Australian National University

You can't conquer

Physical Integration and Power Considerations

with a shoddy olive.

Hitler found that out.

ENGN8537

Embedded Systems

Overview

- Power in Embedded Systems
- Level translation
- Decoupling
- Manufacturability

Power

There are different voltage standards used in Embedded Systems.

Power = Voltage x Current

Increasing the voltage means you need less current and therefore smaller wires, connectors and so on.

This is the reason mains power is transmitted at 100s of kV on the main lines then reduced at substations and on-pole transformers

Power

12 Volts

A large Embedded System will draw on the order of 12W so a 12V input will draw around 1A.

12V is rarely used itself, it’s most often regulated down to a more manageable voltage like 5V or 3.3V.

12V is significant because it’s the programming voltage of EPROM devices

Power

5 Volts

TTL: Transistor Transistor Level

Common voltage for older logic devices and automotive parts that have to be relatively noise-immune.

Power

3.3 Volts

LVTTL: Low Voltage Transistor Transistor Level

Most modern logic devices. Roughly the minimum voltage at which flash memory can be programmed.

Power

~1 Volt

The core voltage of most modern CPUs is kept very low in order to minimise power usage.

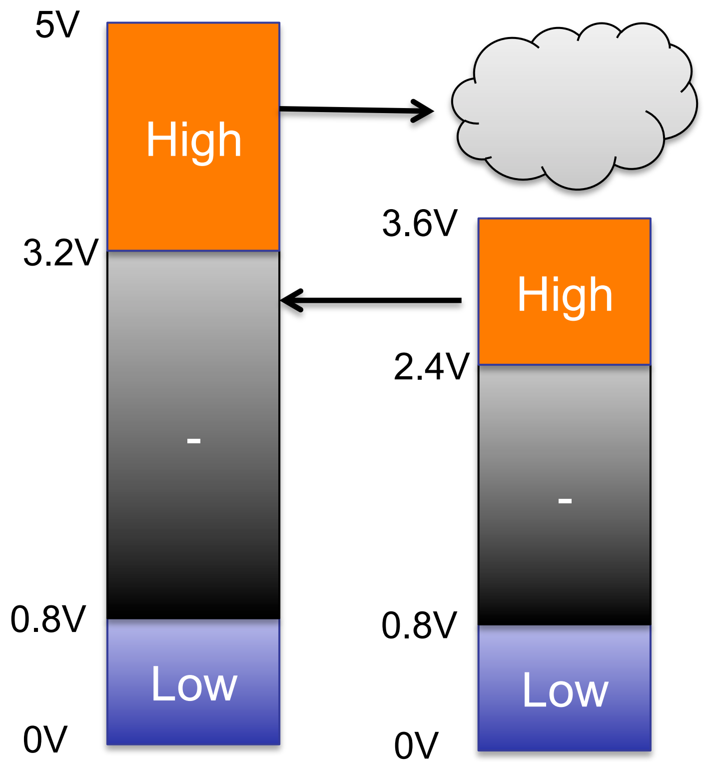
Power

Many voltages in a system brings many potential issues:

- Level translation
- Power rail ordering
- Conversion losses

Power

Level Translation

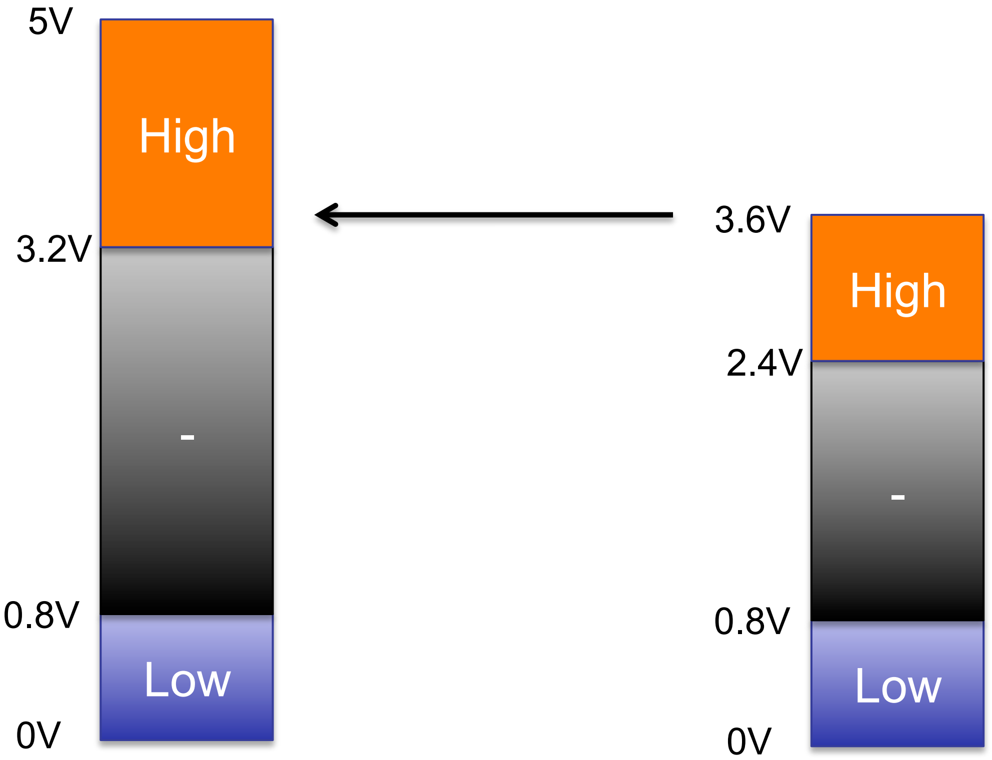


Power

Level Translation

Unidirectional, low to high

Check your data sheet, but often a high voltage output from LVTTL will just trigger a 5V high signal



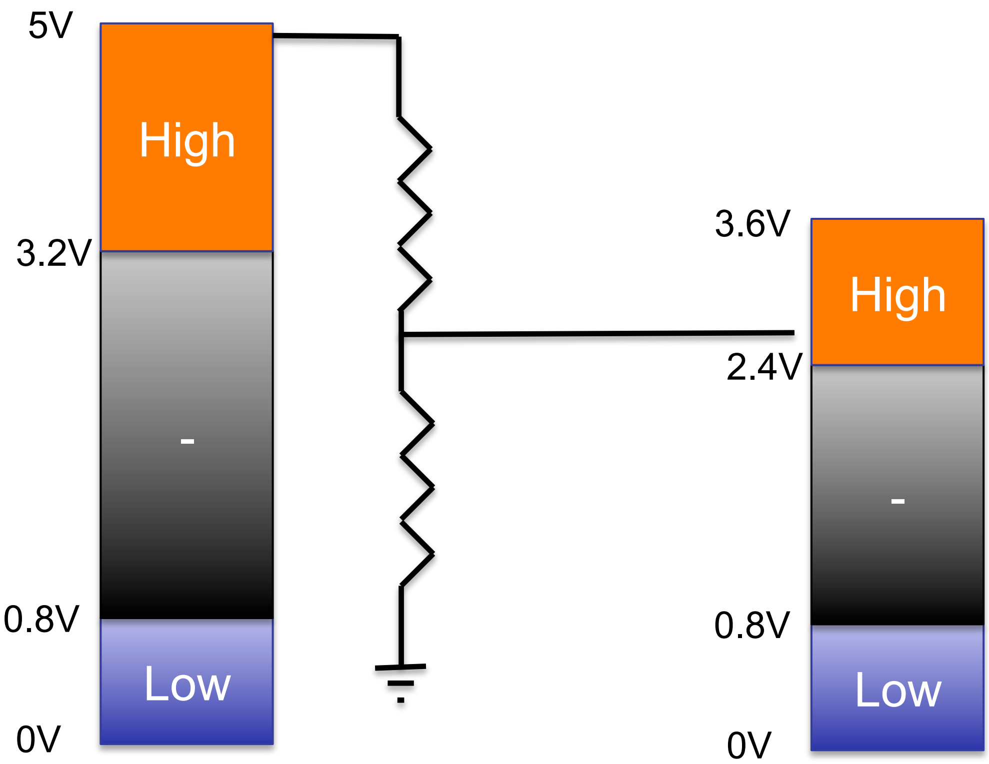
Power

Level Translation

Unidirectional, high to low

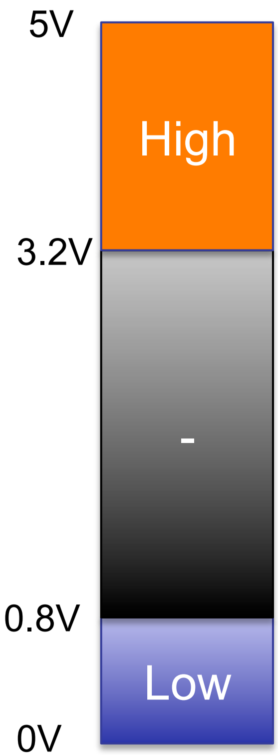
Very simple, use a resistive divider.

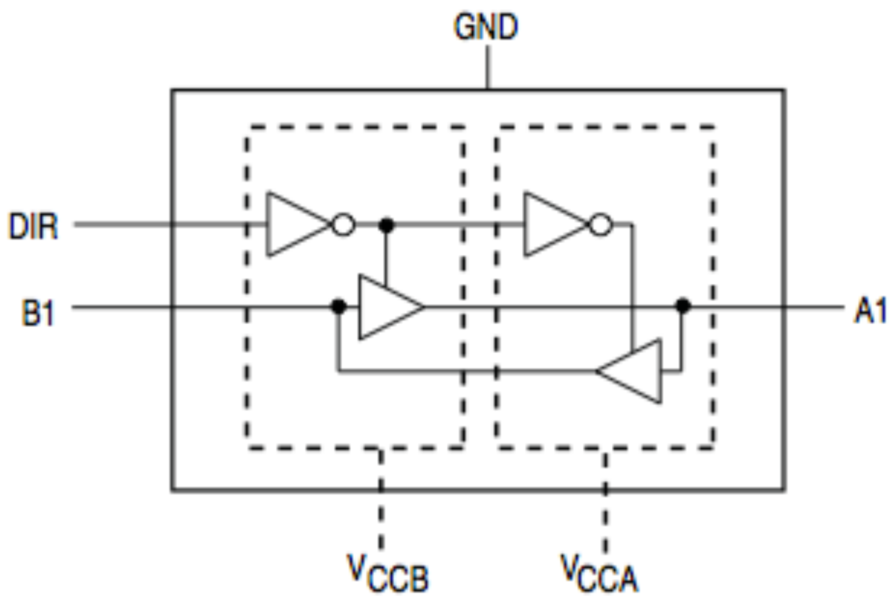
Works for slowly changing signals only, the resistors form an RC network with the stray capacitance around the board.



Power

Level Translation





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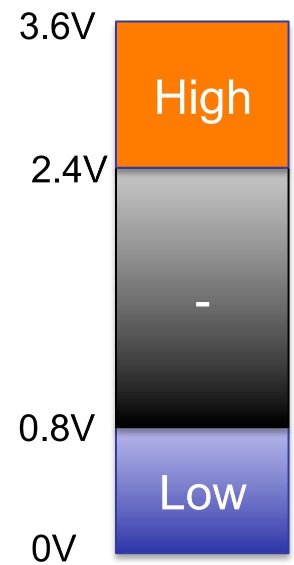
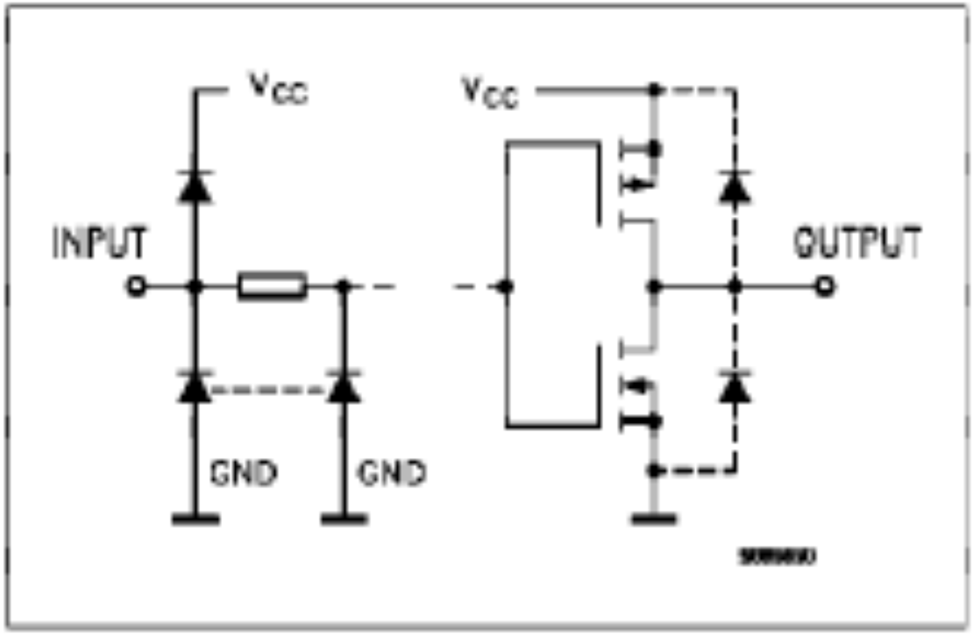


Power

Power Supply Sequencing

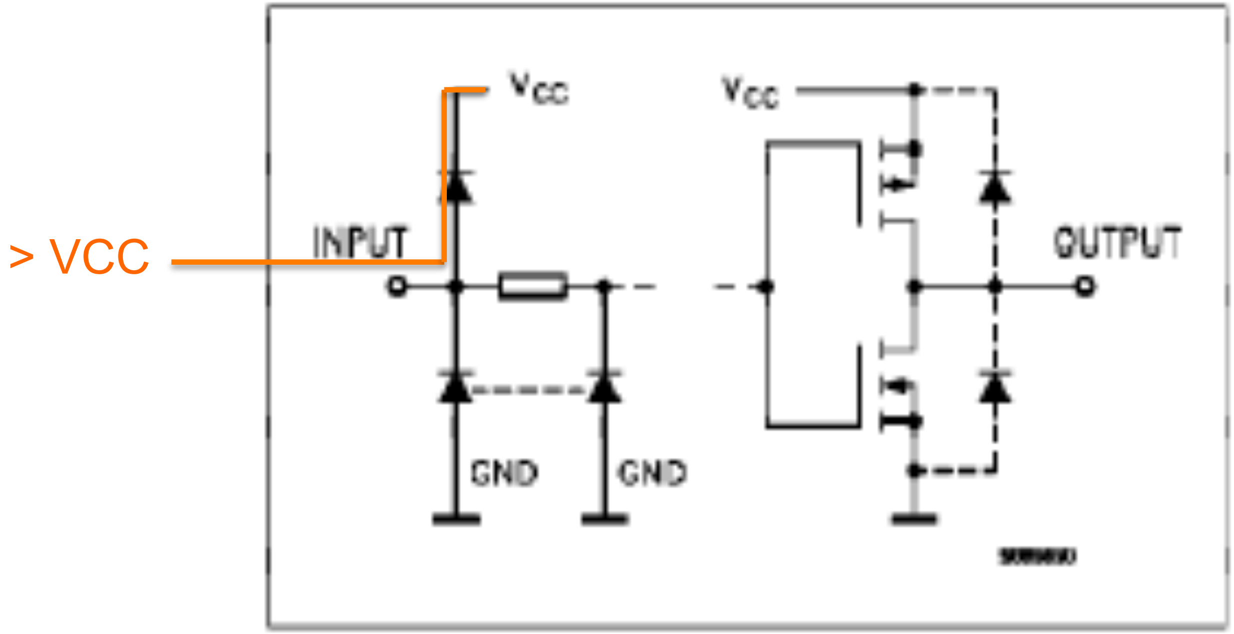
Digital inputs almost always have protection diodes



Power

Power Supply Sequencing

If an input is driven higher than the supply voltage or lower than ground, the diodes clamp the input to those voltages



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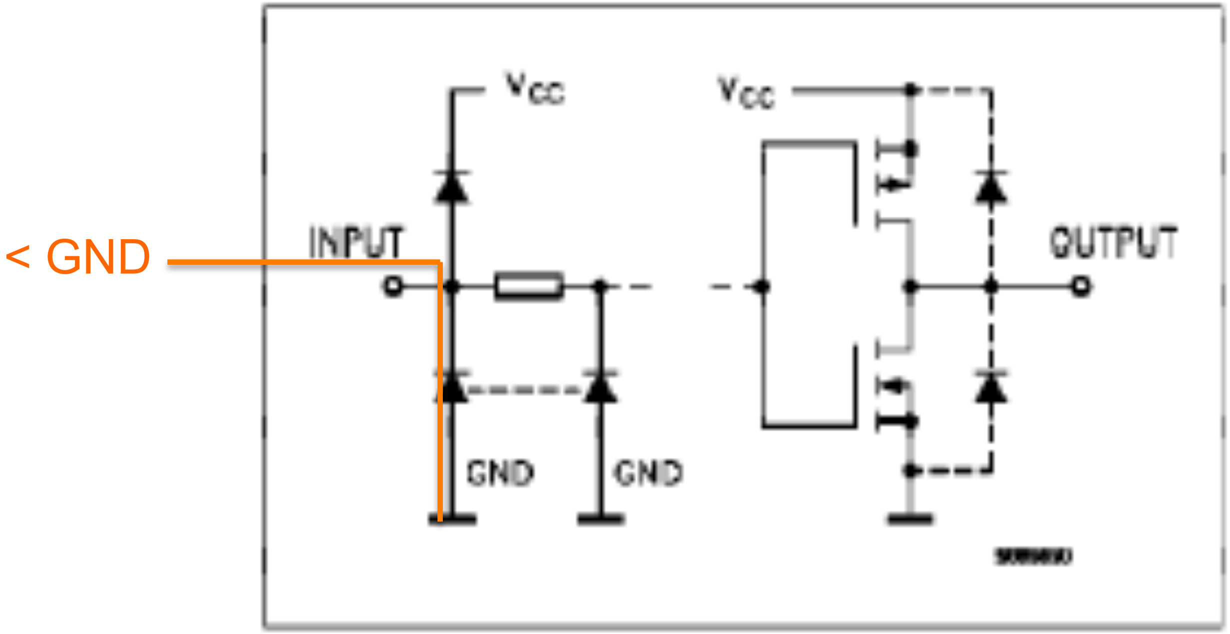
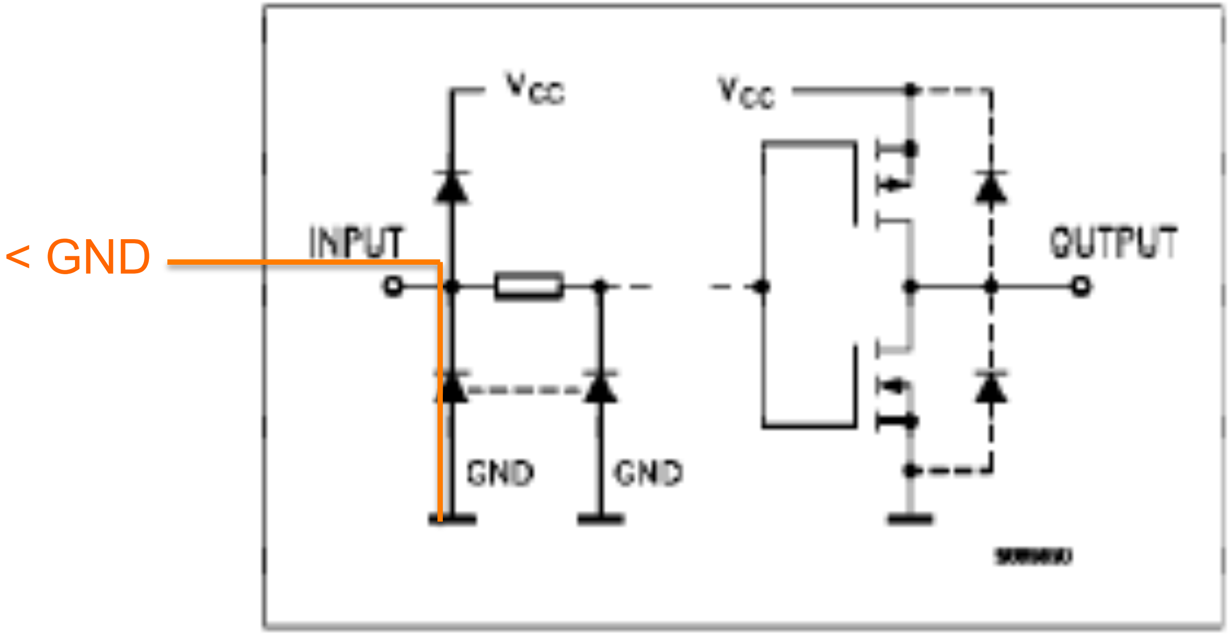


Power

Power Supply Sequencing

This is a major source of ‘smoke’ in multi-voltage systems; incorrect level translation blowing up protection diodes



Power

Power Supply Sequencing

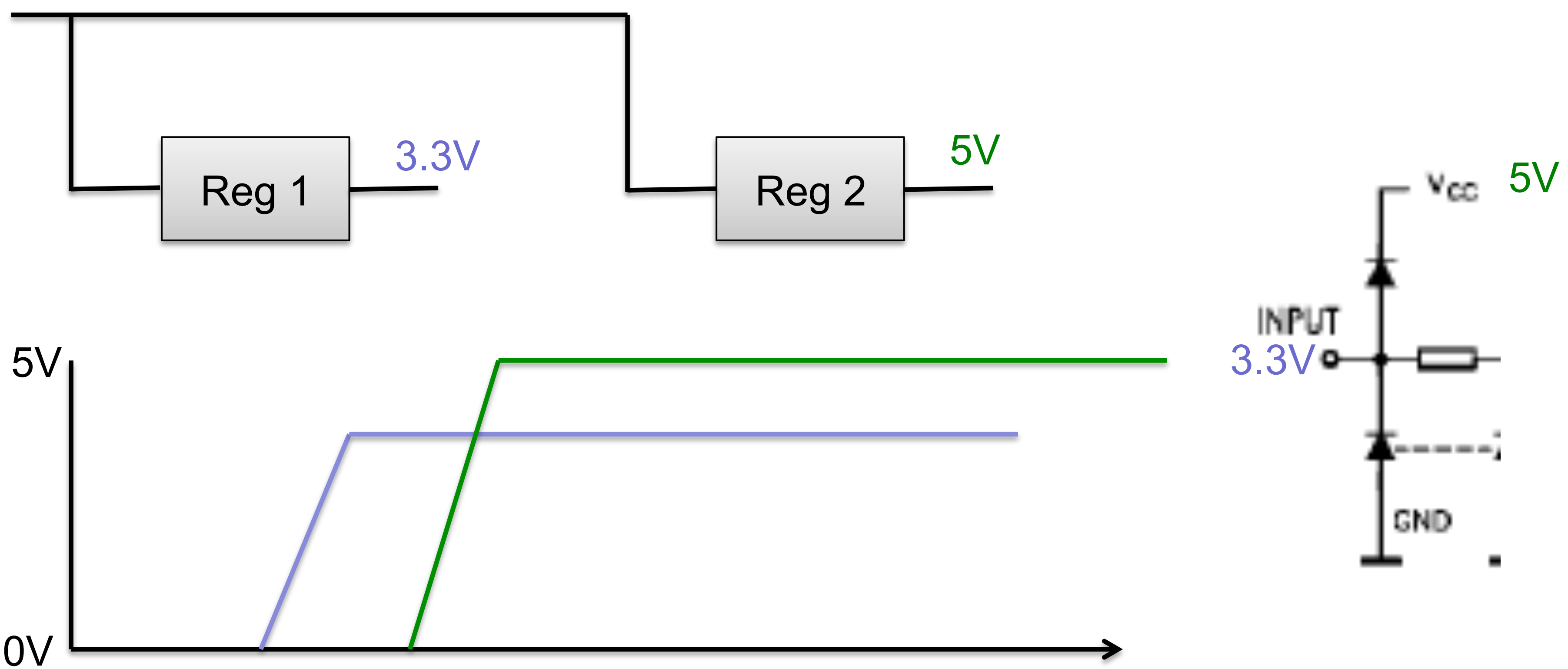
Even correct level translation can cause problems in multi-voltage systems. Imagine 3.3V driving a 5V input with the data sheet stating that the 5V part will work correctly in this scenario. As such, no level translation is used (or necessary).

Regulators are set up in parallel with each other so as not to overload the 5V one.

The regulators have different start-up times.

Power

Power Supply Sequencing



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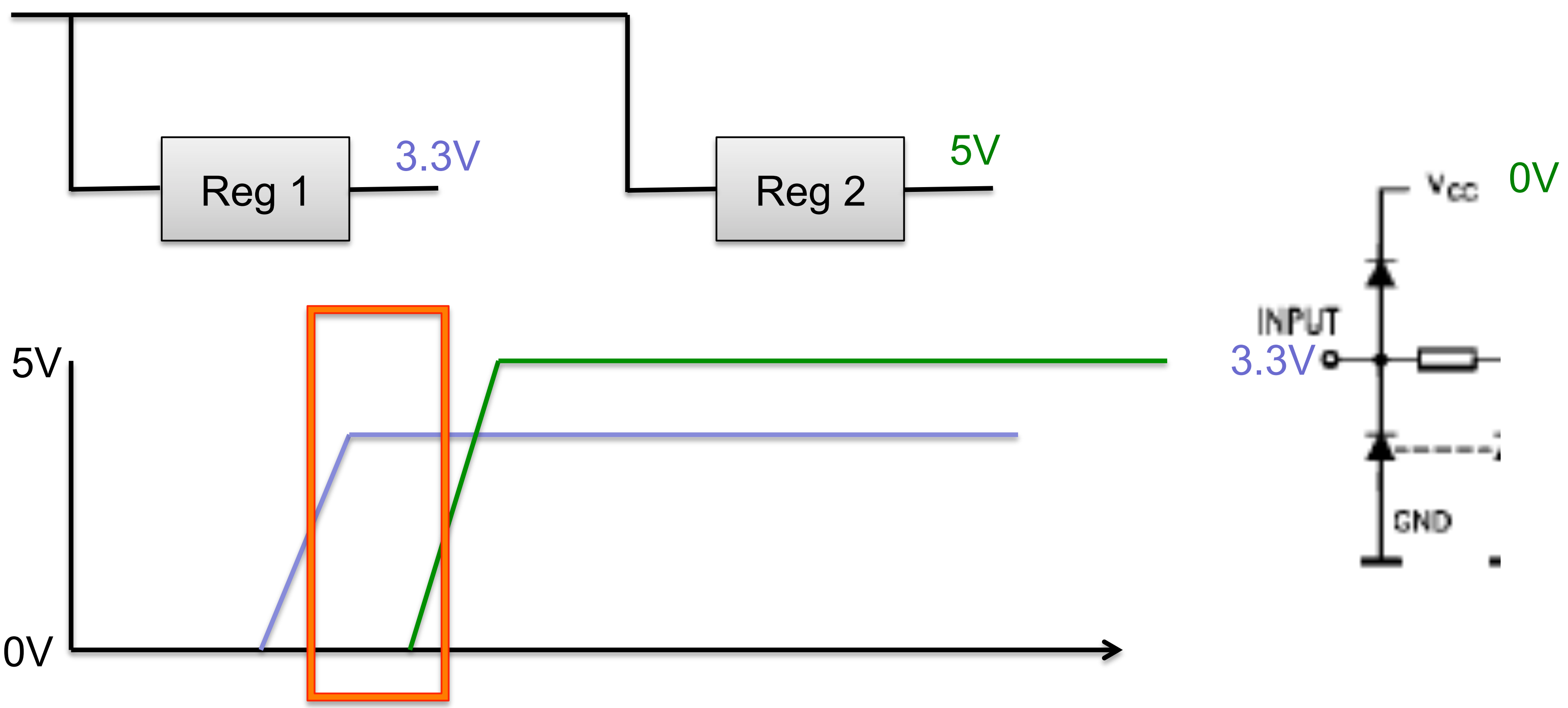
Power Supply Sequencing



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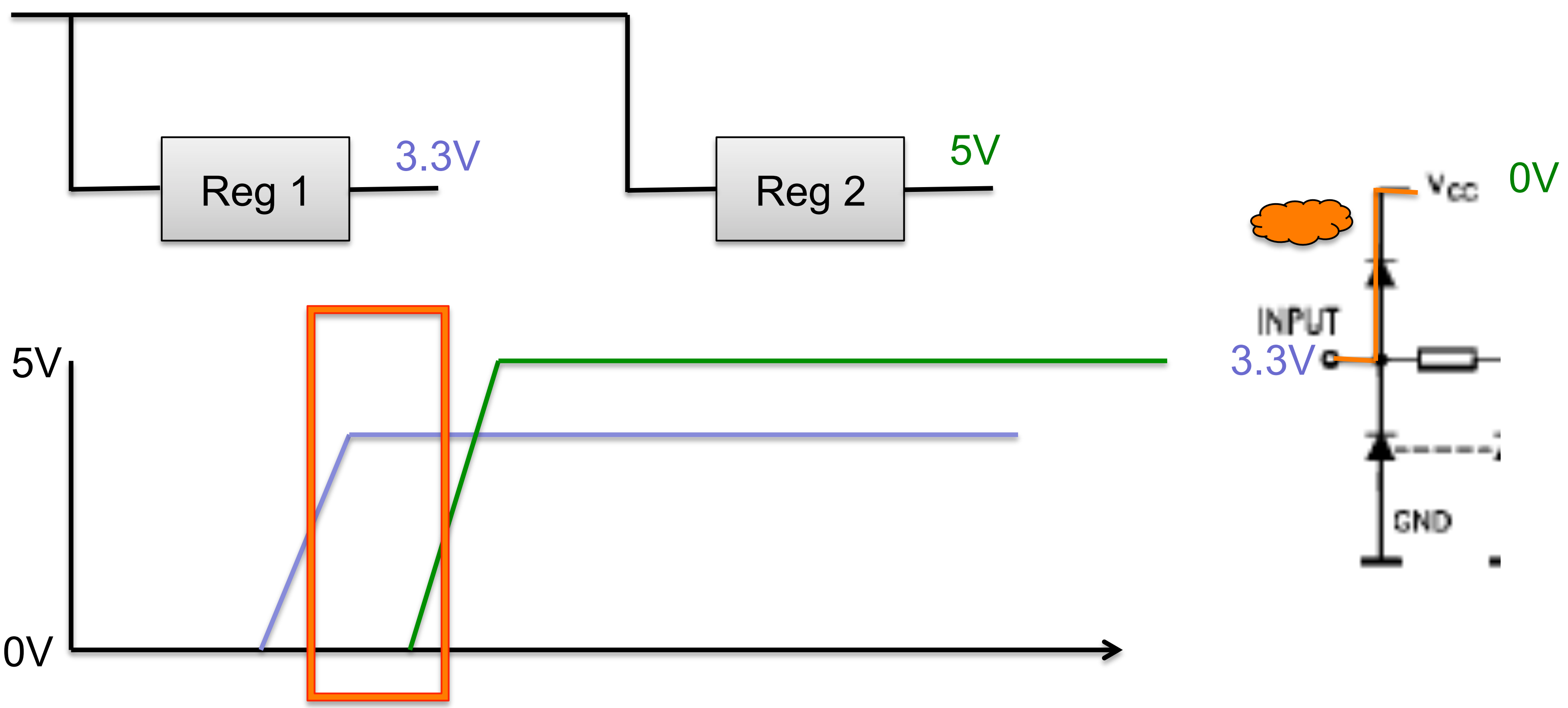

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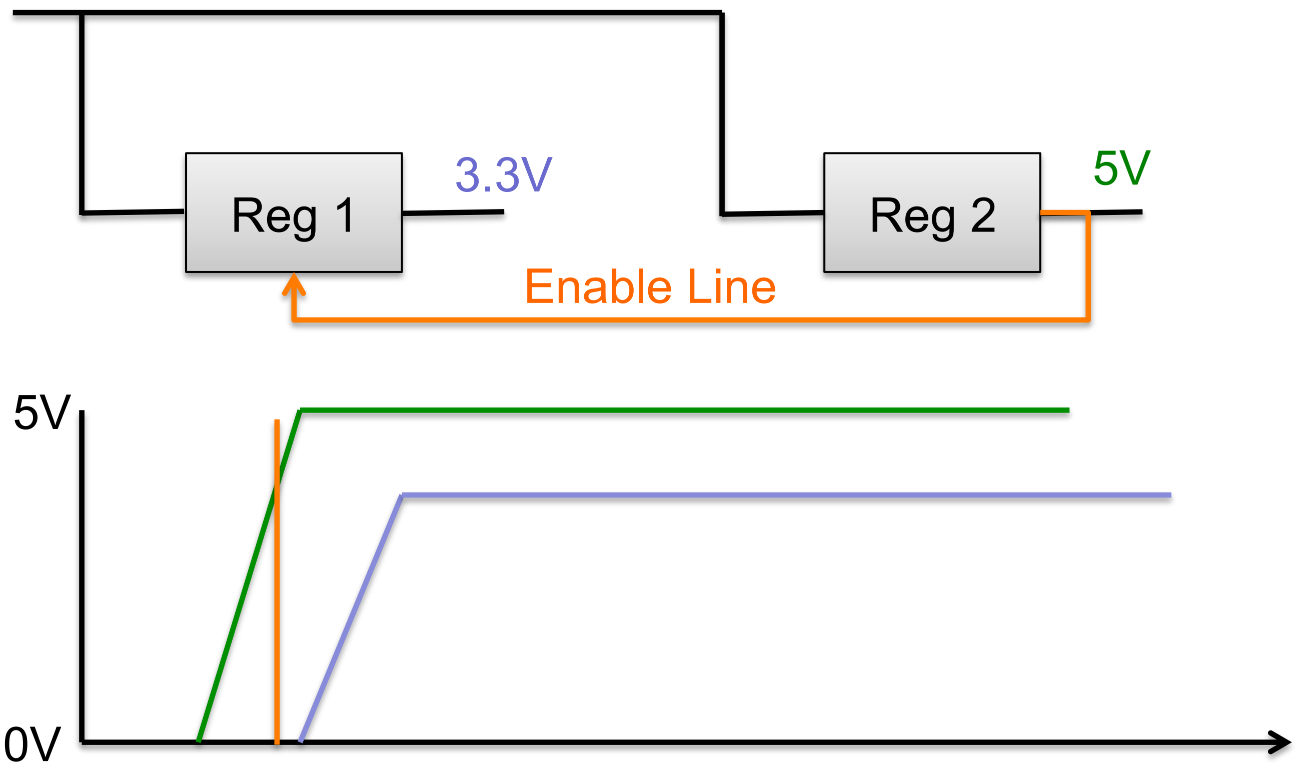
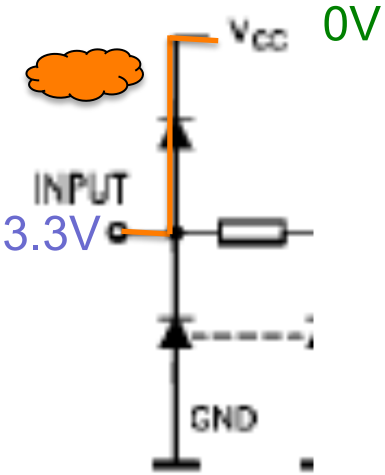
Power Supply Sequencing

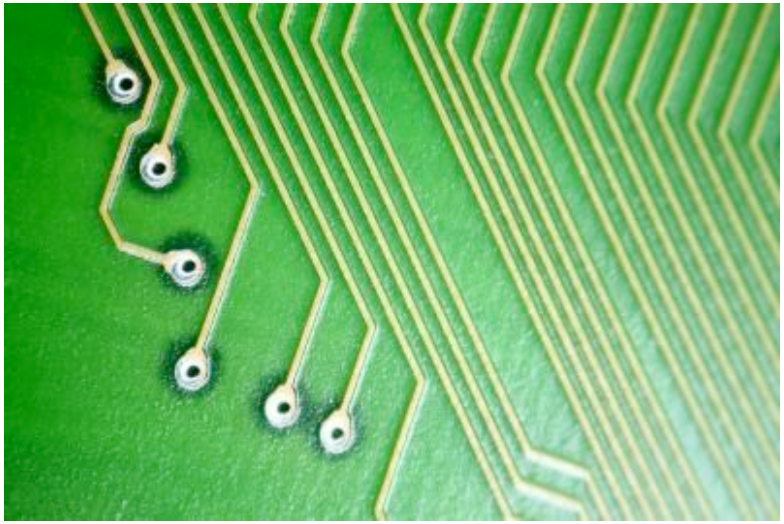


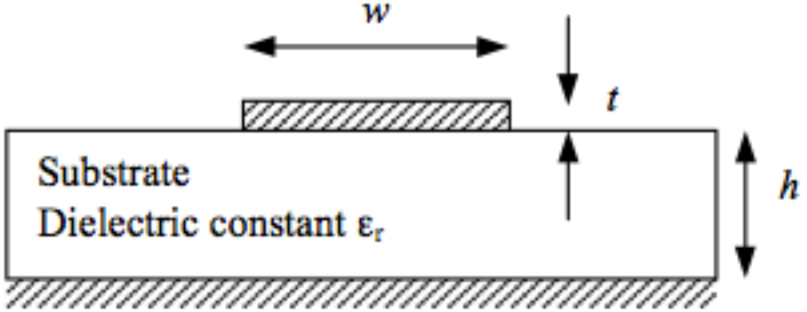


Power

Power traces run over the circuit board

Traces have a complex impedance; that is, both a resistance which dissipates power, but also an inductance and capacitance that stores power in local electric and magnetic fields.

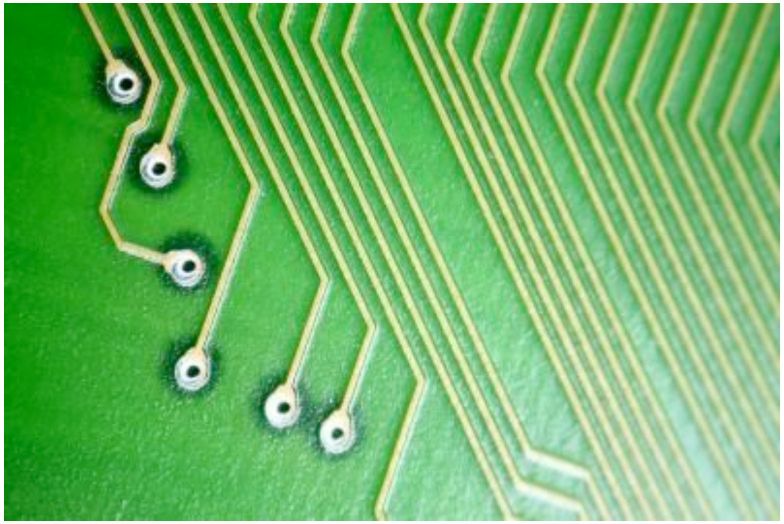




$$Z_0 = \frac{87.0}{(\varepsilon_r + 1.41)^{1/2}} \ln\left[\frac{5.98h}{0.8w + t}\right]$$

Ref Burkhardt et. al.

Power



The impedance typically acts like an inductor

$$v(t) = L\frac{di(t)}{dt}$$

In words: An instant change in current would require an infinite voltage. In practice, a fast change in current causes a significant change in voltage.

Power

Why is this a problem?

A common source of high frequency changes of current is something like a microcontroller. At each clock edge and each change of internal operation, more or less current is drawn from the voltage bus.

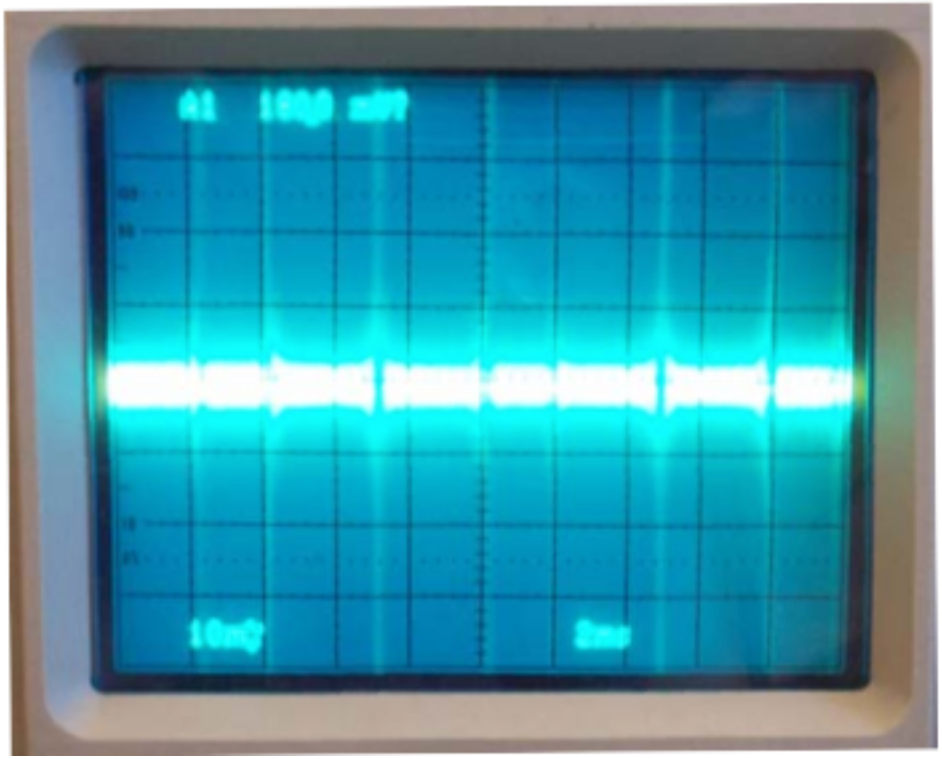
The changes of current coupled to trace impedance causes the voltage rails to fluctuate. If they fluctuate enough, the microcontroller can brown out; i.e. fail.

Power

Trace inductance can be cancelled out by placing a capacitor close to the device drawing the power.

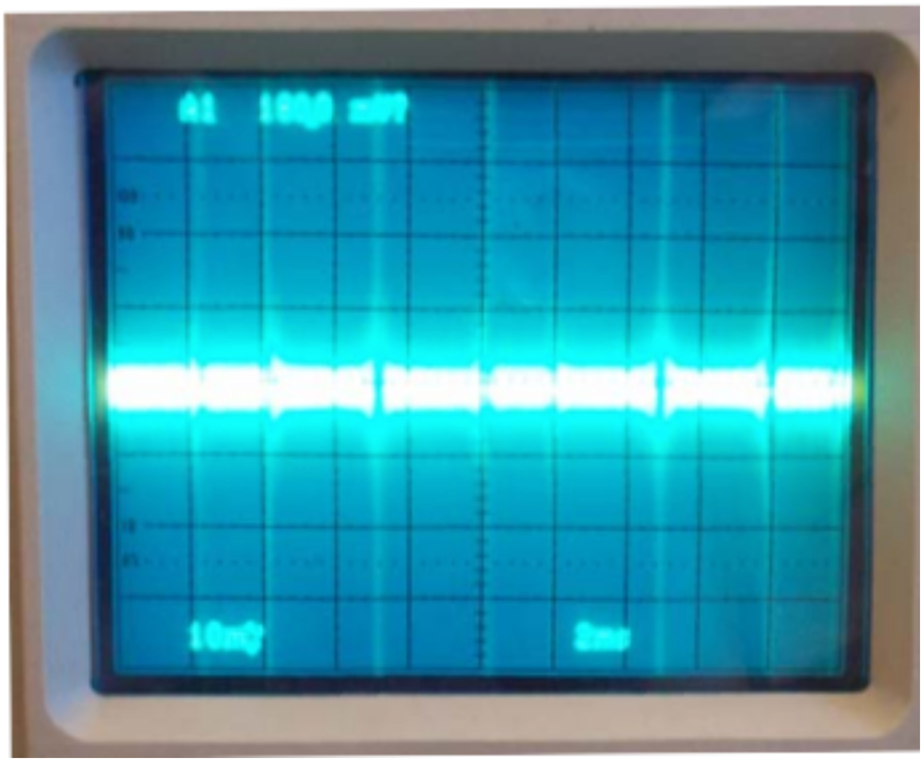
The current peaks are satisfied from the capacitor reserve and don't have to travel down the trace from the power supply.

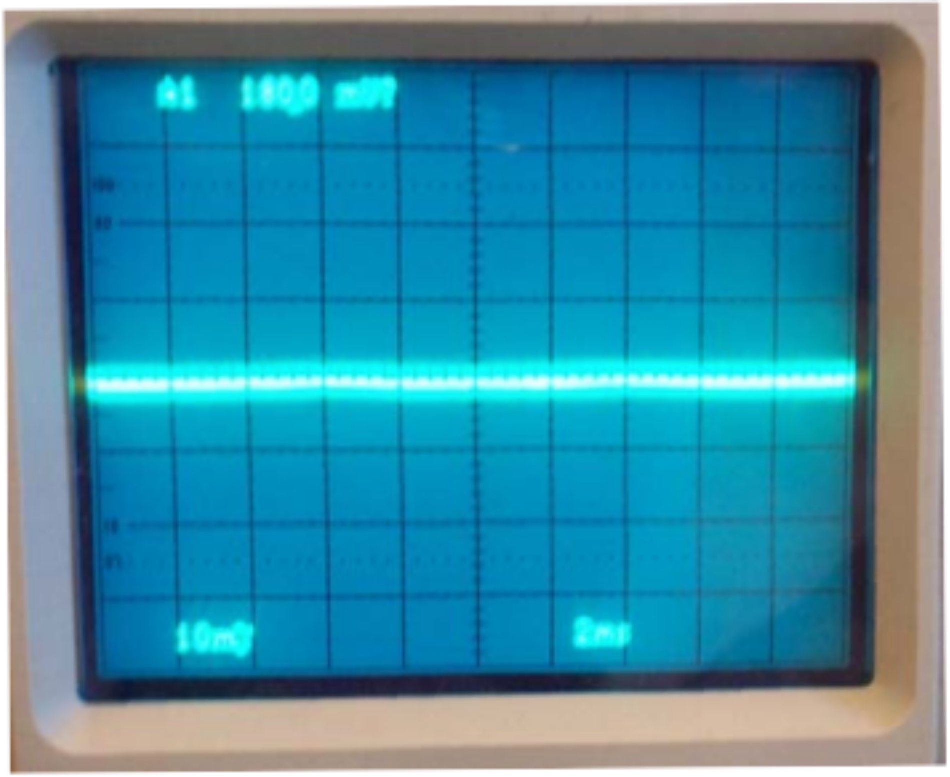
This is called decoupling



Ref Intersil Application Note 1325

Power





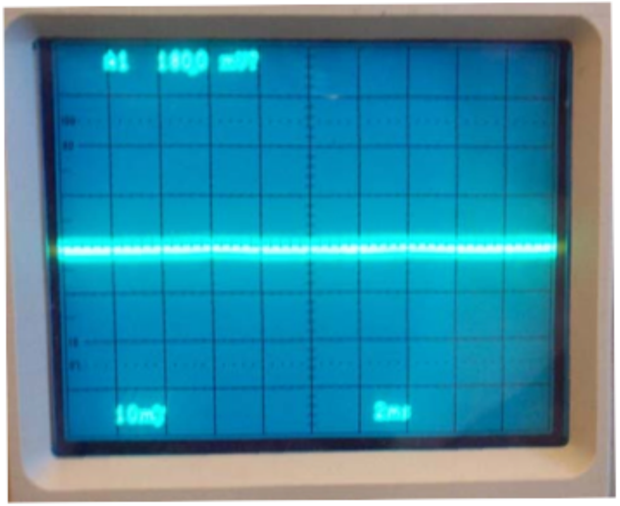
Ref Intersil Application Note 1325

Power

The point of a decoupling capacitor is to cancel out inductance, so the cap itself shouldn't be a source of inductance!

The physical connections to a capacitor are themselves traces and therefore have inductance. The bigger the capacitor, the bigger the inductance and the less effective the decoupling.

Effective decoupling the relies on several capacitors, effectively scaled



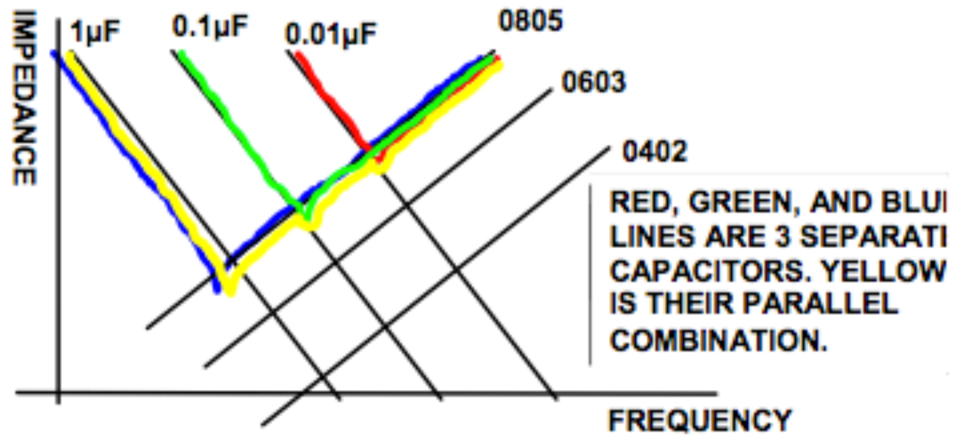
Ref Intersil Application Note 1325

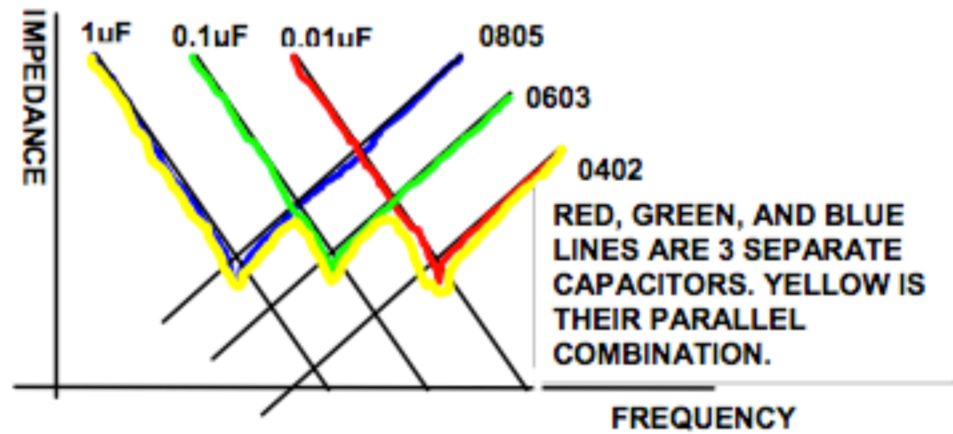
Power

Smaller capacitors also have smaller inductance in general, so have better high frequency response. Big capacitors have better low frequency response.

Multiple capacitors have the best overall response.

The decoupling must then match the frequency response of the current source.

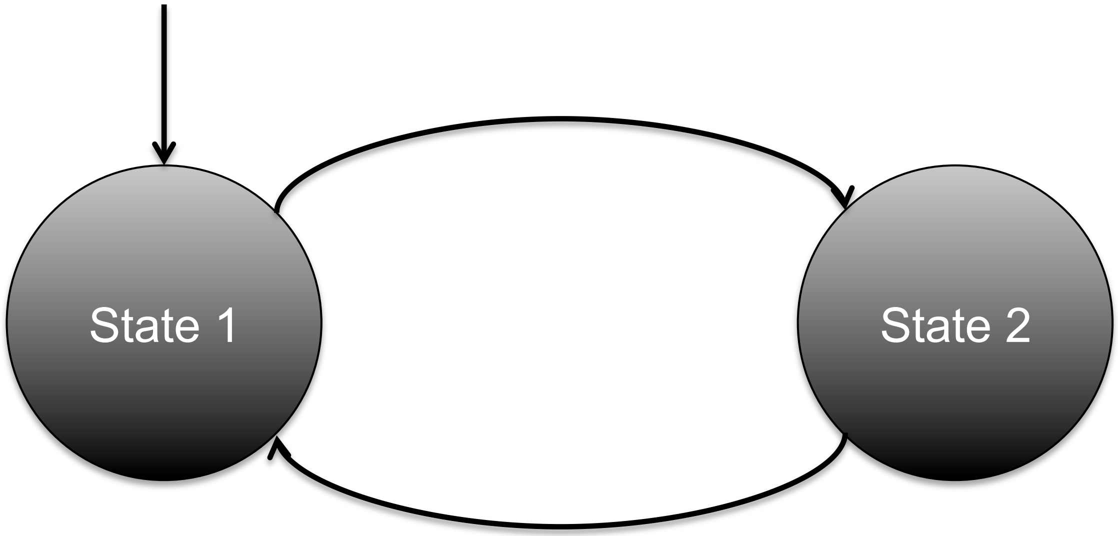




Ref Intersil Application Note 1325

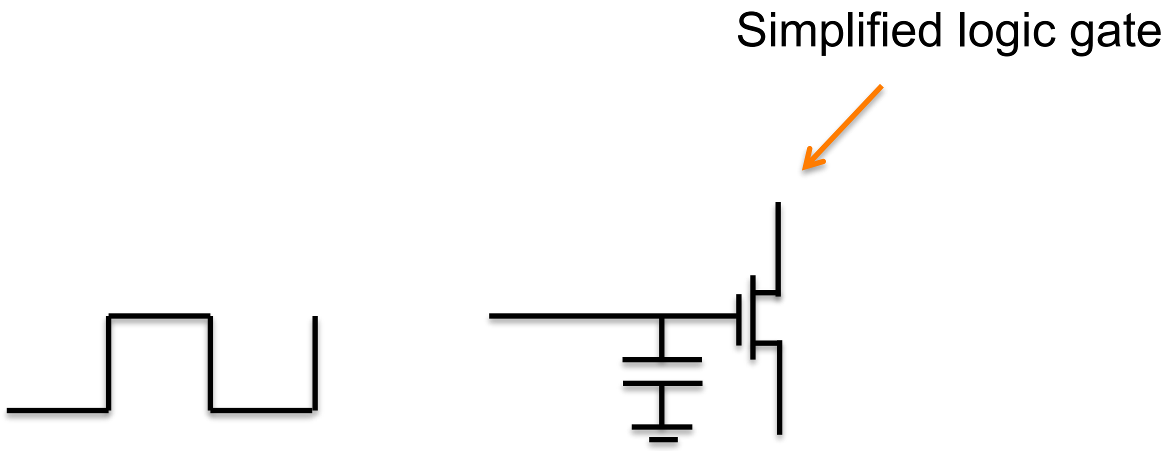
Power

Story time: Microcontrollers, bad decoupling and hard to debug field failures.



Power

Processors are a big source of current draw and especially high frequency changes in current draw. There are a number of reasons for this, but the biggest effect is quite simple: Clocked gate capacitance.



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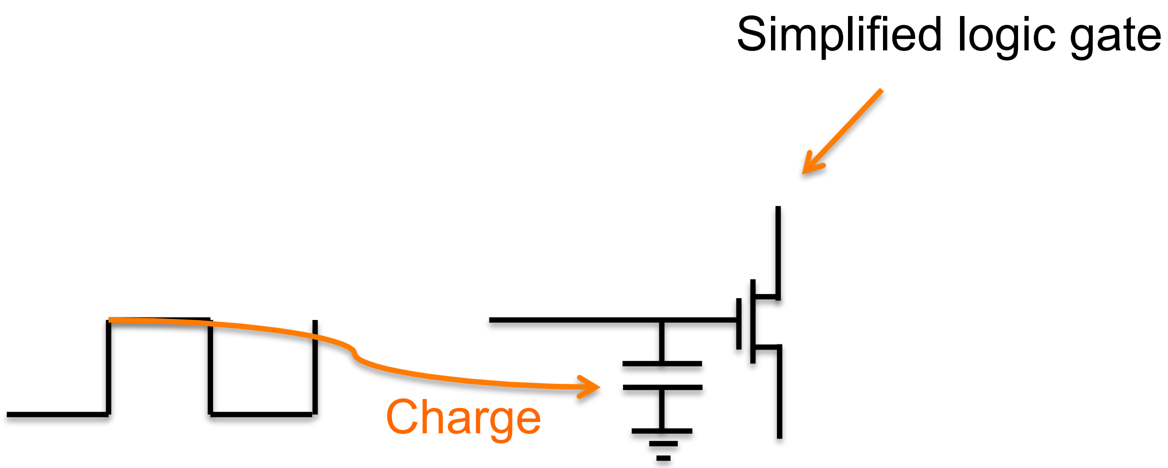

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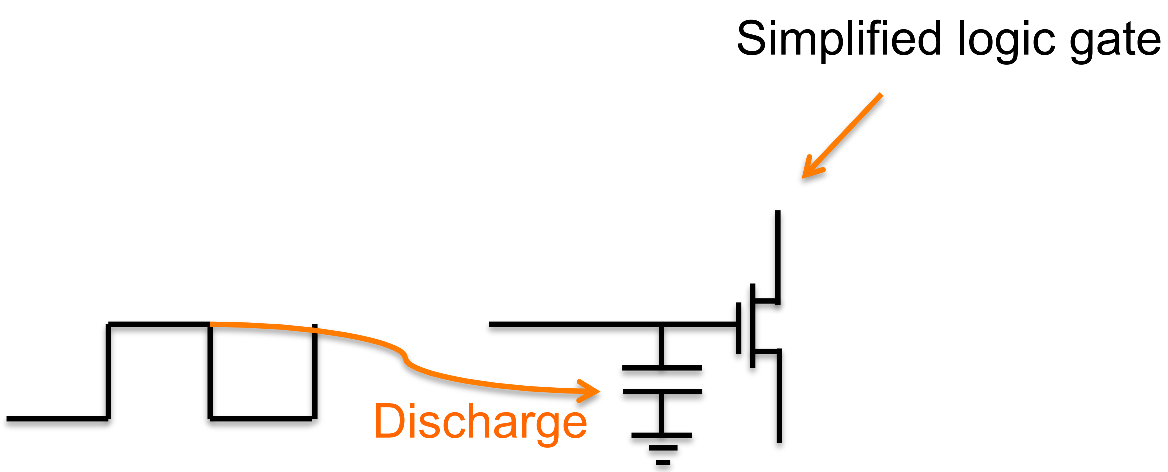


Power

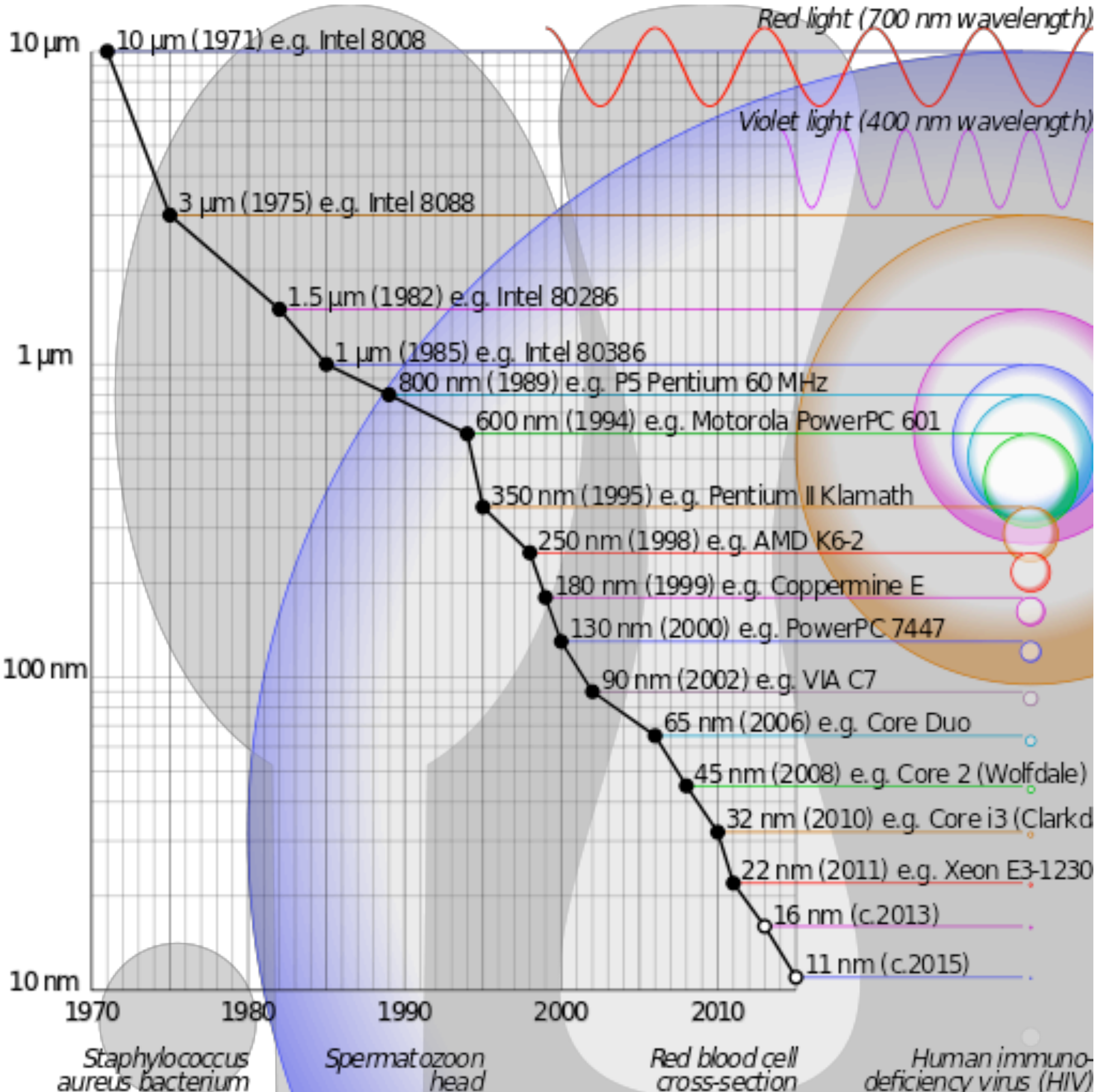
Each clock cycle charges the gate capacitance of each gate, then discharges it again.

This makes power proportional to clock frequency, drive voltage, number of gates and gate capacitance.

Double the clock frequency, double the power!

Power

Lots of things contribute to gate capacitance, but simplistically, smaller gates make smaller capacitors. This is the motivation behind the ever-shrinking CPU dies.



Power

The relationship between clock rate and power is often cited as a motivation to use a slower clock rate. However, while the stated relationship is true for CPUs and other clocked entities, some peripherals don't obey such laws

- Regulators
- DRAM
- Peripherals with a clock fixed by the interface (USB, Ethernet)
- etc.

Power

If your system contains power loads that are fixed while the CPU is on, the best power management might actually be race-to-idle. In this scenario, everything is run as fast as possible to complete the fixed amount of work, then turned off completely.

In this case, total power consumption is dependent on the running power, the idle power and the duty cycle.

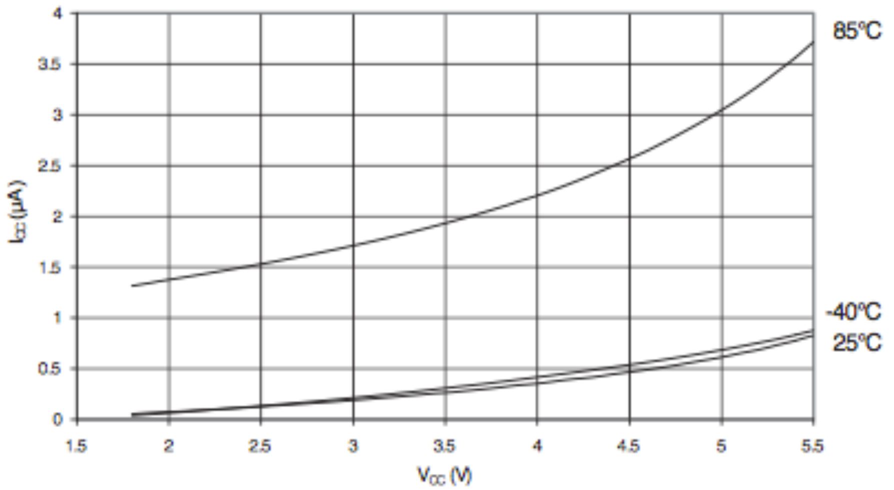
Power

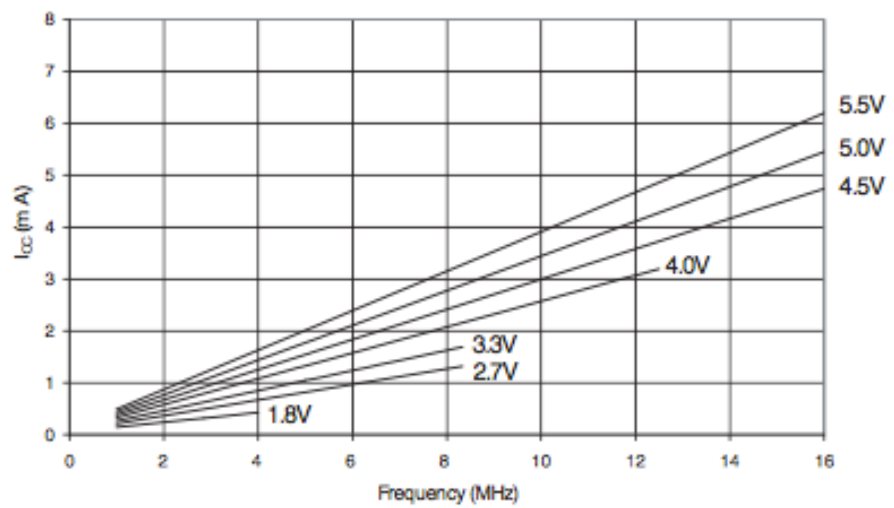
Example: Atmel ATMEGA256

3.3V, 1% on time, room temperature, 8MHz, CPU only:

0.99 * 0.25uA + 0.01 * 1.5mA

~0.0152mA average current.

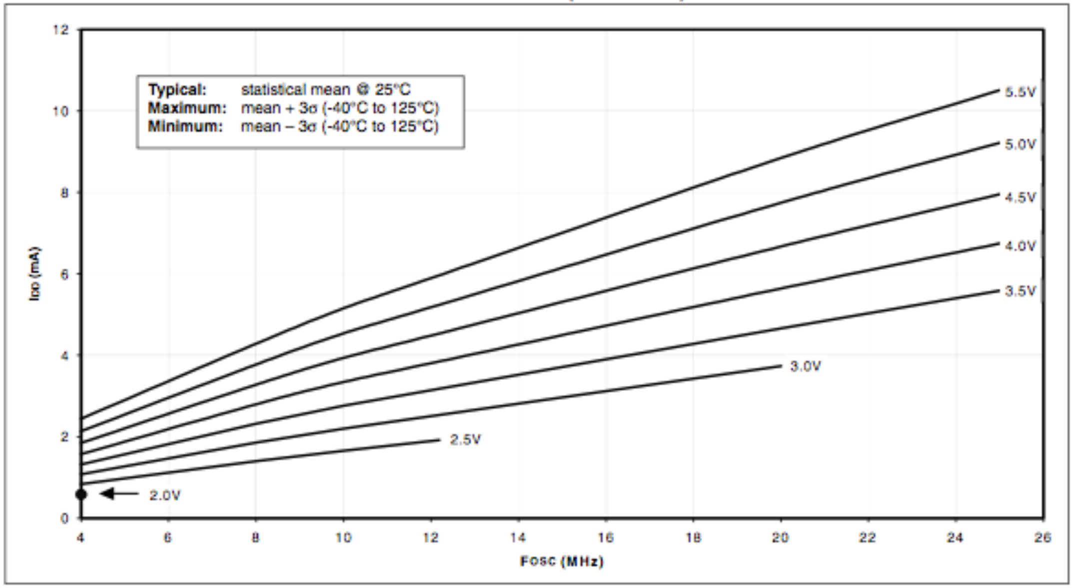


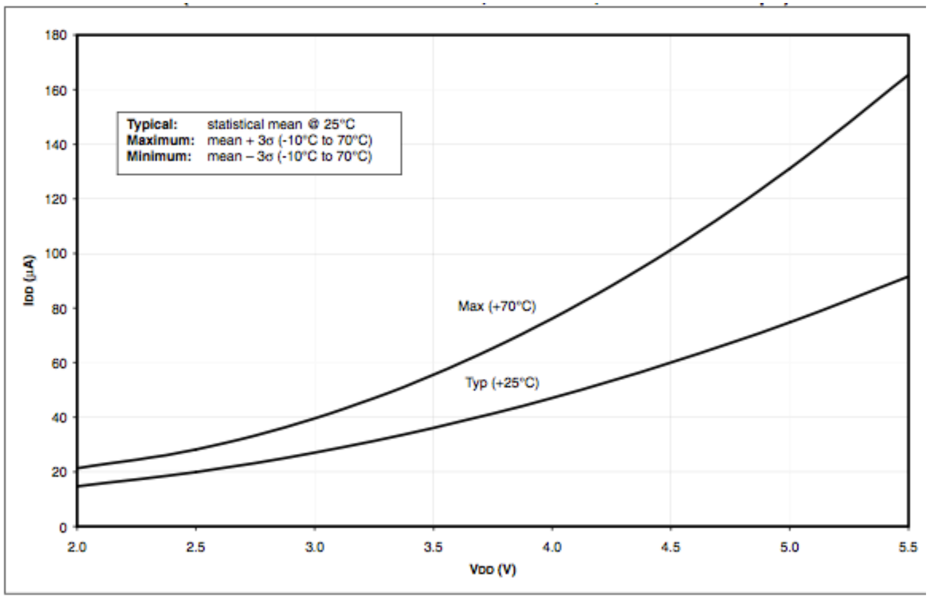


Power

Example: Microchip PIC 18FXX2

3.3V, 1% on time, room temperature, 8MHz, CPU only:





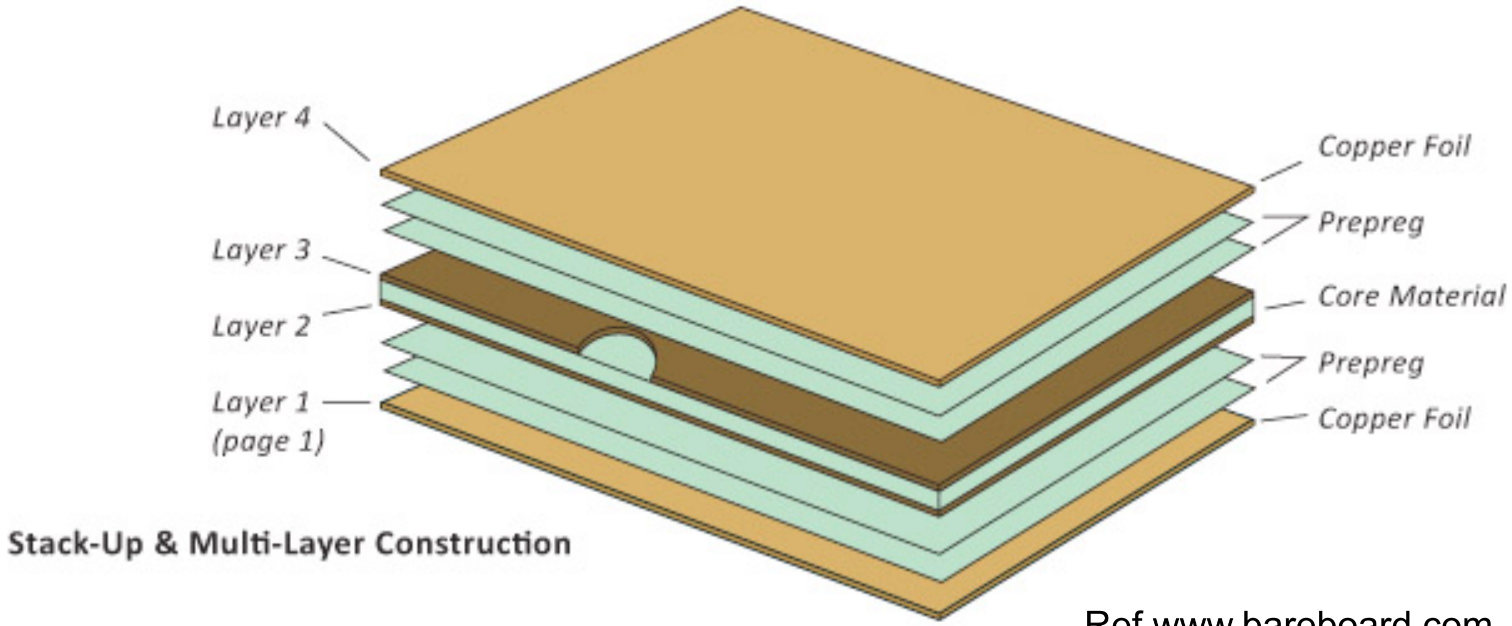
0.99 * 50uA + 0.01 * 2.5mA

~0.0745mA average current.

Manufacturability

An Embedded System can't just be designed, it has to be manufactured.

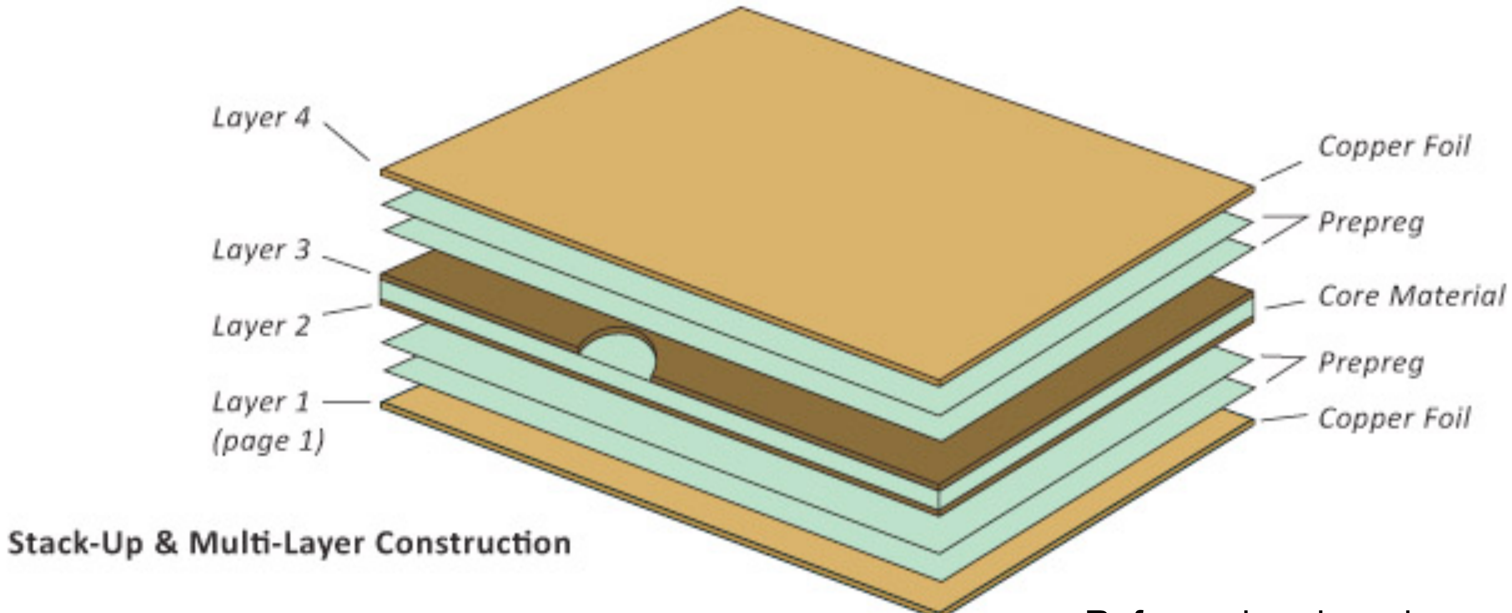
This all starts with the Printed Circuit Board, PCB.



Ref www.bareboard.com

Manufacturability

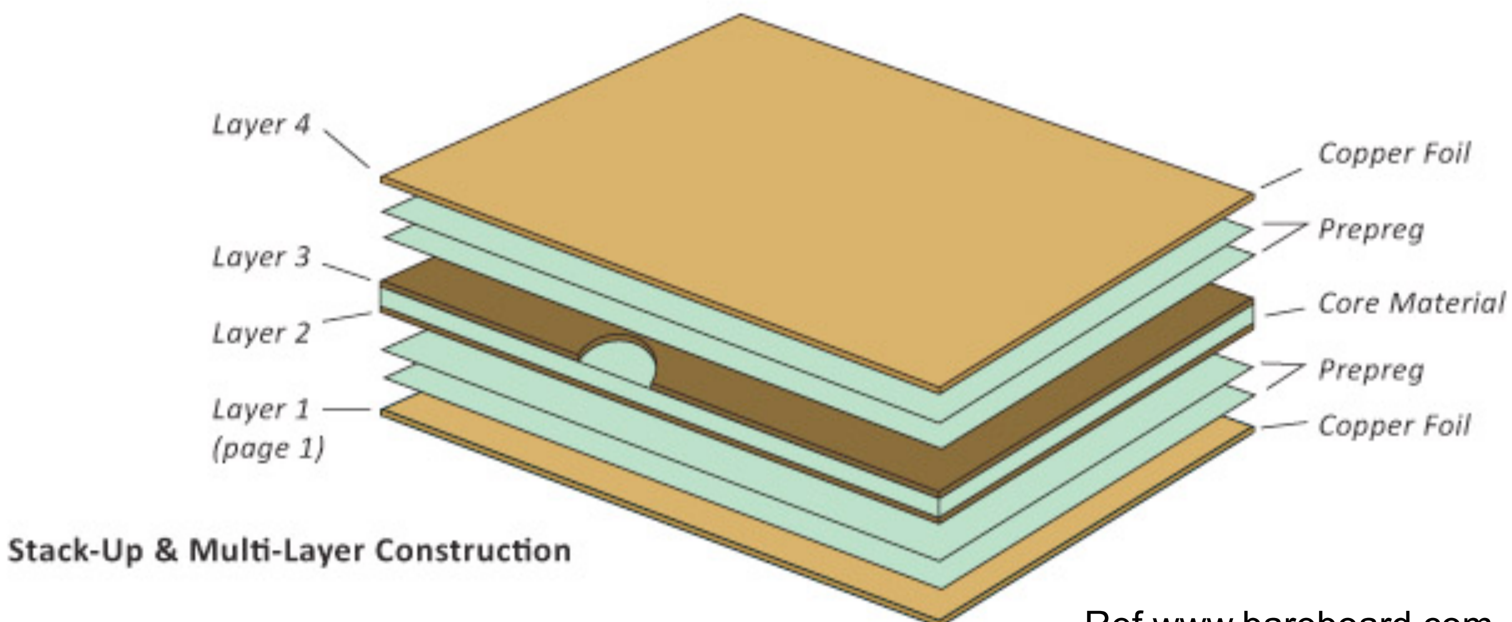
A Core material gives the board stiffness and strength while a prepreg material holds the copper that will be etched to become the circuit traces.



Ref www.bareboard.com

Manufacturability

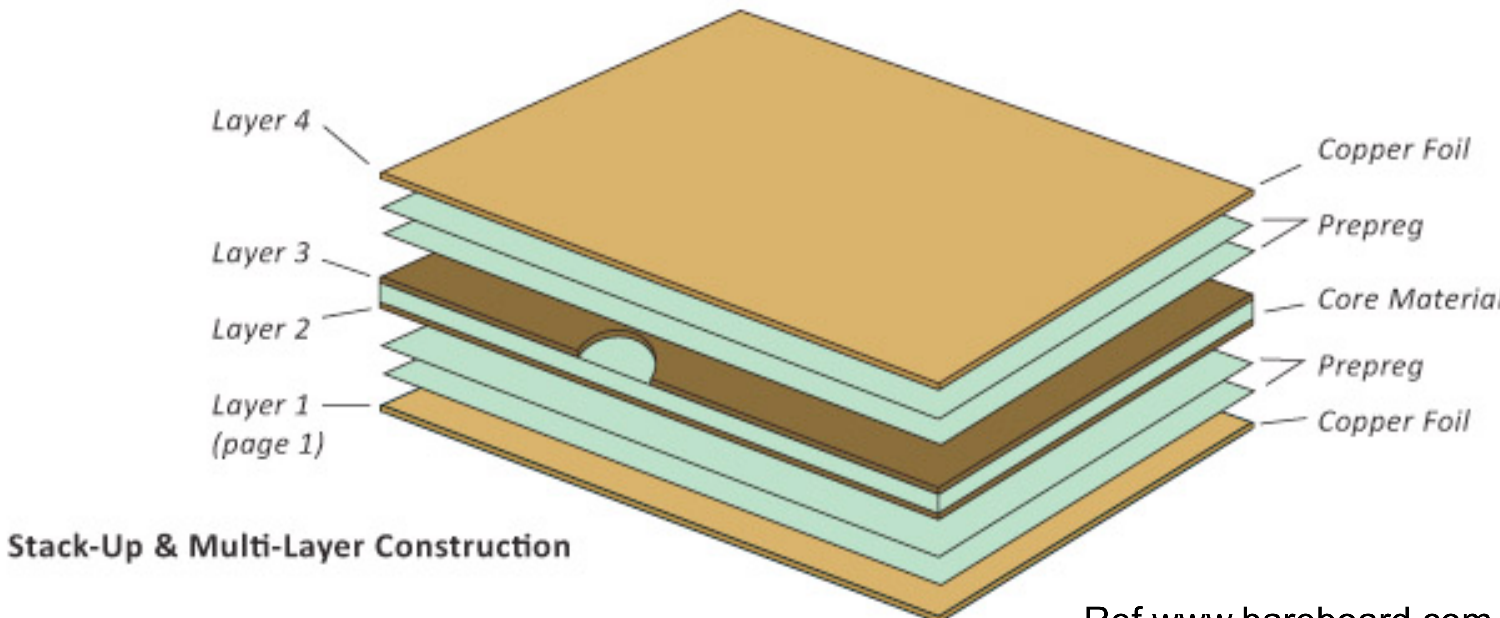
Prepreg is short for pre-impregnated material, and refers to the fact that it is usually a glass fiber matting pre-impregnated with an epoxy resin.



Ref www.bareboard.com

Manufacturability

The most common prepreg is FR4; “type 4 fire retardant”. This is cheap, tough and doesn’t burn (easily) but has poor RF performance and a poor coefficient of expansion. Other materials include aluminium substrates for good thermal dissipation, Teflon for good RF performance etc.

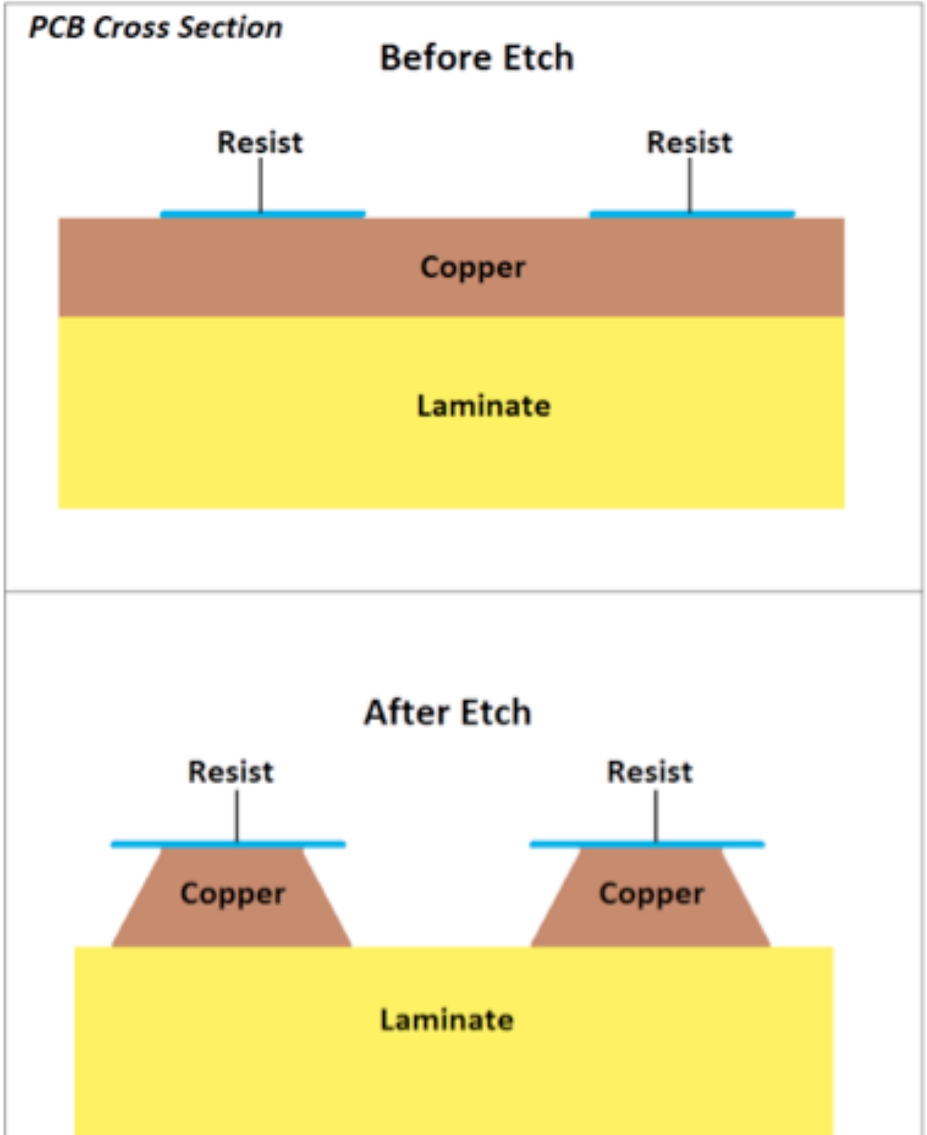


Ref www.bareboard.com

Manufacturability

Each pair of layers comes precoated with copper foil on each side. A resist material is coated on each side in the correct pattern for the traces and the board exposed to an etching chemical.

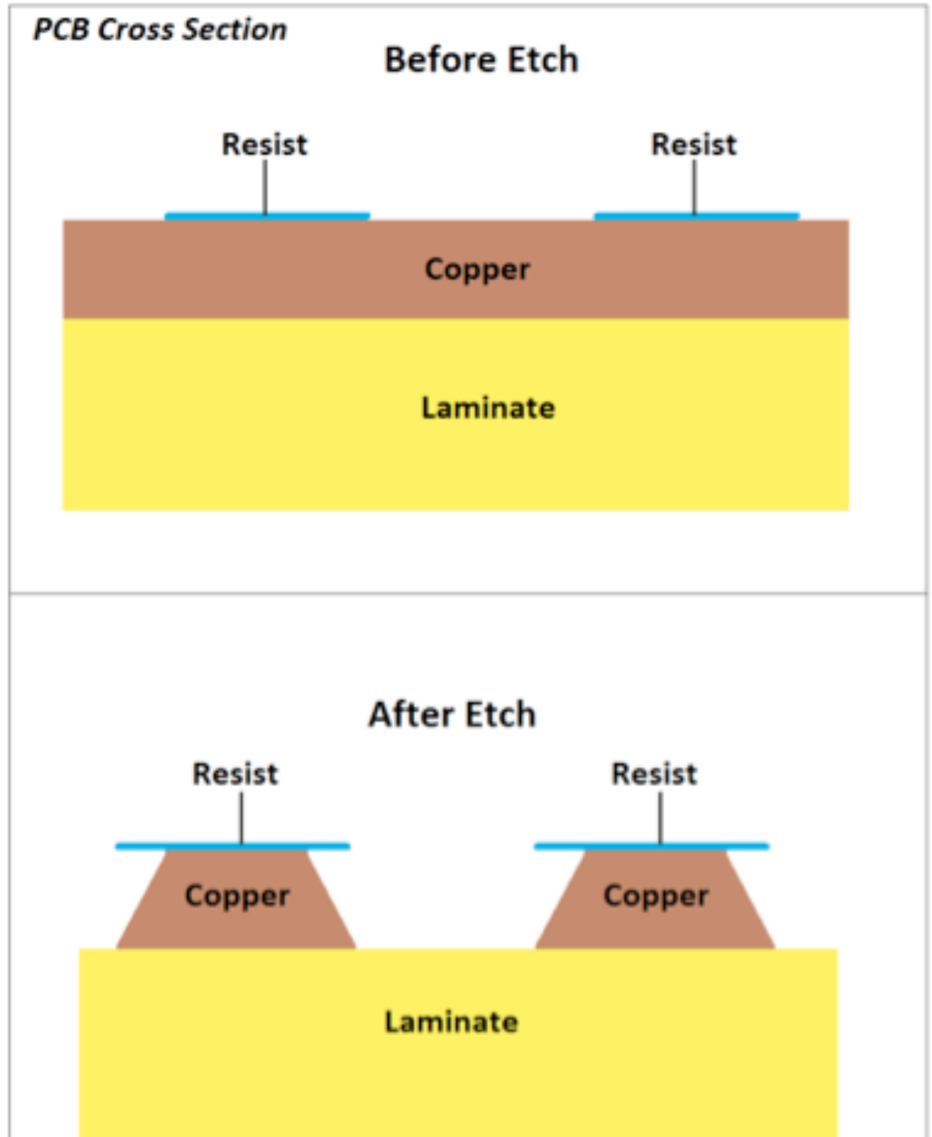
The chemical gets under the resist so the traces end up trapezoidal rather than the ideal rectangle.



Ref www.pcbunivserse.com

Manufacturability

This process introduces minimum track and space widths. A track that's too thin might etch completely through and form an open circuit; a space too thin might not provide enough surface area for the etchant to work and cause a short circuit between adjacent traces.

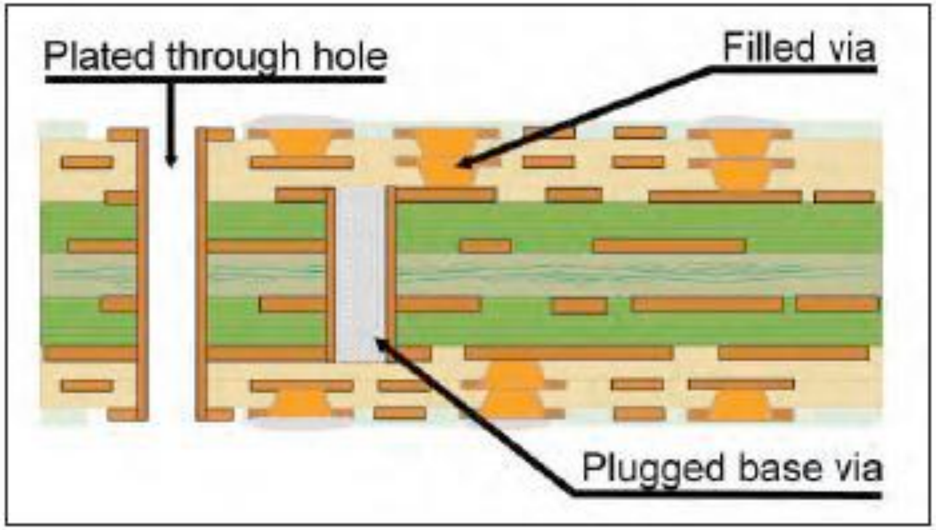


Ref www.pcbunivserse.com

Manufacturability

Any connections between layers are made by connections called vias. Holes for the vias are drilled and the layers are glued together under pressure.

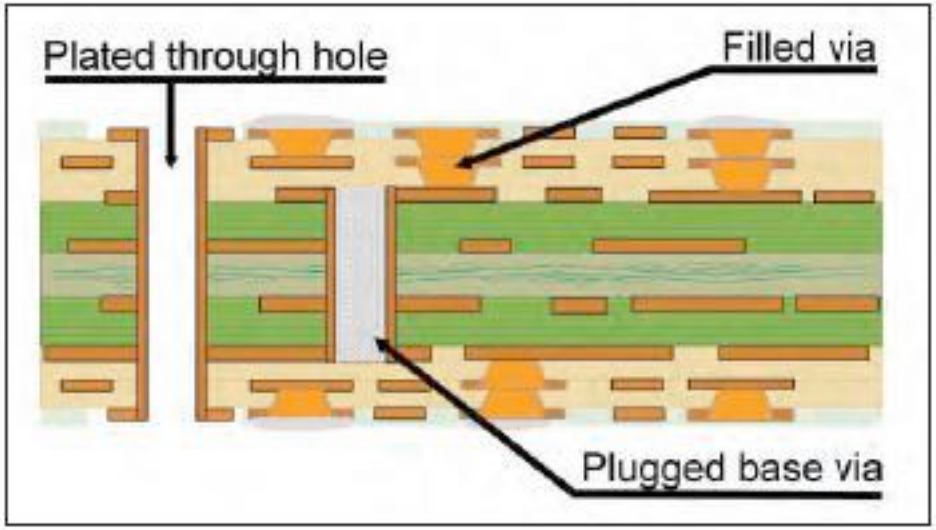
Once glued, the holes are electroplated to make the connections through.



Manufacturability

Vias come in different types:

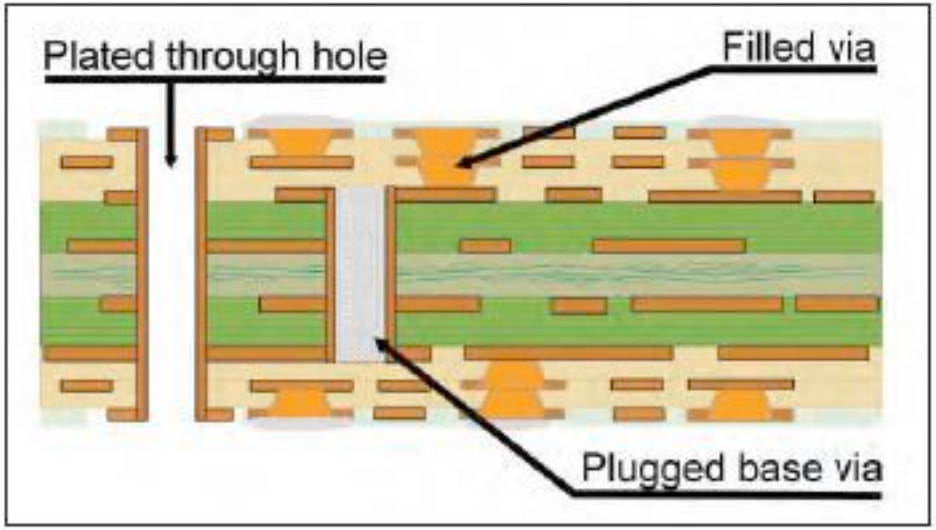
- Through
- Blind
- Buried
- Microvia



Manufacturability

Through vias are drilled and plated through all layers. Blind vias are open on one side only, buried vias aren't exposed on either side of the sandwich.

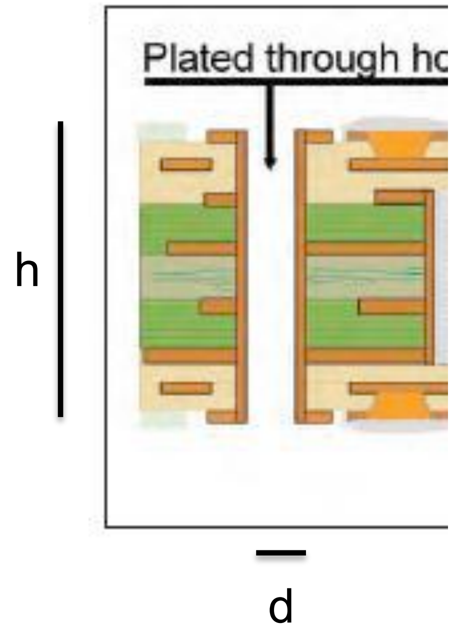
Microvias are done differently, with the inner layer left solid copper. A laser is used to burn the outer layers away and is stopped by the terminating copper. The resulting hole is filled with copper to form the connection



Manufacturability

The creation of a via relies on electroplating solution making it down the hole and adhering to the sides.

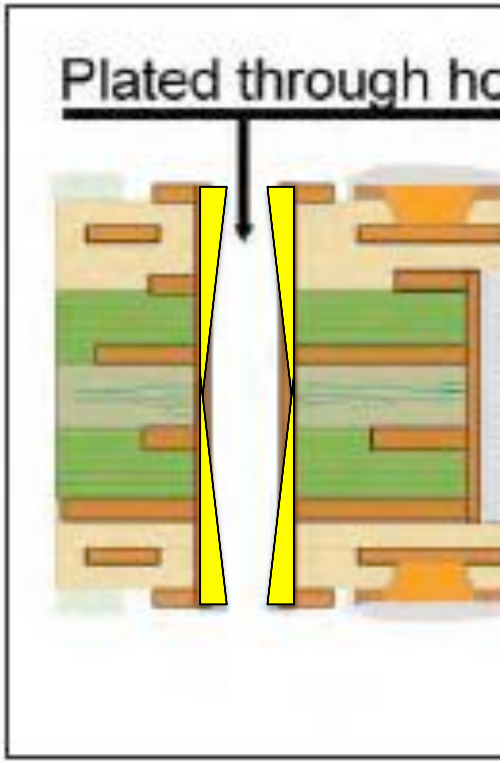
This places a limit on the aspect ratio of the via. The deeper or thinner the via, the harder it is for the plating material to get through and make a good connection.



Manufacturability

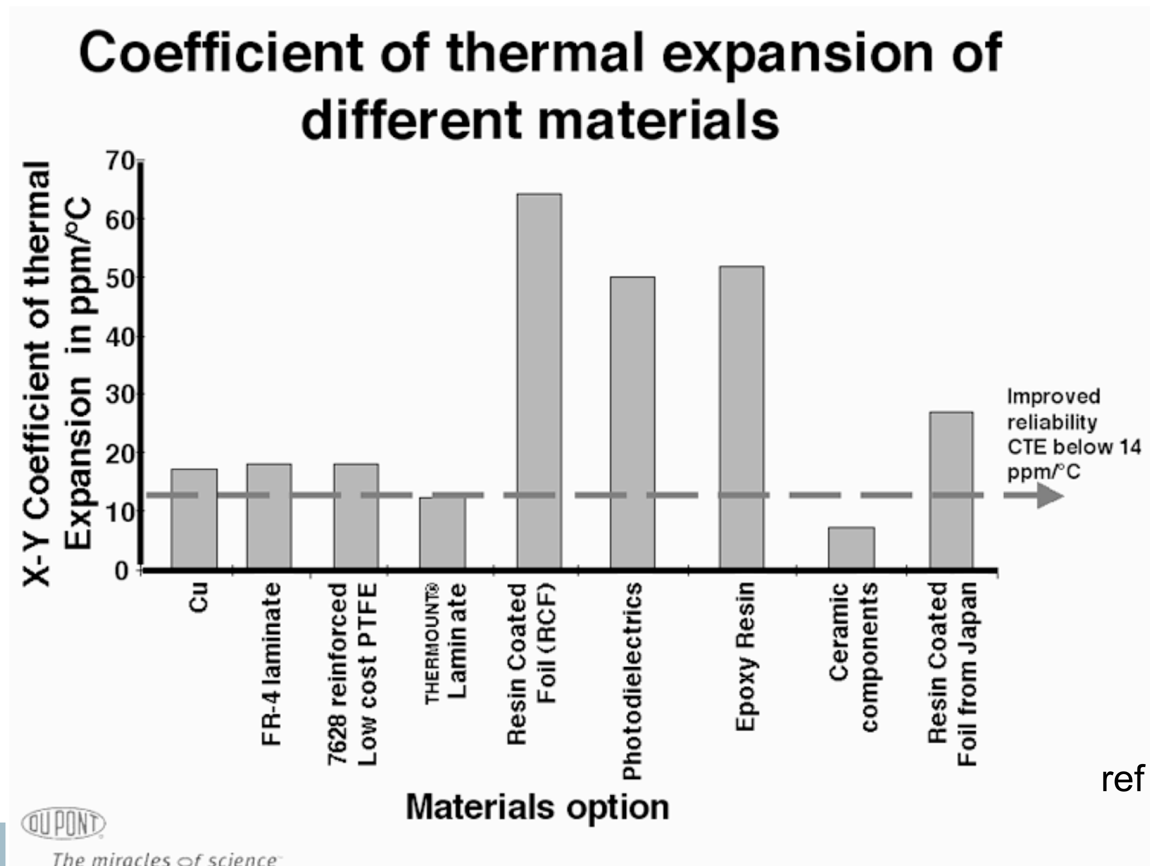
A via with an aspect ratio that's too big will end up with less copper in the middle than desired.

This means that the via might seem to be in tact during initial testing but might 'fuse out' out during normal operation



Manufacturability

All components of the system must have matched coefficient of thermal expansion. Mismatches will cause stress under different temperature conditions



ref emerald insights

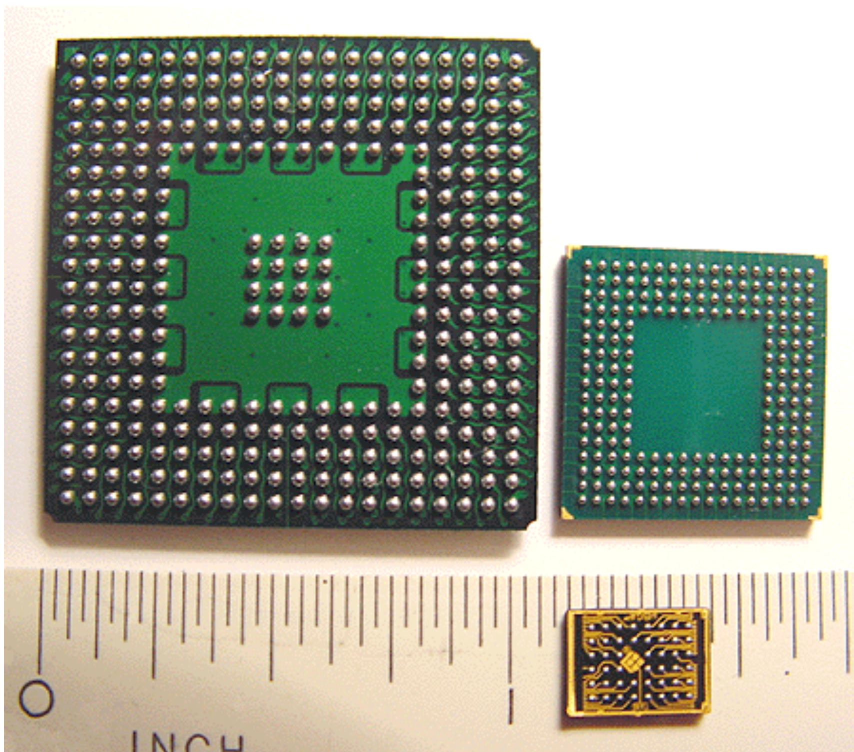
Manufacturability

There is a slight mismatch in the CTE of Copper and FR4, but they're pretty close. Copper is fairly ductile so doesn't usually fracture due to thermal stress, however if it's already brittle (e.g. in the middle of a badly-filled via), thermal cycling can break it.

A more common source of thermal failures is between ceramic IC packages and the circuit board itself.

Manufacturability

A common example is large Ball Grid Array (BGA) parts. The board underneath the package can expand twice as much as the package itself, cracking the solder balls



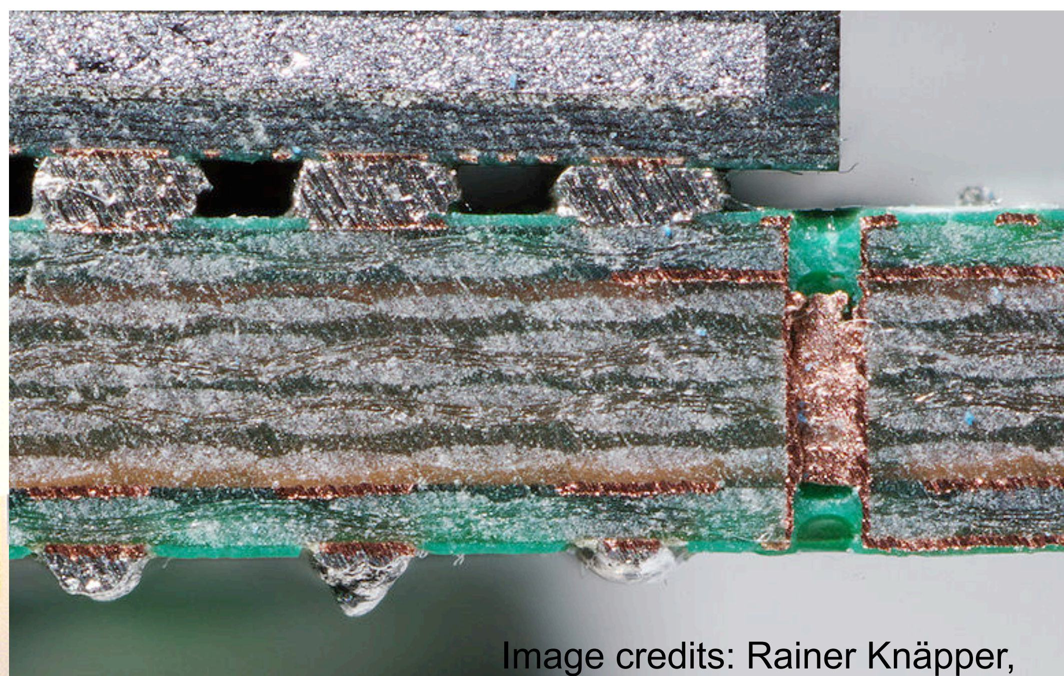
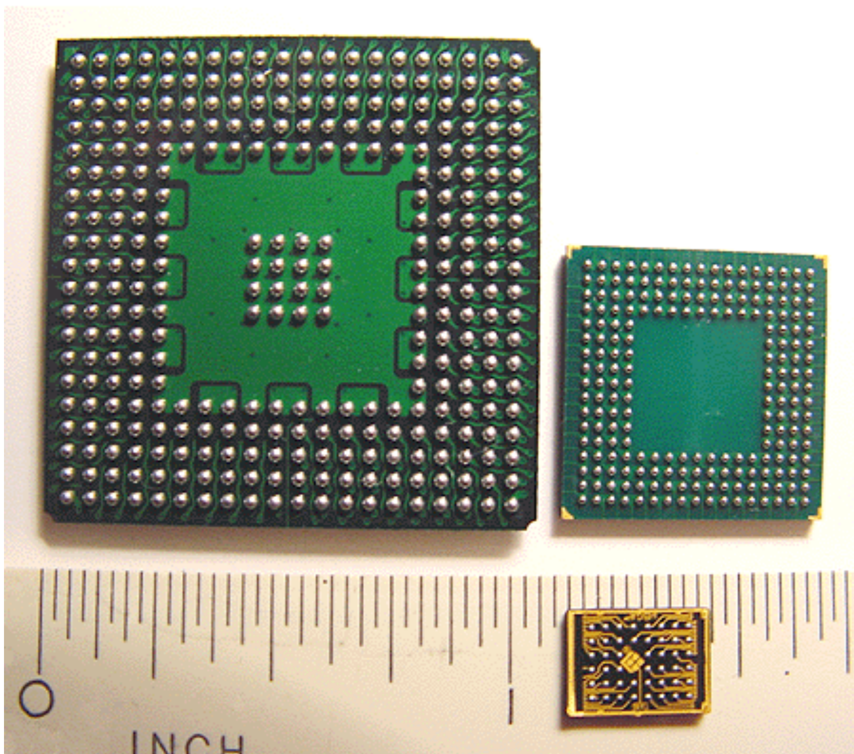


Image credits: Rainer Knäpper,

Manufacturability

For standard temperature parts the solder is ductile enough that this is rare. In high temperature environments the package can be underfilled, literally gluing the device to the board. The glue takes the strain and the solder doesn't fracture.



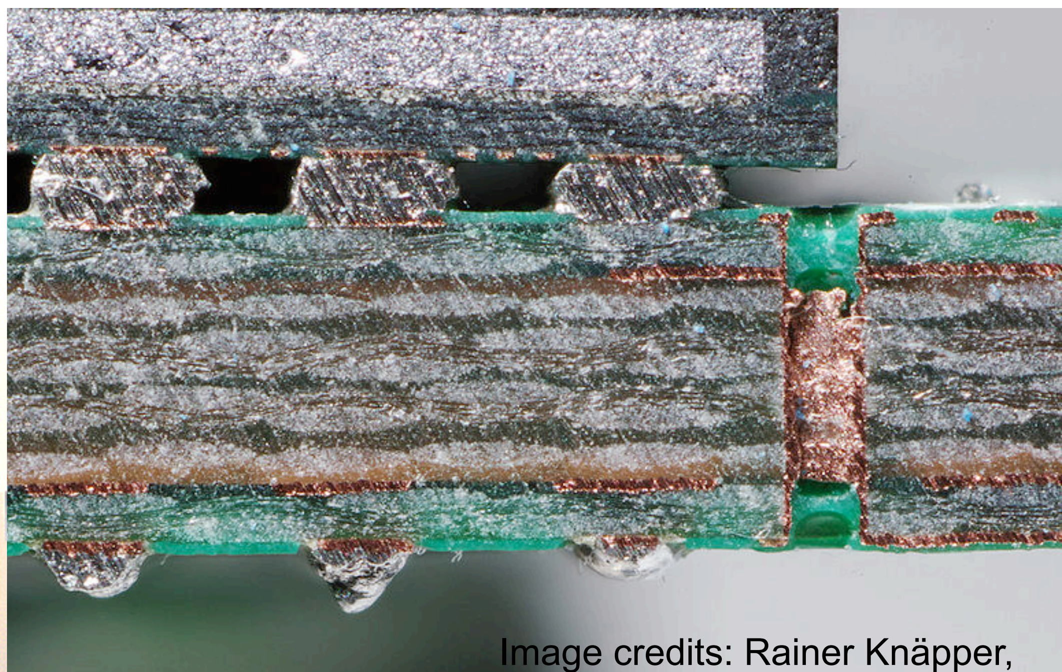


Image credits: Rainer Knäpper,

Manufacturability

As Systems Engineers, all designs should consider factors such as the system lifecycle cost and environmental impact.

In the electronics industry, you’re forced to consider the environment in at least one way: The European Union Reduction of Hazardous Substances directive (RoHS).

Most electronic devices imported in to the EU (and more recently most of the rest of the world) must conform to the RoHS standard.

There is an exception for some classes of electronics, e.g. Defence-related equipment.

RoHS

Manufacturability

The RoHS directive states that certain chemicals cannot be used in consumer electronics:

- Lead (Pb)
- Mercury (Hg)
- Cadmium (Cd)
- Hexavalent chromium (Cr^{6+})
- Polybrominated biphenyls (PBB)
- Polybrominated diphenyl ether (PBDE)

Manufacturability

Historically, solder has been made from Lead and Tin (SnPb).

This is not RoHS-compliant; modern solder is made from other alloys of Tin, Copper, Silver and more exotic materials.

Many electronics professionals speak of RoHS derisively as the quality of Lead-free solder is only recently approaching that of old-school SnPb. It's generally harder to rework, doesn't flow as smoothly, is more brittle and doesn't look as nice.

Summary

- Power considerations are critical to Embedded Systems.
- Obvious factors such as voltage and current can have unexpected side-effects
  - level translation
  - decoupling.
- Designing circuit boards requires attention to
  - trace impedance
  - actual track thicknesses including etching effects
  - via sizes and aspect ratios
  - coefficients of thermal expansion
- Modern consumer electronics may not use leaded solder due to the RoHS directive. This may affect reliability