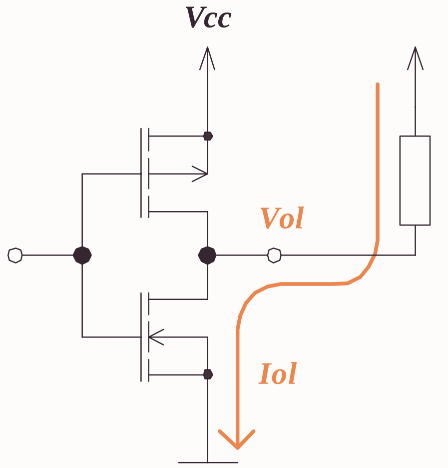
IC Power Dissipation/Driver Power/Static

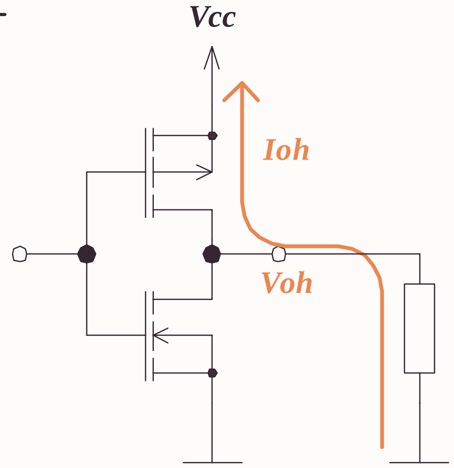
- Equivalent driver output impedances and maximum high/low state output currents

Logic Family	I_{OH} (max)	I_{OL} (max)
74	-0.4mA	16mA
74LS	-0.4mA	8mA
74AS	-2mA	20mA
74ALS	-0.4mA	8mA
74F	-1mA	20mA
4000	-0.4mA	0.4mA
74HC/HCT	-4mA	4mA
74AC/ACT	-24mA	24mA
74AHC/AHCT	-8mA	8mA

$$R_{driver_{low}} = \frac{|V_{ol}|}{|I_{ol}|}$$

$$R_{driver_{high}} = \frac{|Vcc - V_{oh}|}{|I_{oh}|}$$

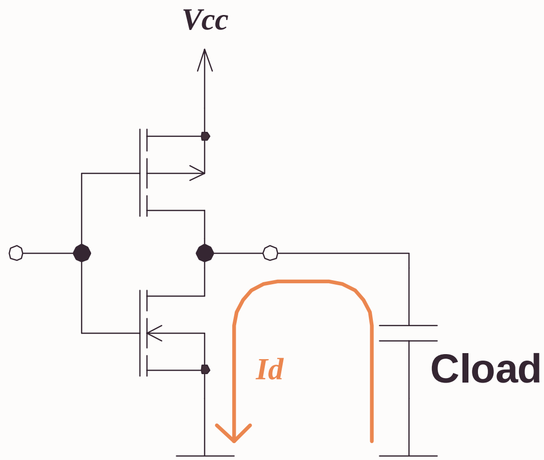


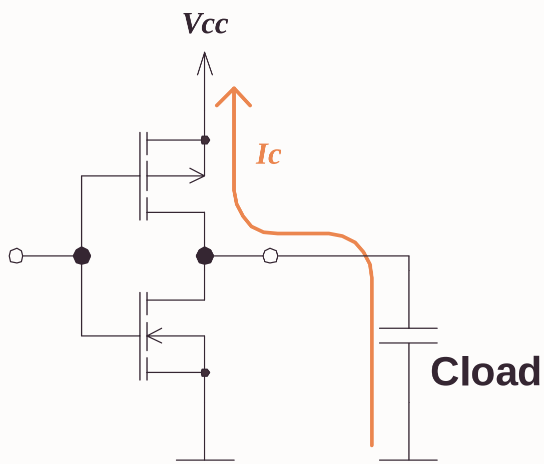


IC Power Dissipation/Driver Power/Dynamic

- Dynamic driver power dissipation due to
  - charge/discharge of load capacitances

$$P_{driver_{dyn}} = C_{load} \cdot Vcc^2 \cdot f_{cycle}$$

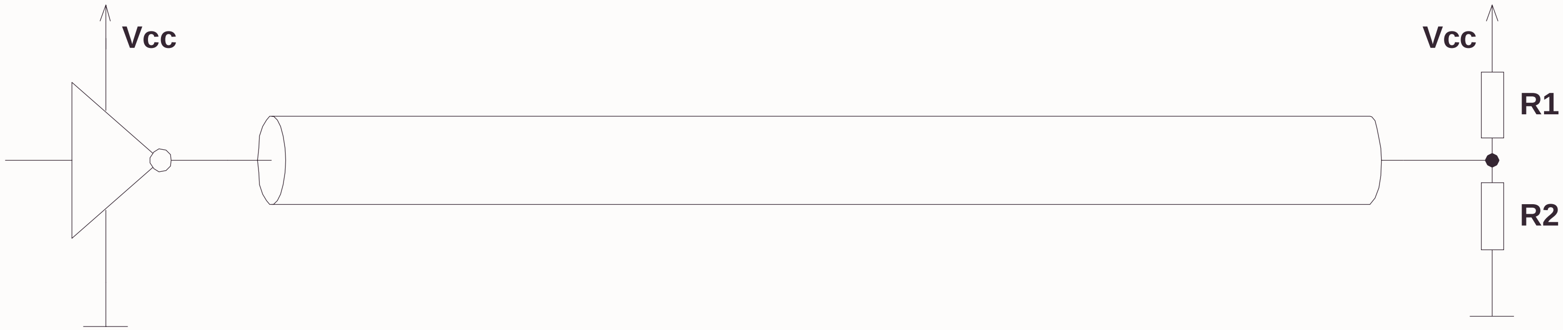




C_{load} is typically the sum of input capacitances of gates driven by the output.

IC Power Dissipation/Output Power

- Output power dissipation
  - mainly in termination resistors

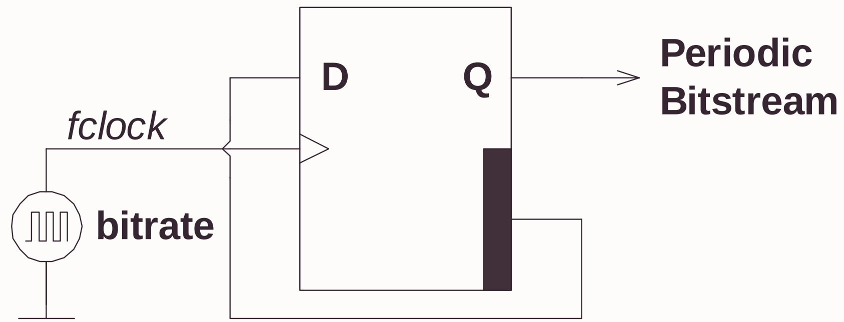


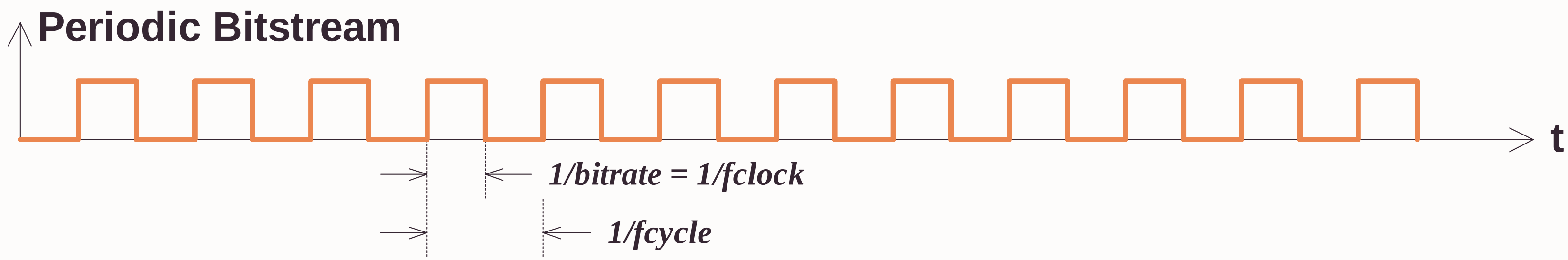
$$P_{R1_{worstcase}} = \frac{Vcc^2}{R1} \qquad P_{R1_{average}} = \frac{1}{2}\frac{Vcc^2}{R1} \qquad P_{R1_{average}} \neq \frac{\left(Vcc/2\right)^2}{R1}$$

Don’t under-estimate power dissipation in termination resistors! Use termination resistor types which can handle the power. Consider worst case conditions for each resistor.

Bitstreams/Effective Cycle Frequency/Max

- Worst case cycle frequency of bitstreams
  - Regular pattern
  - One transition per bit



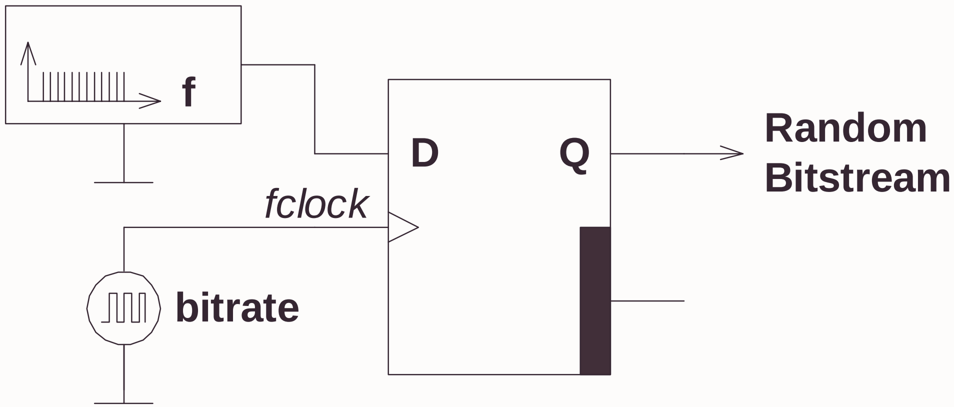


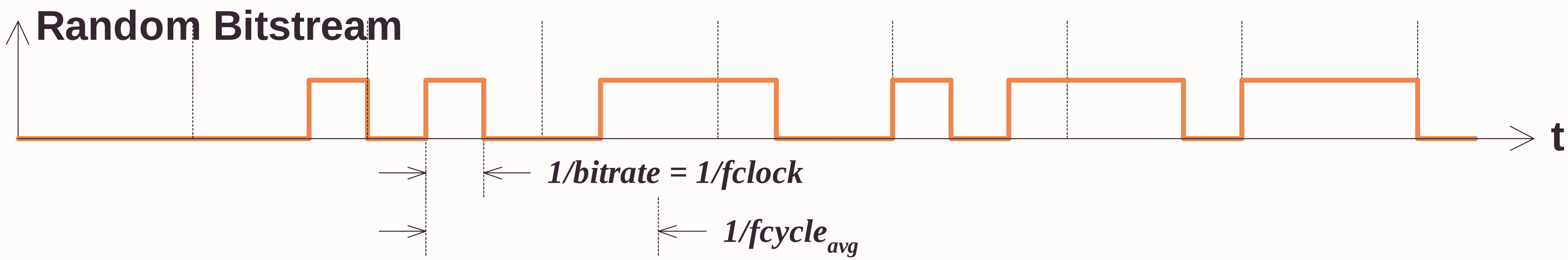
$$f_{cycle} = \frac{bitrate}{2} = \frac{fclock}{2}$$

It takes two transitions (i.e. 2 bits) to complete a cycle !

Bitstreams/Effective Cycle Frequency/Average

- Average cycle frequency of a random bitstreams
  - Random pattern
  - 0.5 transitions per bit (statistically)

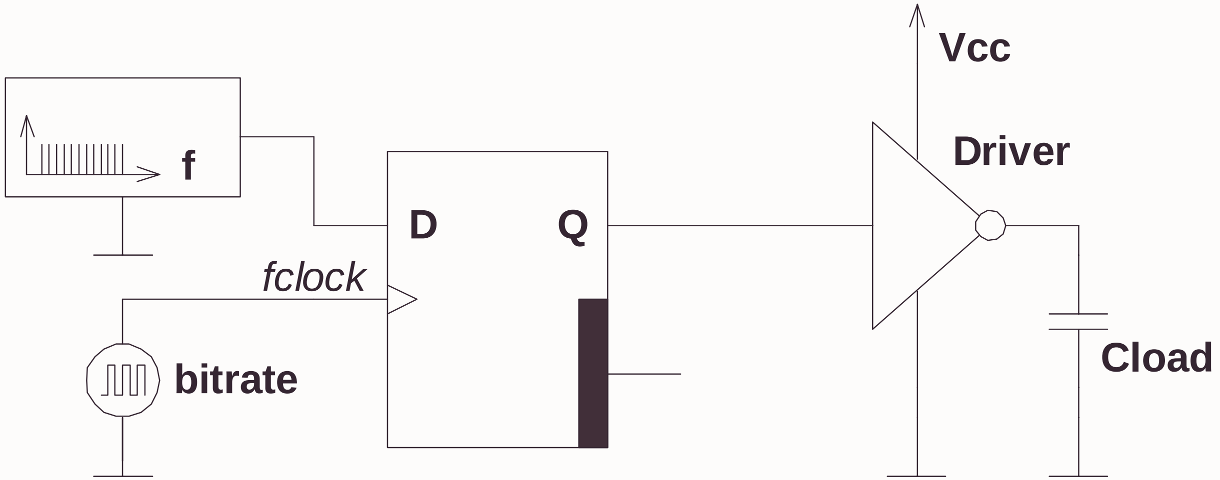




$$f_{cycle_{avg}} = \frac{bitrate}{4} = \frac{fclock}{4}$$

It takes two transitions to complete a cycle ! On average it will take 4 clock periods to complete a cycle.

IC Power Dissipation/Driver Power



Worst case and average drive power dissipation:

Worst case $$P_{diss\,wc} = \frac{1}{2} Cload \cdot Vcc^2 \cdot bitrate$$

Average $$P_{diss\,avg} = \frac{1}{4} Cload \cdot Vcc^2 \cdot bitrate$$

Thermals/Objectives

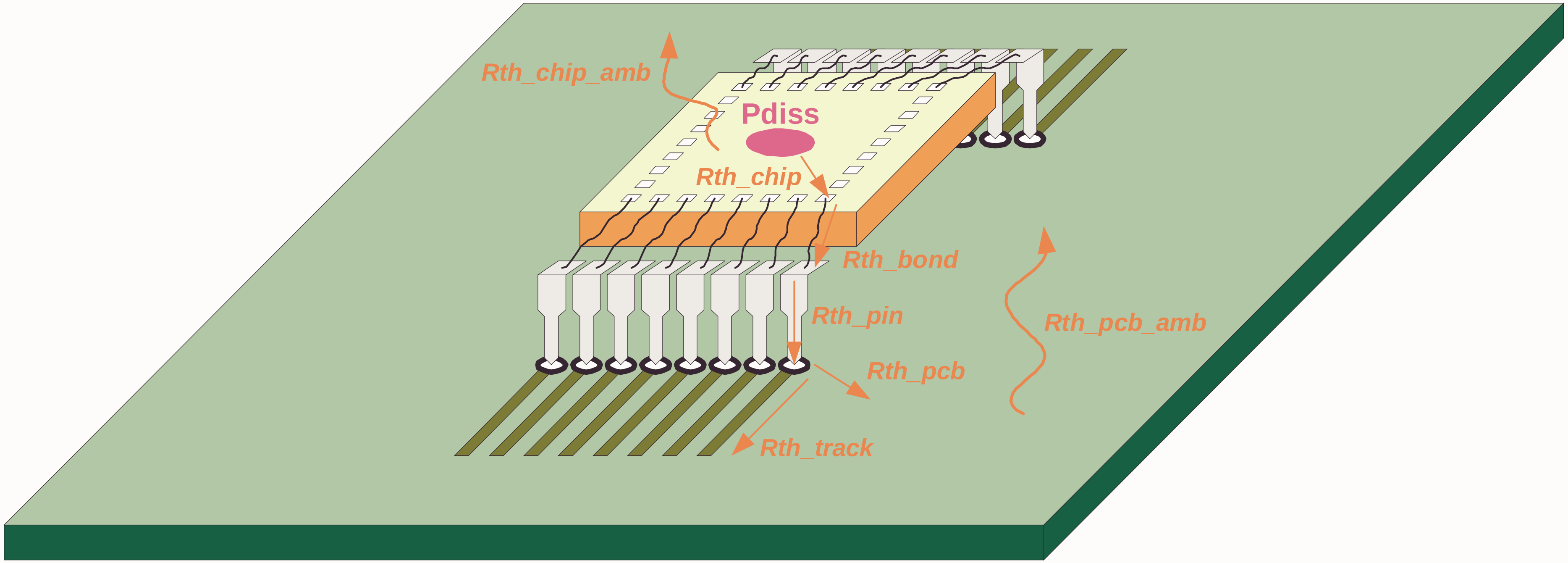
- Thermal Basics
  - Modes of heat transfer
  - Thermal modelling
- IC Packaging
  - Categories (PTH, SMT)
  - Materials
  - Electrical package modelling
- Measurement Techniques
  - Scopes and scope probes

Thermals/Basics

- Exponential relationship between temperature of a device and its failure rate
- MTBF: Mean Time Between Failures
- Modes of heat transfer
  - Conduction
    Transfer through solid material
  - Convection
    Transfer through a medium of fluid (air for our purposes)
  - Radiation
    Transfer of heat through EM waves

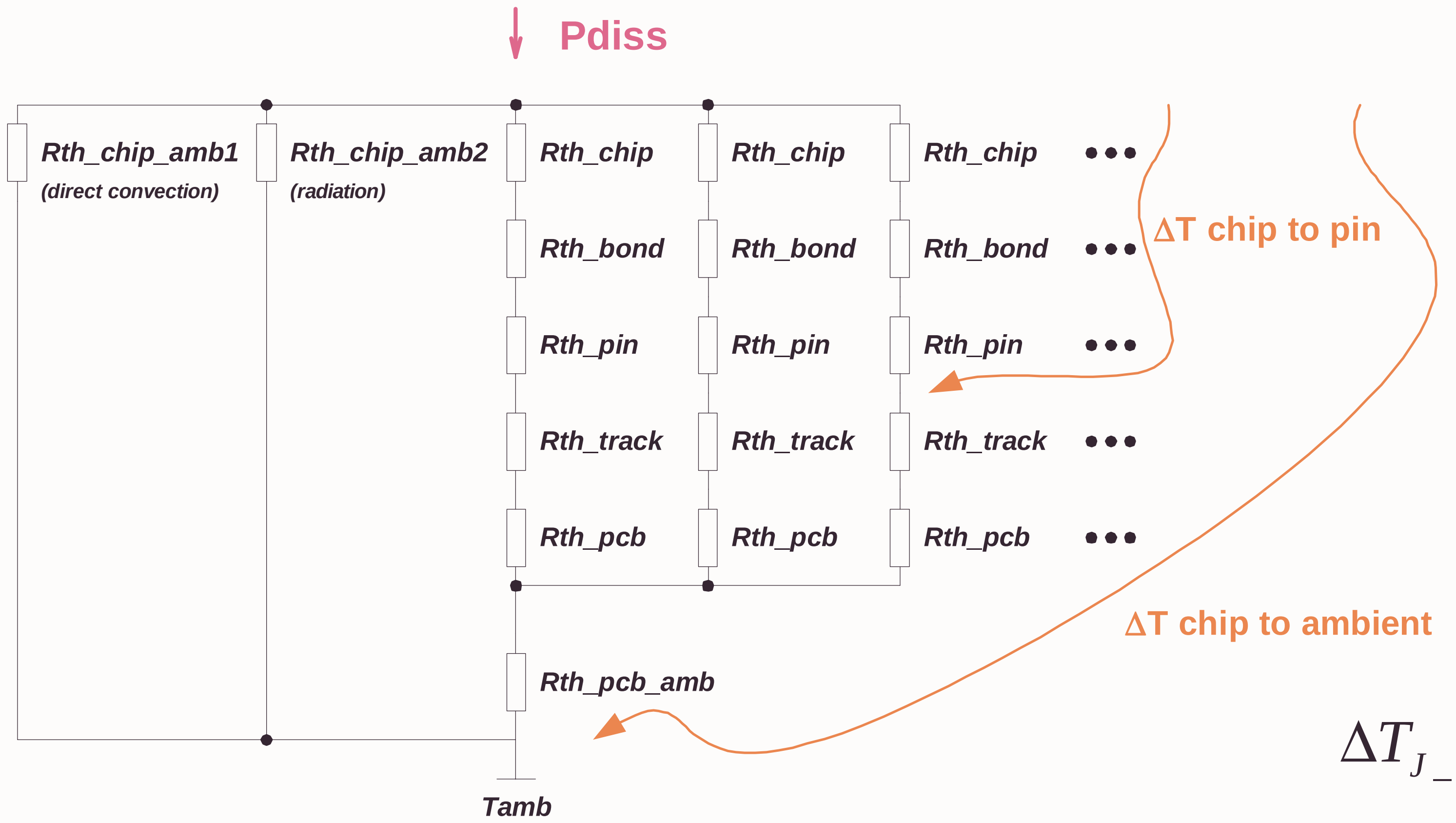
Arrhenius Law for chemical processes near room temperature:
Failure rate of devices approx. doubles with every 10°C increase in its temperature…

Thermals/IC Thermal Paths Junction-Ambient



Thermal arrangement:
Often complex pathes from heat source (e.g. power dissipation on an IC) to heat sink (e.g. ambient).

Thermals/IC Thermal Paths Junction-Ambient



$$\Delta T_{J\_Pin} = P_{diss} \cdot Rth_{J\_Pin}$$

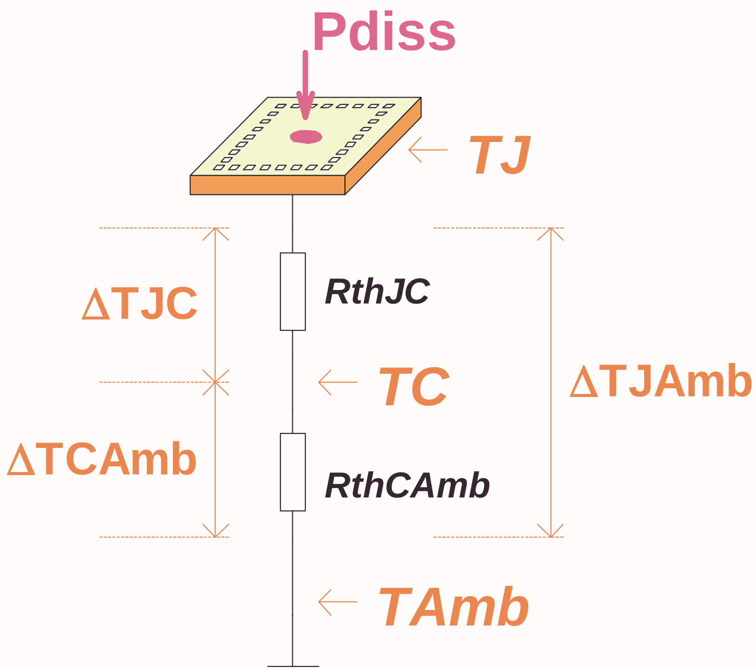
$$\Delta T_{J\_Amb} = P_{diss} \cdot Rth_{J\_Amb}$$

Complex thermal networks

Identification of significant thermal paths is difficult. Quantification of thermal resistances even more so. For proper analysis: Use appropriate SW tools (Thermal FEM Tools, e.g. Flotherm).

Thermals/IC Thermal Paths Junction-Ambient

- Highly simplified
  - but often adequate for estimating the junction temperature
  - Thermal resistances RthJC and/or RthJAmb specified in most IC datasheets



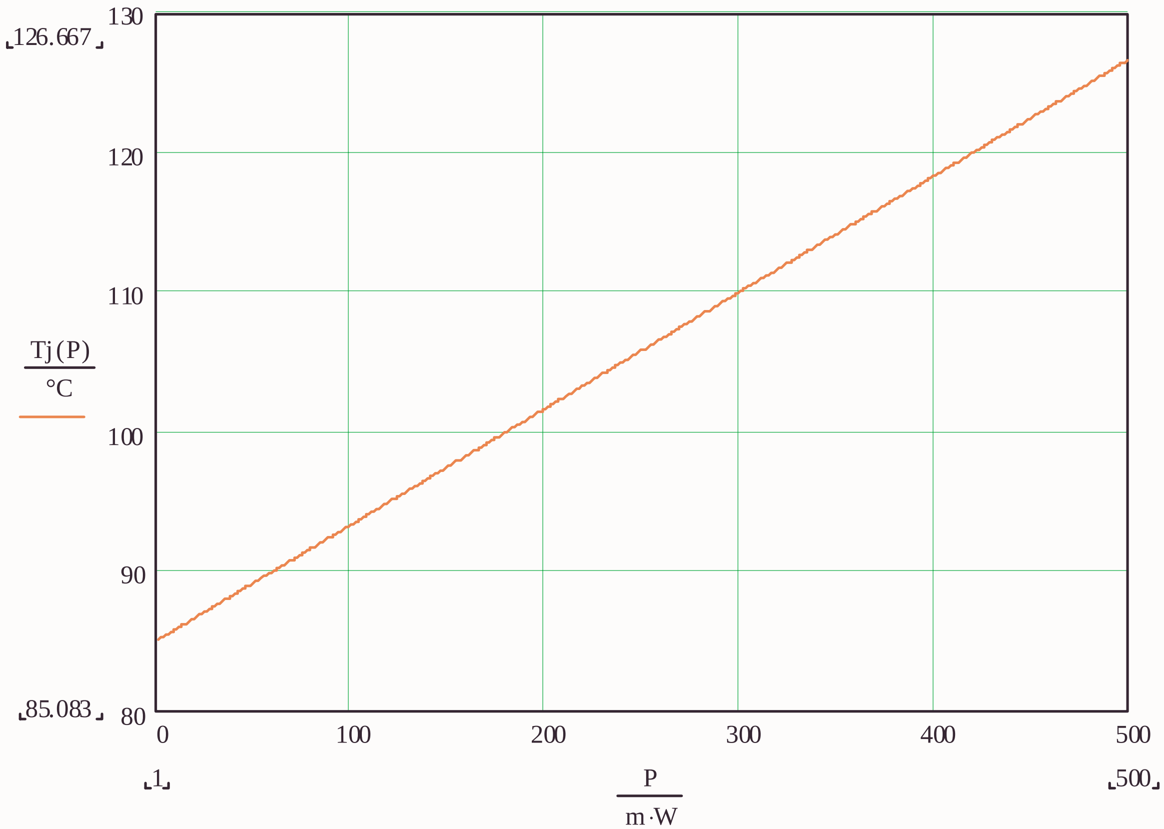
$$T_J = T_C + P_{diss} \cdot Rth_{JC}$$

$$T_J = T_{amb} + P_{diss} \cdot \left(Rth_{JC} + Rth_{CAmb} \right)$$

Thermals/IC Thermal Paths Junction-Ambient

Example Parameter:

- Fairchild 74HC00
- RthJA=83.3K/W (still air)
- Tambmax=85°C
- Pdmax=500mW (SO14)

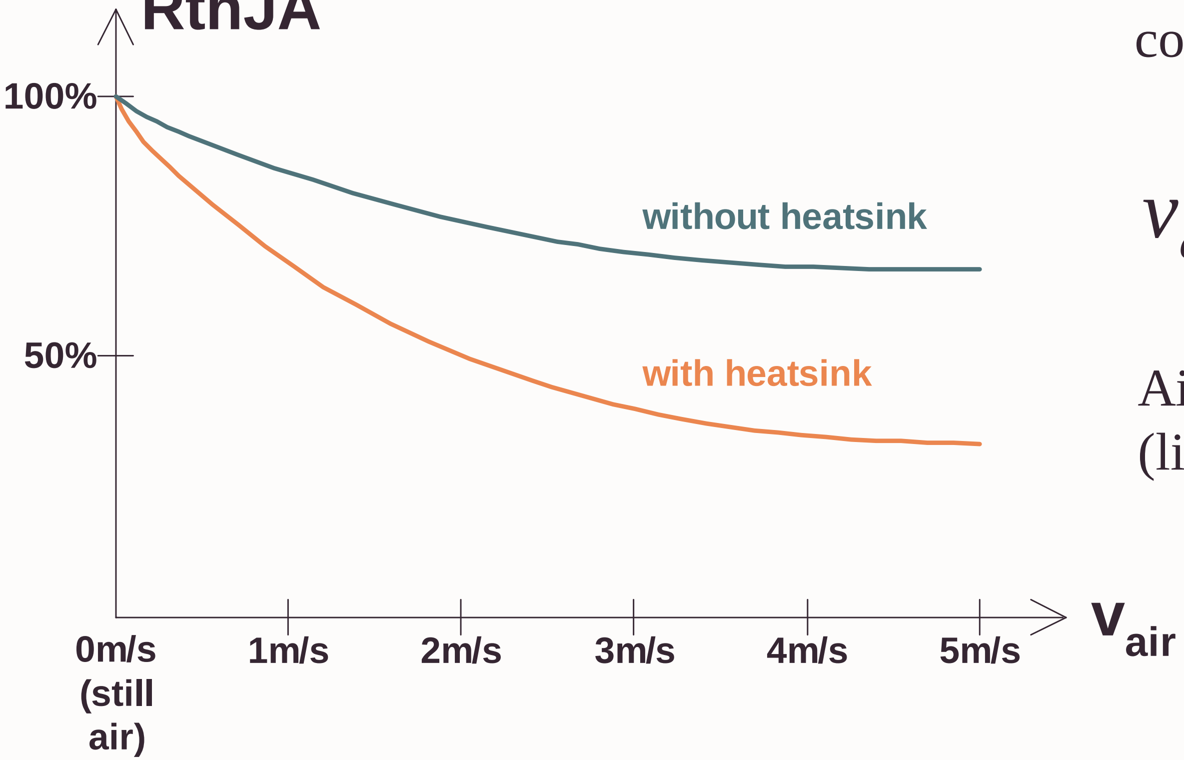


$$T_J = T_{amb} + P_{diss} \cdot \left(Rth_{JC} + Rth_{CAmb}\right)$$

Thermals/IC Thermal Paths Junction-Ambient

Forced Air Convection:

Typical behavior thermal resistance versus air velocity in forced air convection:



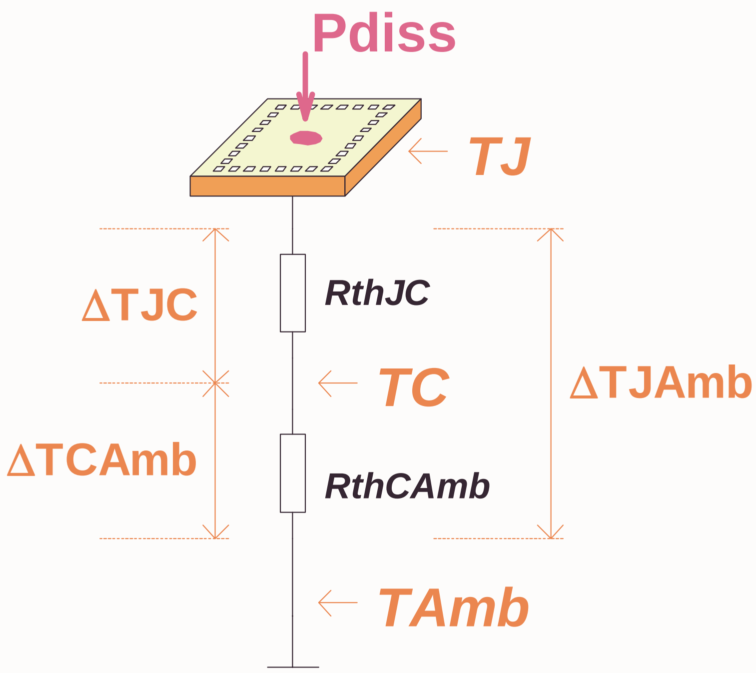
In a typical system with forced air convection:

$$v_{air} = 0.5\frac{m}{s}..2\frac{m}{s}$$

Air velocity often quoted in LFPM (linear feet per minute)…

$$100\ LFPM \approx 0.5\frac{m}{s}$$

Thermals/IC Thermal Paths Junction-Ambient



- Watch Out!
  - Definition of ambient temperature Tamb can be ambiguous (ambient temperature of a system vs local ambient of an electronic sub-assembly)
  - IC manufacturers tend to specify RthJAmb. Read the small-print! RthJAmb is often specified using unrealistically large copper areas around the IC
  - Always: Verify your thermal predictions through thermal measurements!
    - » IR camera
    - » no-contact Laser thermometer
    - » thermo-couples