Lecture #2

Embedded Hardware

18-348 Embedded System Engineering

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Friday, 15-Jan-2016

Electrical & Computer ENGINEERING

Carnegie Mellon

Announcements

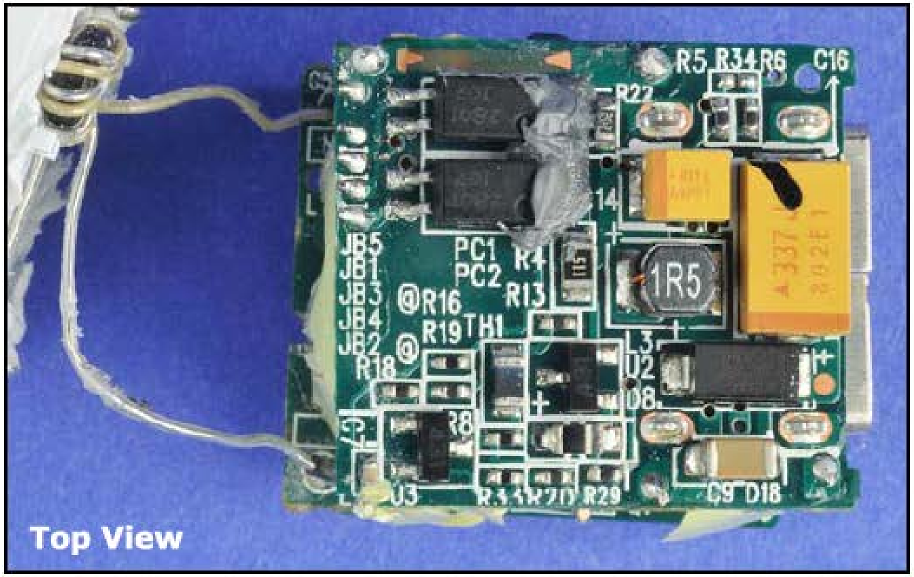
- **Many posted materials are accessible only from a CMU IP Address**
  - Look for this on course web page:
    If you can't access a file due to access restrictions, you need to get a campus IP address for your web browsing requests. Use Cisco VPN Anyconnect....
- **Course web page has schedules, assignments, other important info**
  - http://www.ece.cmu.ecu/~ece348
  - Blackboard will have grades, announcements, sample tests
  - Look at blackboard announcements before sending e-mail to course staff
- **Lab board handouts in progress**
  - See Blackboard/admin page for TA office hours
  - OK to go to any scheduled lab section (but, give priority to scheduled students)
  - For Friday prelab give a good faith attempt to get things working by the deadline
    - If you hit a showstopper get it fixed on Tuesday so you can do Prelab 2 on time.

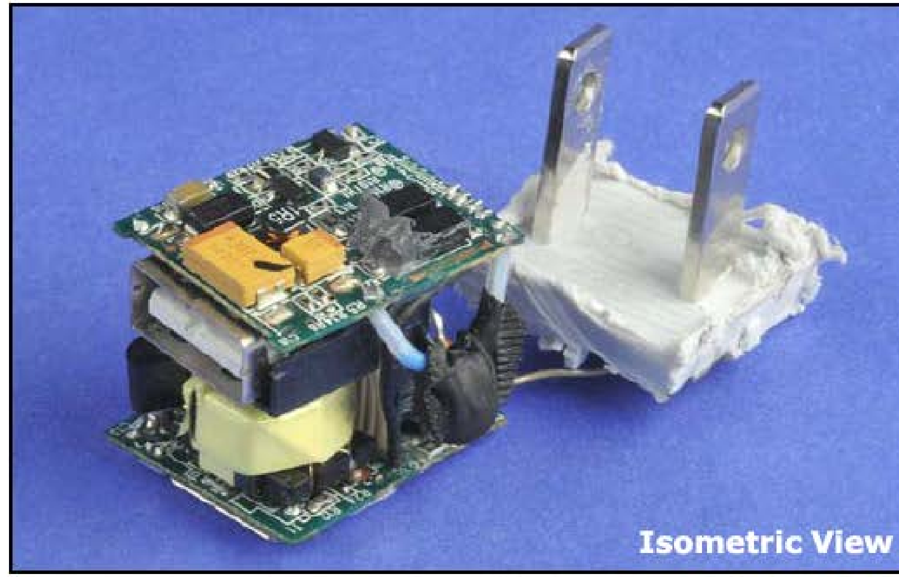
Design Example: Rack-Mount Power Supply

- **Power supply for server**
  - AC to DC conversion (750-1000W)
  - Coordinates 2 redundant supplies to maximize uptime
  - Safeguard against power problems (under/over-voltage; over-current; over-temp)
- **Typical approach:**
  - General microcontroller for AC, alarms, housekeeping
  - DSP runs control loop on DC side at > 10 KHz to provide stable DC power
- **Key requirement: "Doesn't emit smoke"**

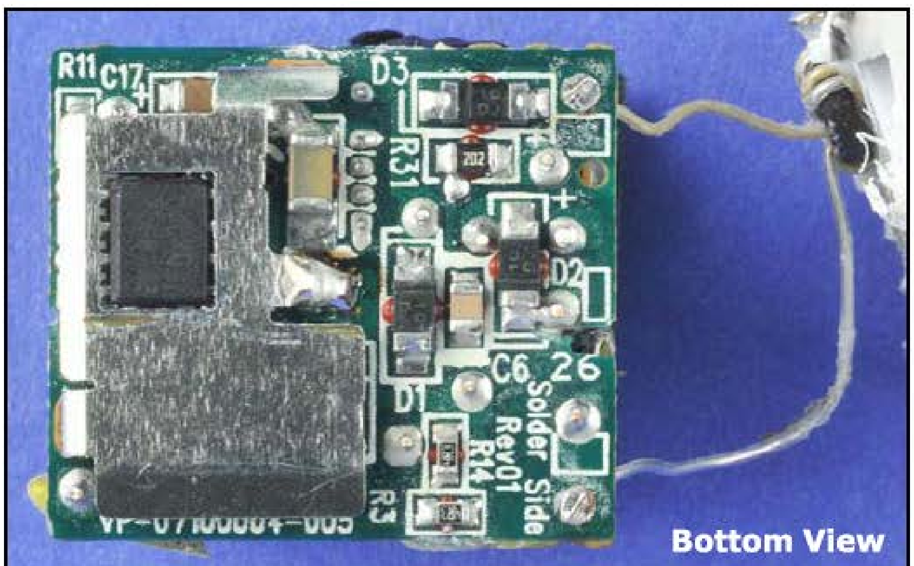
http://accessories.us.dell.com
Dell 870W Power Supply for PowerEdge R710 Server

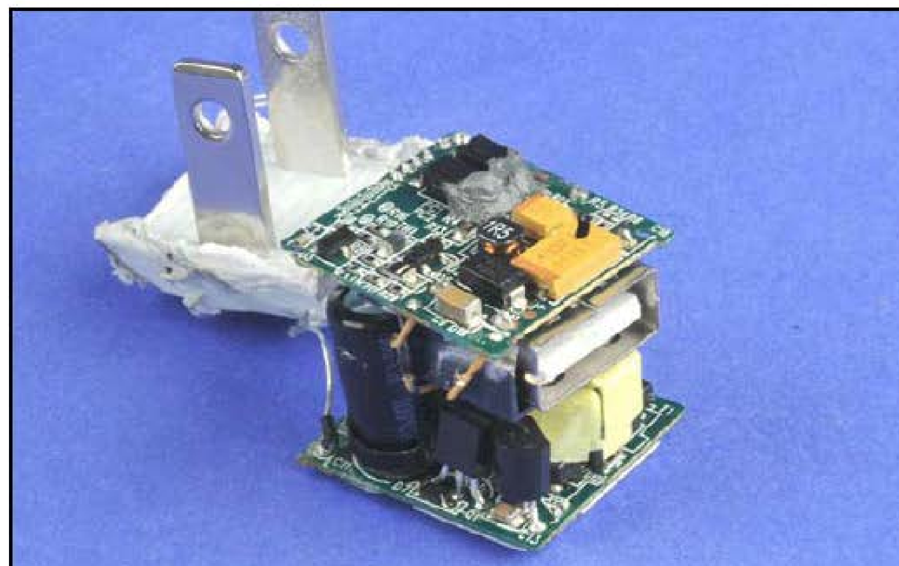
AC Adapter (Internal Components) iPhone 3G





Top, Bottom, and Isometric views show two PCBs, each populated on both sides.





Comments about costing?
Email us at feedback@teardown.com

Where Are We Now?

- **Where we've been:**
  - Course Intro
- **Where we're going today:**
  - Embedded system hardware
- **Where we're going next:**
  - Microcontroller assembly language
  - Engineering design approaches
  - Embedded-specific C
  - …

Preview

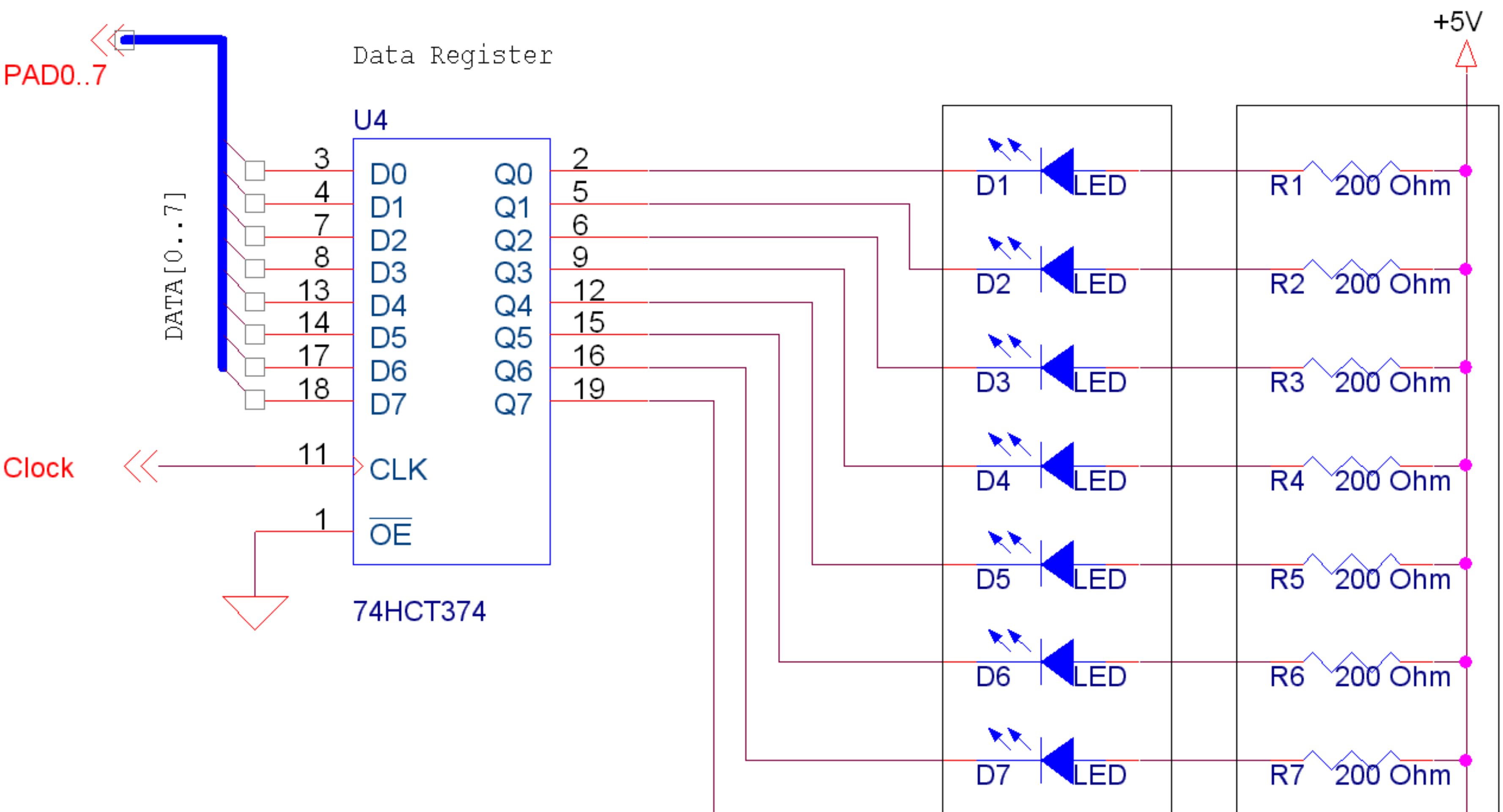
- **Microcontroller Hardware**
  - How does a microcontroller connect to the rest of the system?
  - I/O bus
  - Support circuitry
  - Power supplies

- **Hardware implementation**
  - Prototyping techniques
  - Printed circuit boards

- **Data sheets**
  - Tour of typical data sheet values

Hardware Schematics For Digital Electronics

- **Conventions:**
  - Chips are rectangles (except small logic gates); inputs on left; outputs on right
  - Pin numbers shown to make wiring easier
  - Thick blue line indicates a "bus" (8 wires bundled into one in this case)



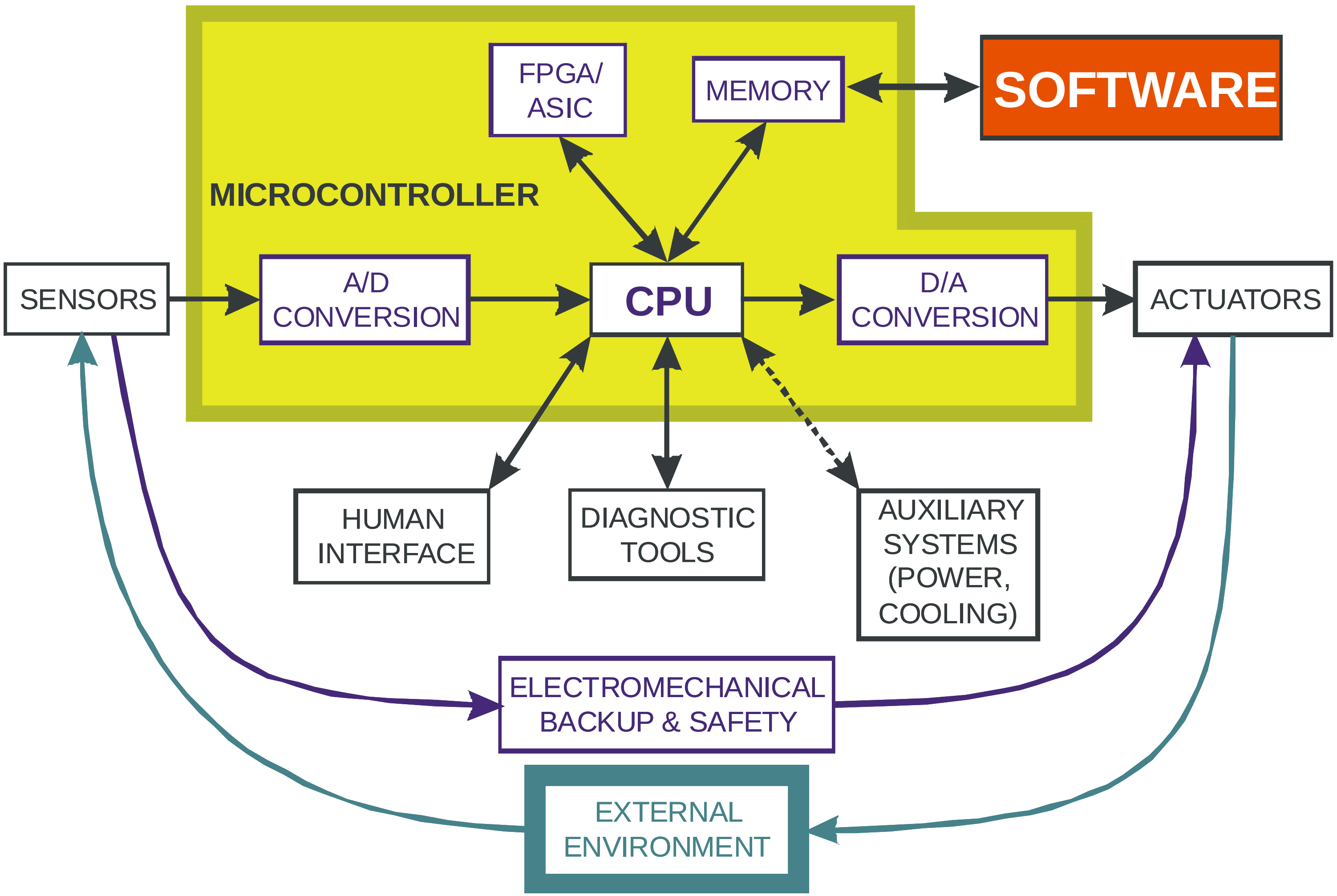
Schematic Capture Tools

- **OrCad or other professional-grade tools**
  - (Schematic on previous page drawn with demo OrCad)

- **Free tools from PCB vendors   ("Printed Circuit Board")**
  - For example, www.expresspcb.com (although I've never used their actual board service); there are several such vendors
  - http://www.freepcb.com/   open source (GPL)
  - Search term: printed circuit board prototype

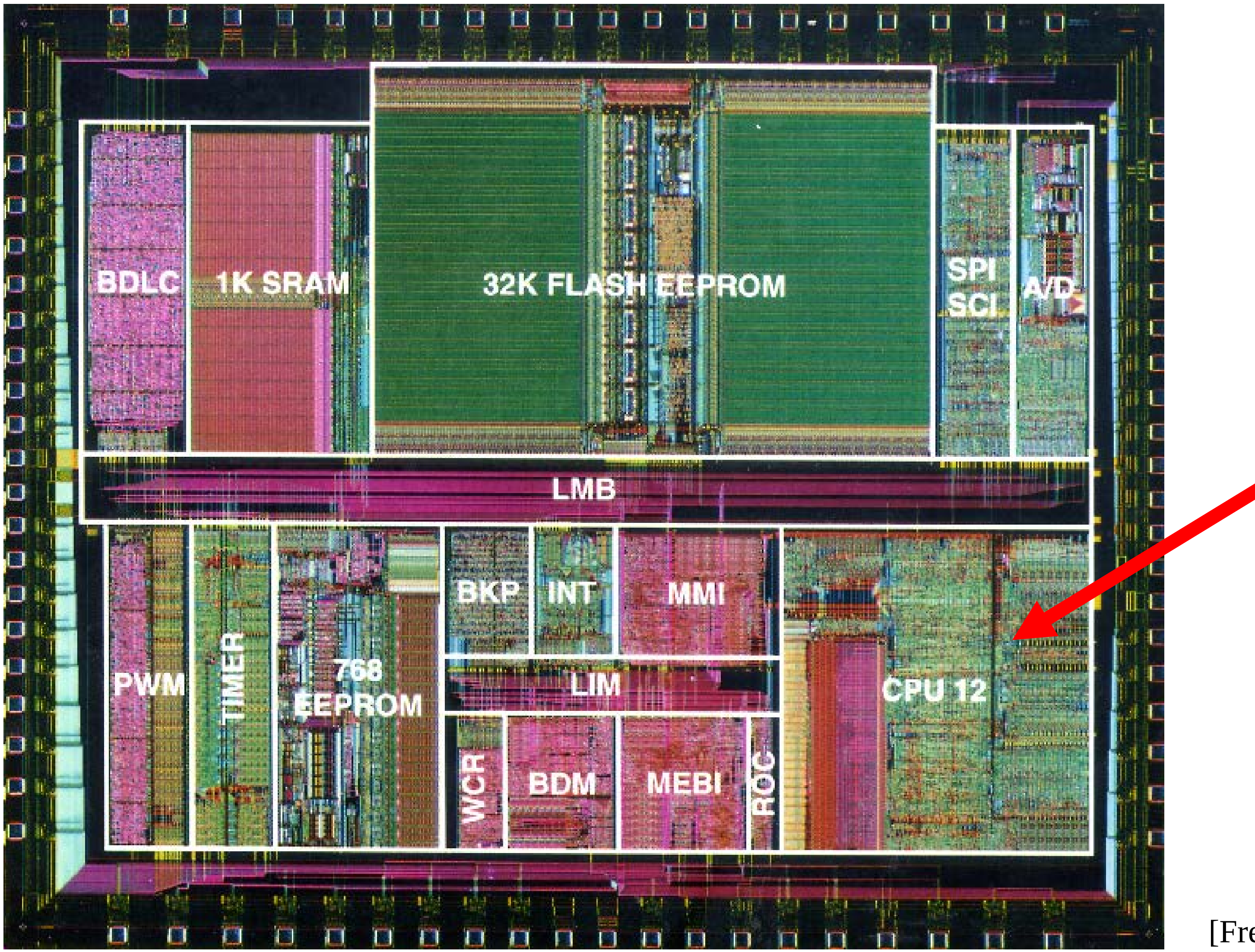
Stuff that goes around a microcontroller/overview

- **A microcontroller can't do much without surrounding parts**
  - Even though it has a lot of things already built into it
  - Let's talk about how you hook a chip up into a system



CPU 12 Microcontroller

- **The actual "CPU" is only a part of the chip**
  - Many peripherals and memory already integrated onto the chip



[Freescale]:

MC9S12 Block Diagram & Pinout

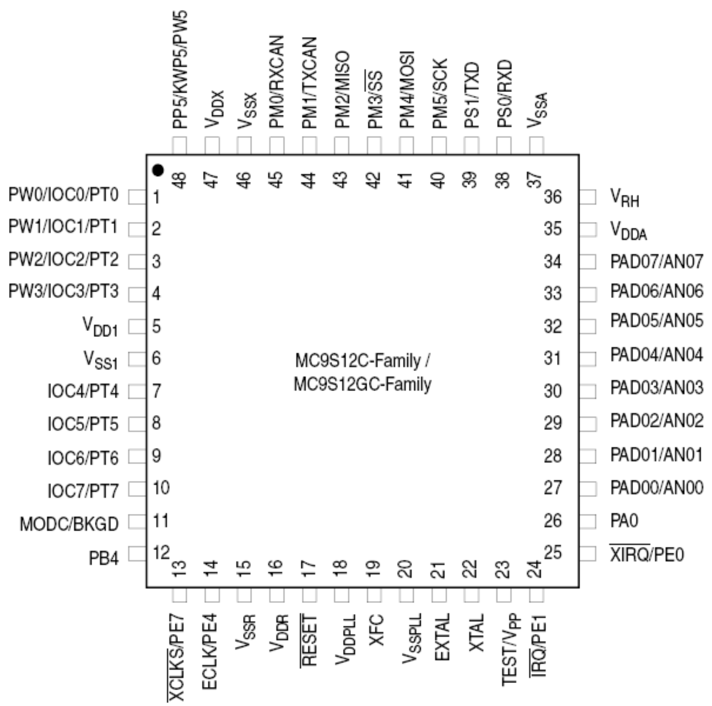


Figure 1-9. Pin Assignments in 48-Pin LQFP

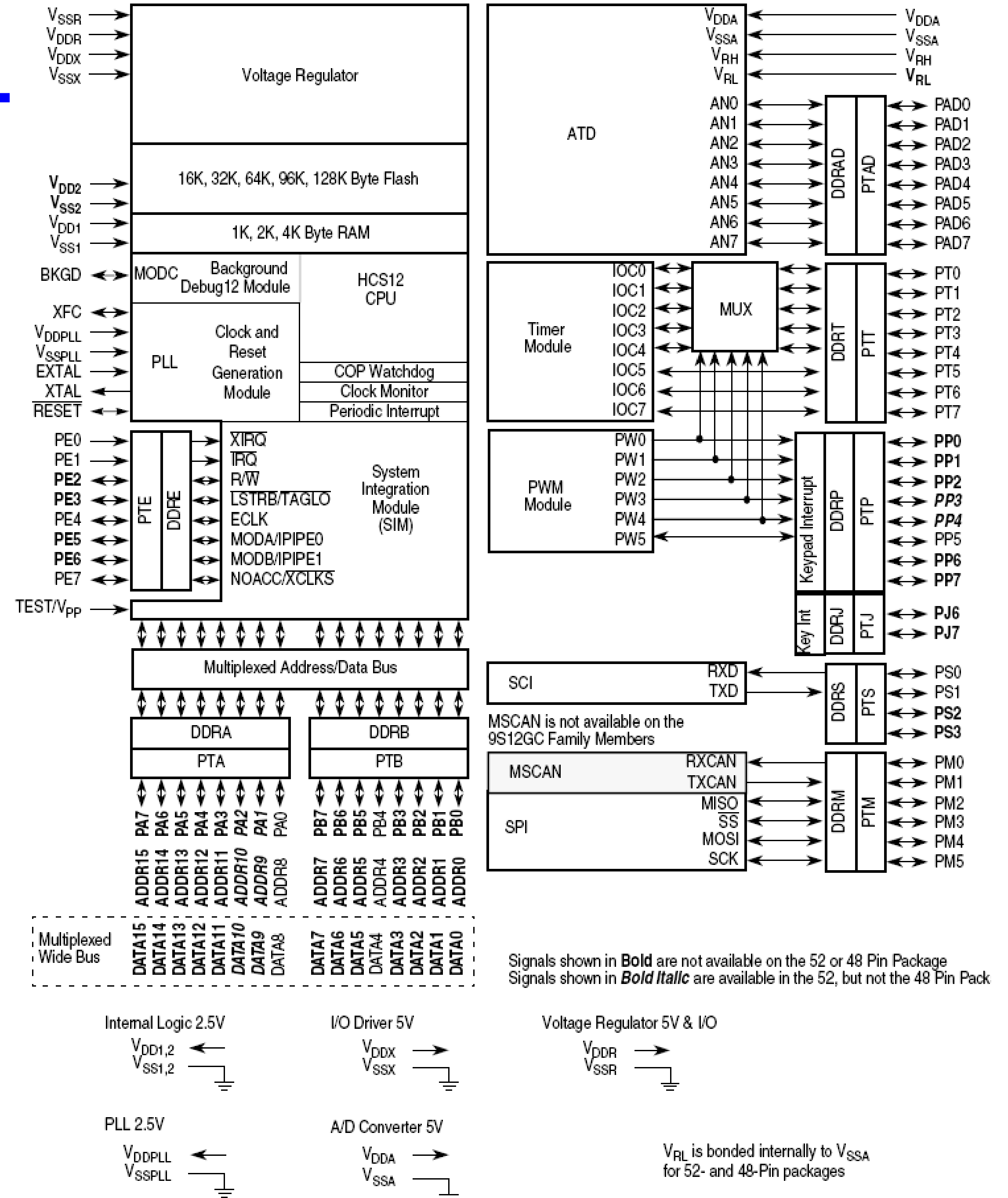
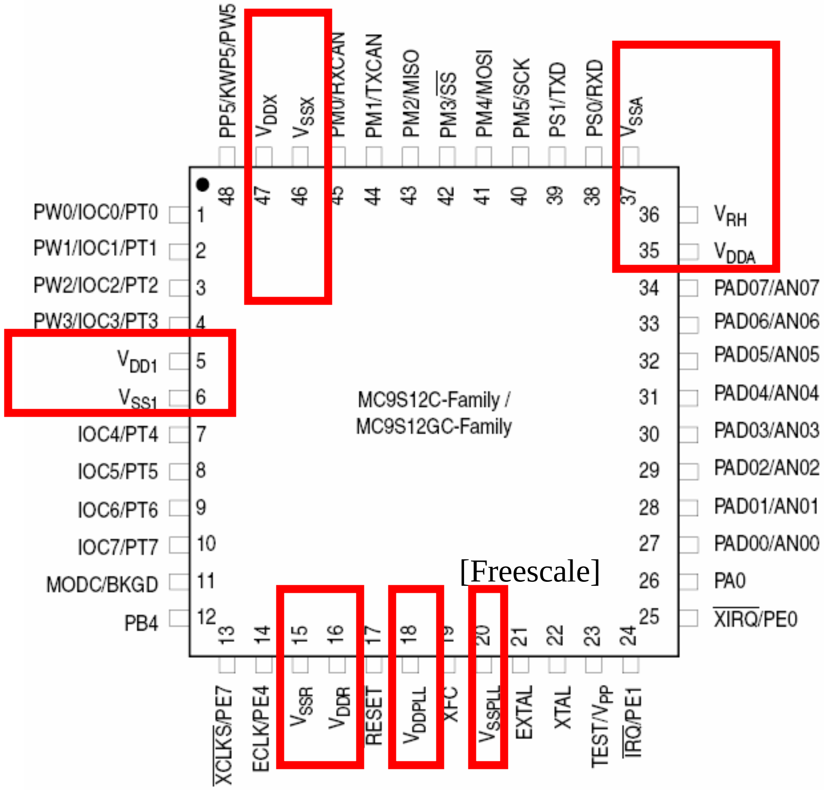


Figure 1-1. MC9S12C-Family / MC9S12GC-Family Block Diagram

[Freescale]

Power

- **DC electrical power to run the CPU and power I/O circuits**
- **Some standard voltages**
  - 5V DC – old style from the first commercial logic chips, but still in common use ("TTL logic levels")
  - 3.3V DC – common in newer designs
  - Lower voltages often used for low power



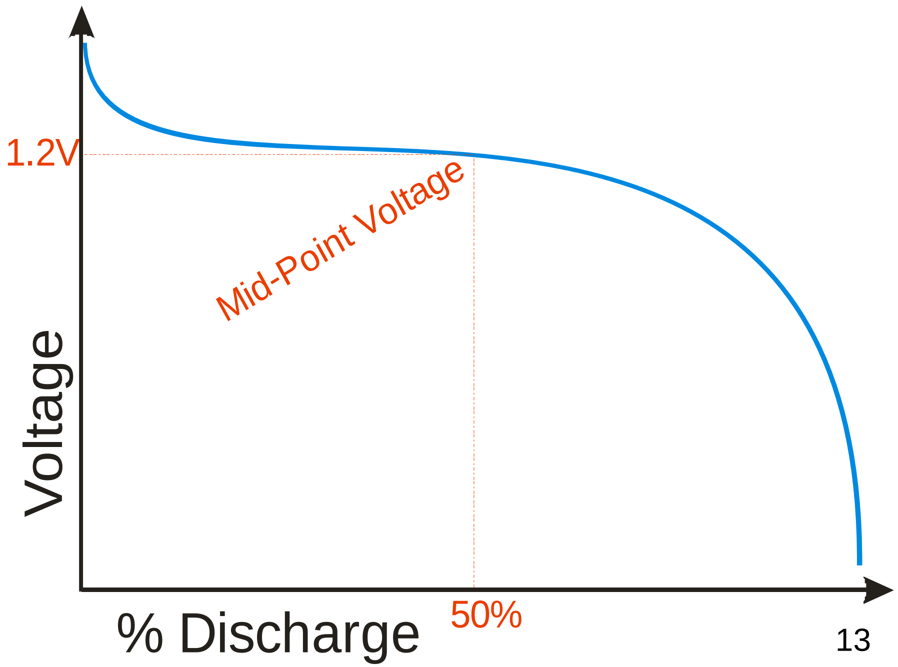
- **MC9S12C family:**
  - 5V for Analog functions and 5V interface
    - 2.97 to 5.5 volts allowed; can run at 3.3V
  - 2.5V for internal logic
    - 2.35 to 2.75 volts allowed
  - 25 mA maximum per pin drive current
  - Multiple power/ground pins
- **Actual voltages used depend on power strategy**
  - **Will this chip run on two NiCd or NiMH batteries? Does that provide 3V?**

Embedded Power Supplies

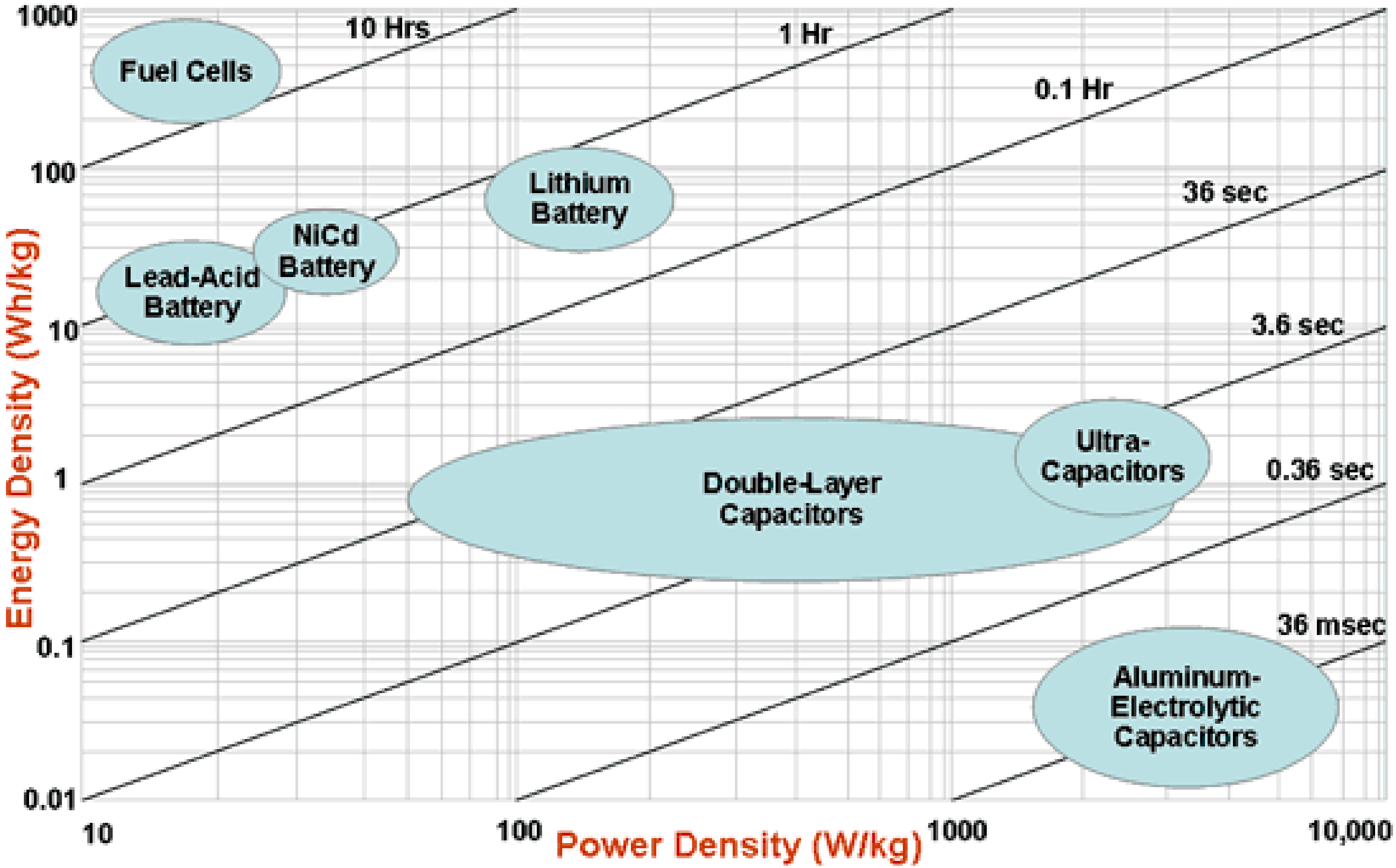
- **Battery**
  - Primary battery – alkaline is 1.5V nominal
  - Secondary battery (rechargeable) – NiMH is 1.2V nominal (so is NiCd)
- **Wall transformer**
  - A/C to DC conversion (a.k.a. "wall wart") – usually 5V to 12V DC output
- **Sometimes, on-board battery recharging (e.g., solar cells)**

- **Need DC voltage regulation – even for batteries**
  - Battery voltage isn't constant
  - Nominal rating at mid-point voltage
  - 4 @ NiMH cells 1.2V nominal => 4.8V
  - Mostly discharged, 1.1V/cell => 4.4V total

- **On-circuit board power regulation:**
  - Usually DC to DC converters
  - "Boost" converter increases DC voltage
    - Usually inefficient
    - But, reduces # of battery cells needed
  - "Buck" converter decreases DC voltage



High Power or High Energy (but not both)



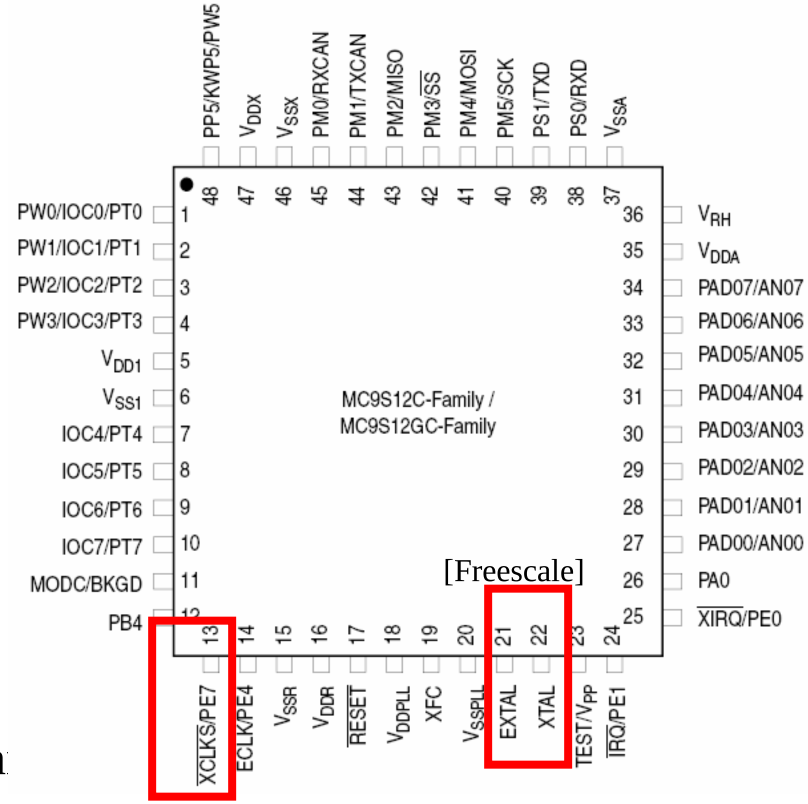
Source US Defence Logistics Agency

http://www.mpoweruk.com/performance.htm

Oscillator/“clock”

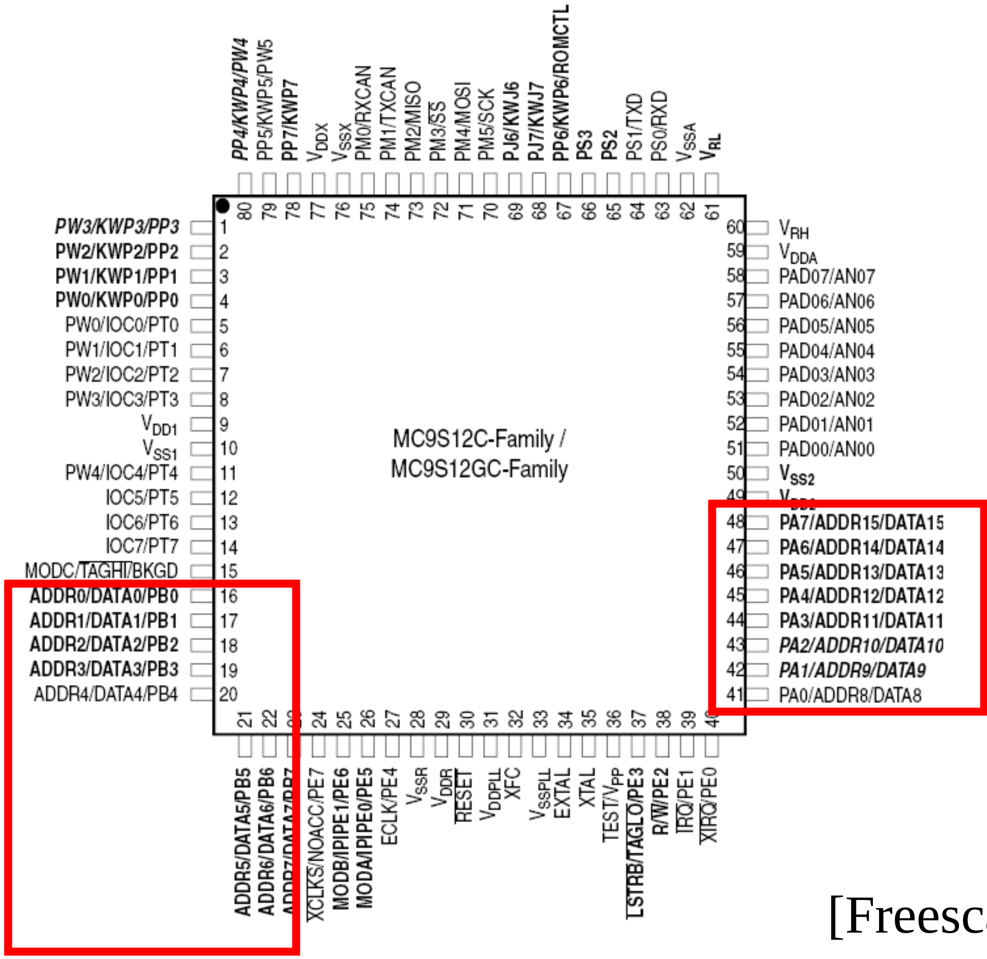
- **Periodic square wave for clocking the CPU**
  - Has an internal low-quality oscillator
  - Permits use of an external high-quality oscillator
  - ***Why both options?* -- *cost***

- **MC9S12C family oscillator speeds**
  - 0.5 to 16 MHz on internal oscillator
  - 0.5 to 40 MHz external
    (input must be ~50% duty cycle)
    - Each edge triggers internal actions
  - XCLKS used at startup to select internal vs. external oscillator
  - Why “slow” clock speeds?
    - Keeps costs down – can use old process tech
    - Saves power; reduces need for cooling
    - Fast enough for many purposes
    - Reduces emitted radio interference



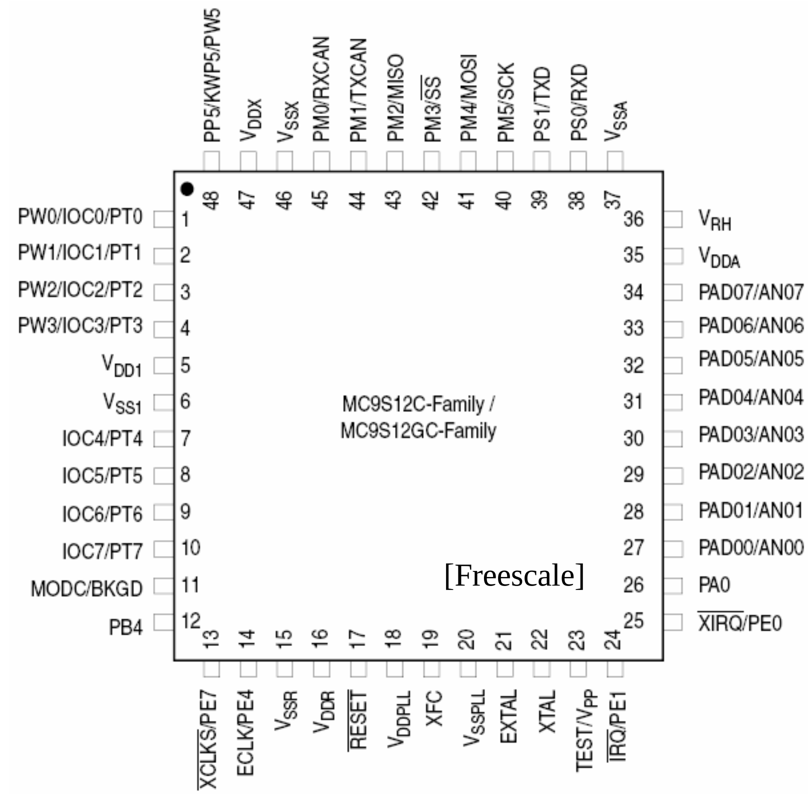
I/O bus: data; address

- **We’re using a smaller package (48 pin) to reduce costs**
  - That package doesn’t put the memory bus on the pins



Signals shown in **Bold** are not available on the 52- or 48-pin package
Signals shown in ***Bold Italic*** are available in the 52-pin, but not the 48-pin package

Figure 1-7. Pin Assignments in 80-Pin QFP



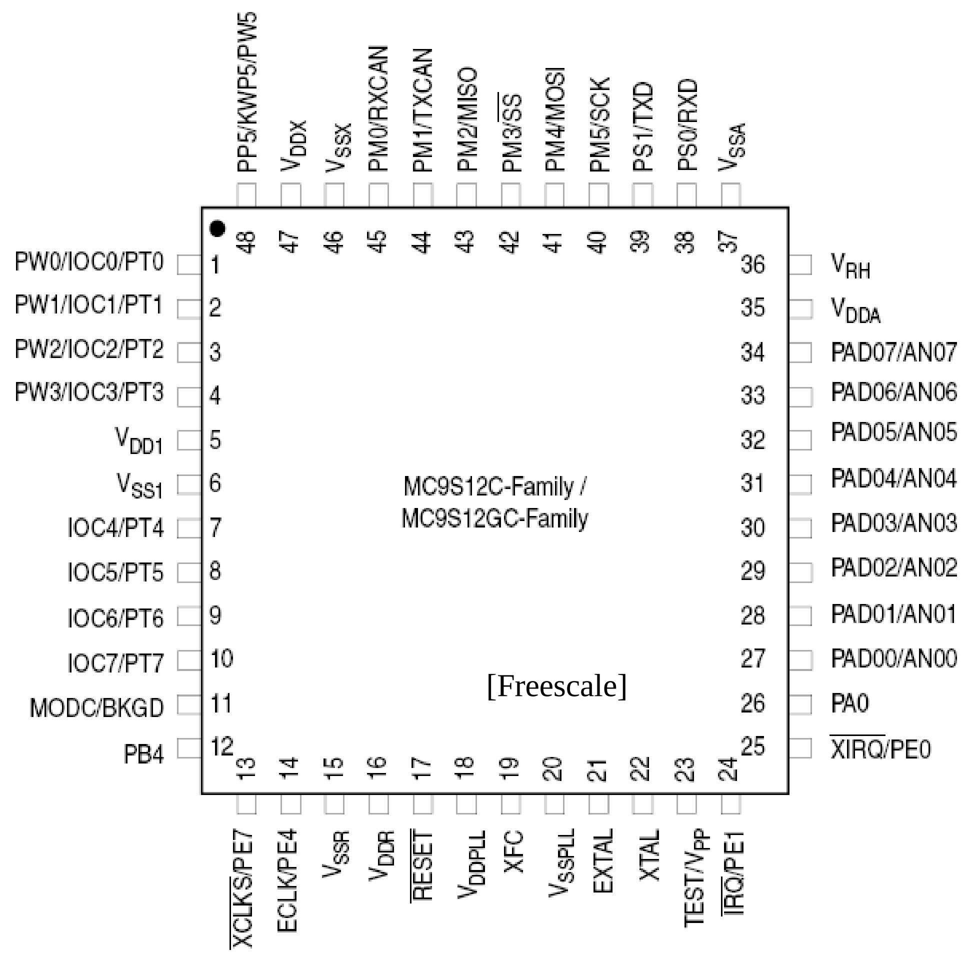
[Freescale]

Available I/O pins

- **Pins are used for multiple purposes to reduce packaging costs**
  - Configuring chip to put right signals on the right pins is chapter 2 of data sheet
    - It's really tricky and confusing
  - Initially, we'll give you code to set up chip the right way for labs

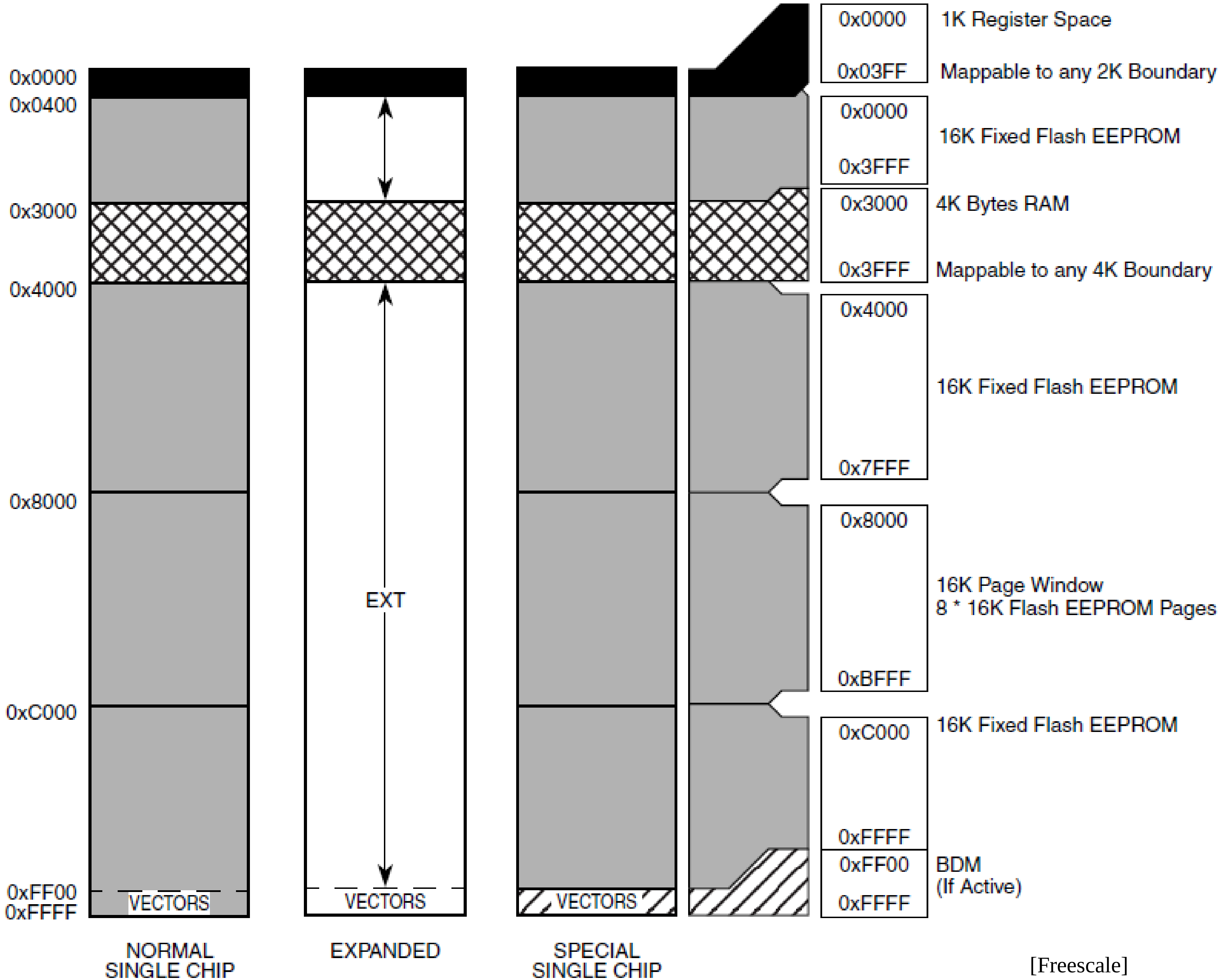
- **Most important pins:**
  - PAD00..PAD07 // AN00 .. AN07
    provides digital and analog I/O
  - PT0..PT7
    provides additional digital I/O
  - PW0..PW3
    provides hardware-assisted
    pulse generation

- **Data sheet lists all the signals**



Registers & Memory Maps

- **How do you get data on and off the pins?**
  - Interface to I/O is done via **“registers”** (a set of flip-flops on the chip)
  - Write to registers to configure the pins – e.g., is it digital or analog?; in or out?
  - Read/write other registers to actually do I/O
    - Read a byte from switches by reading register associated with digital inputs
    - Write a byte to LEDs by writing a register associated with digital outputs
    - But in both cases, first configure I/O via setting some register, then read/write values from a different register
- **How do you access these registers?**
  - In some processors, an I/O instruction (x86: IN and OUT)
  - In our processor, I/O is **“memory mapped”**
    - Use “load” and “store” instructions to special memory addresses
- **A memory map tells you where things are in memory**
  - Some of memory is RAM
  - Some of memory is ROM
  - Some of memory is I/O register space
  - Look for the memory map in the data sheet. Lots more detail in later lectures

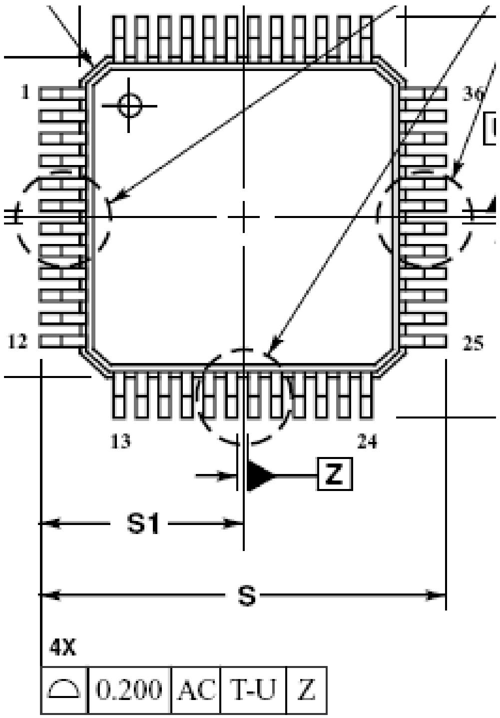


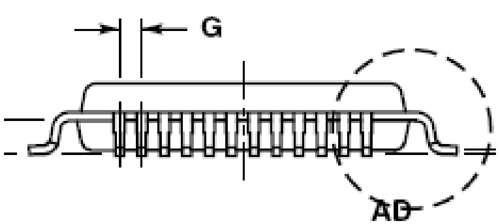
0x0000
0x0400
0x3000
0x4000
0x8000
0xC000
0xFF00
0xFFFF
VECTORS
VECTORS
VECTORS
EXT
NORMAL SINGLE CHIP
EXPANDED
SPECIAL SINGLE CHIP
0x0000
0x03FF
1K Register Space
Mappable to any 2K Boundary
0x0000
0x3FFF
16K Fixed Flash EEPROM
0x3000
0x3FFF
4K Bytes RAM
Mappable to any 4K Boundary
0x4000
0x7FFF
16K Fixed Flash EEPROM
0x8000
0xBFFF
16K Page Window
8 * 16K Flash EEPROM Pages
0xC000
0xFFFF
16K Fixed Flash EEPROM
0xFF00
0xFFFF
BDM
(If Active)

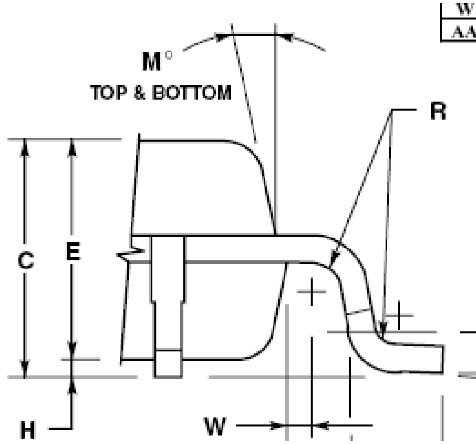
[Freescale]

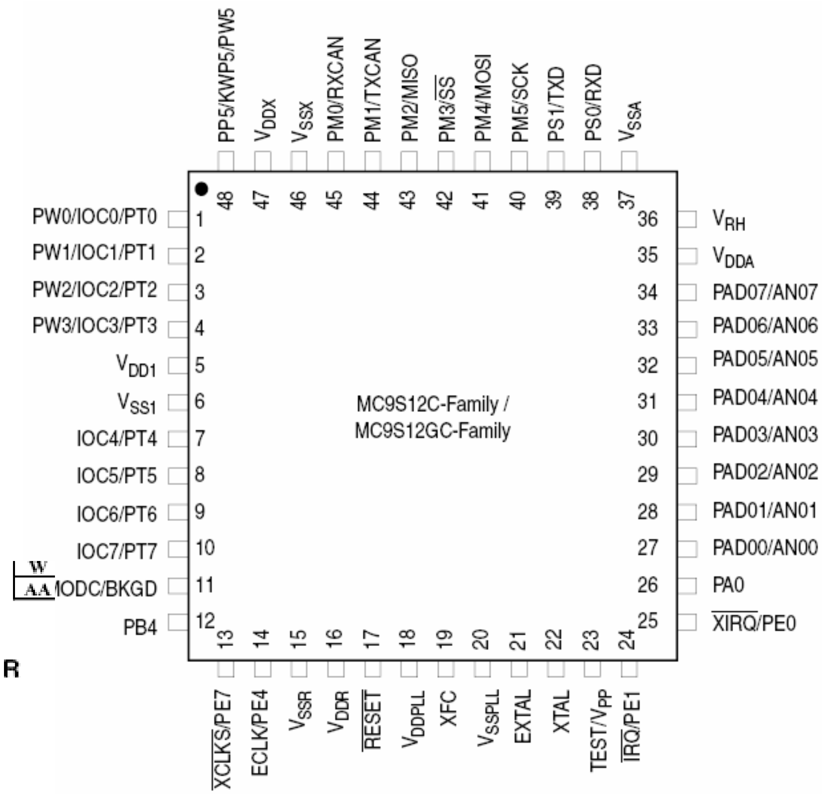
Chip packaging

- **48-pin LQFP (low-profile, quad, flat package)**
  - (surface mount – pins soldered to top layer of circuit board)
  - Pin 1 is found at the molded circle in the package





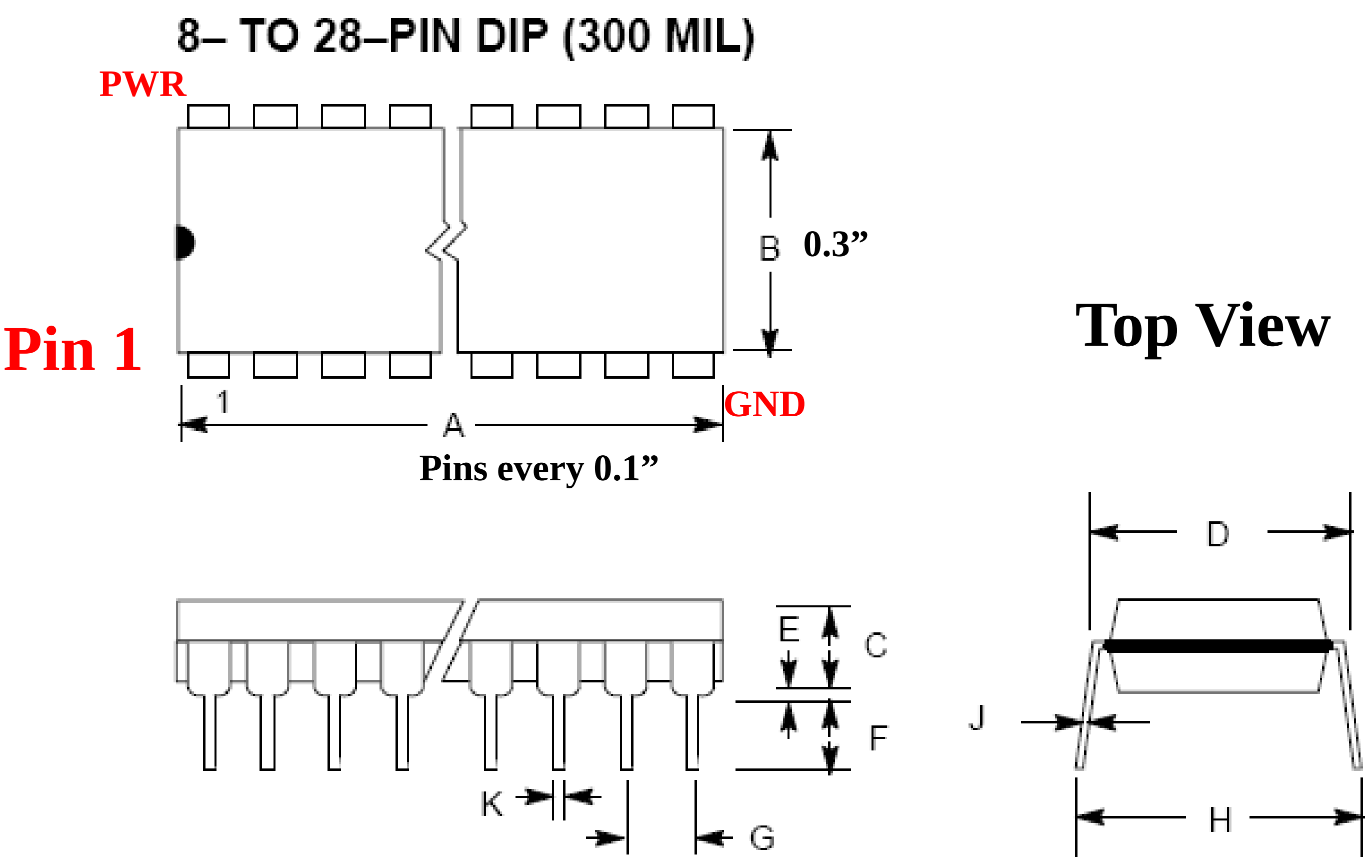




[Freescale]

Which one is pin 1???

- **DIP = “dual in-line package”**
  - Through-hole mounting – chip pins go through circuit board
  - For N-pin DIP, ground is pin N/2; power is pin N
    e.g., 20-pin DIP – pin 10 is ground; pin 20 is power
  - ***If you put the chip in backward, you reverse power & ground; smoke ensues***



[maxim-ic]

Breadboards/proto-boards

- **Simple to use – push in wires, DIPs, other components**
  - Easy to use, but fragile (easy to pull out wires)
  - After a few hundred insertions, they wear out

- **Tips:**
  - Try to keep wires neat
  - Put all pin 1s to the left (if horizontal) or top (if vertical)

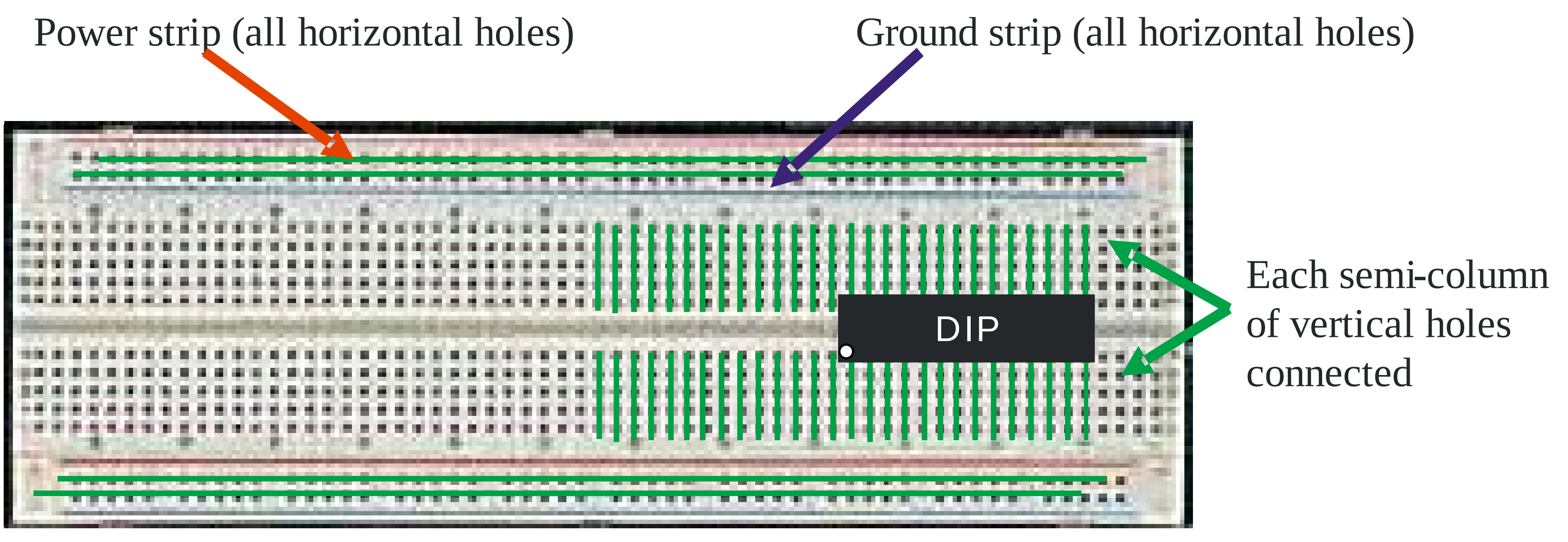
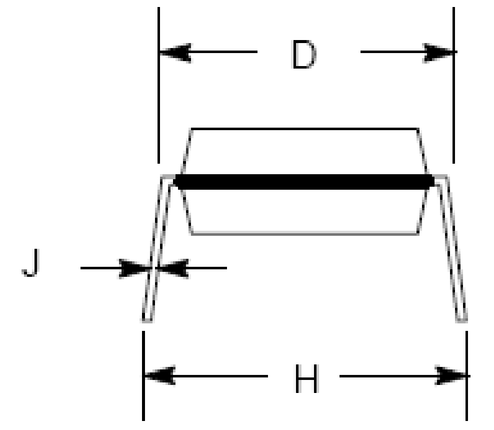


Photo portion: [Axiom]

How to insert a chip in a socket or proto-board

- **Pins are further apart than socket holes**
  - Dimension “H” is bigger than Dimension “D” but sockets are sized for Dimension “D”
  - This keeps pins from dropping out of holes for printed circuit boards without sockets – but it makes using sockets a problem

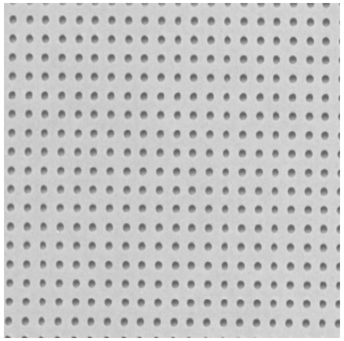


[maxim-ic]

- **To insert a chip**
  - Touch something metal first to discharge any static (in industry, use a grounding strap on your wrist or ankle)
  - Use a chip insertion tool if you have one (it pushes the pins straight)
    OR
    gently bend the pins together using a flat table top so they are straight
  - Push the DIP in, making sure than no pins get bent under
- **To remove a chip**
  - Use a chip removal tool if you have one
  - Else use a small screwdriver to pry the chip loose at each end, then rock it free

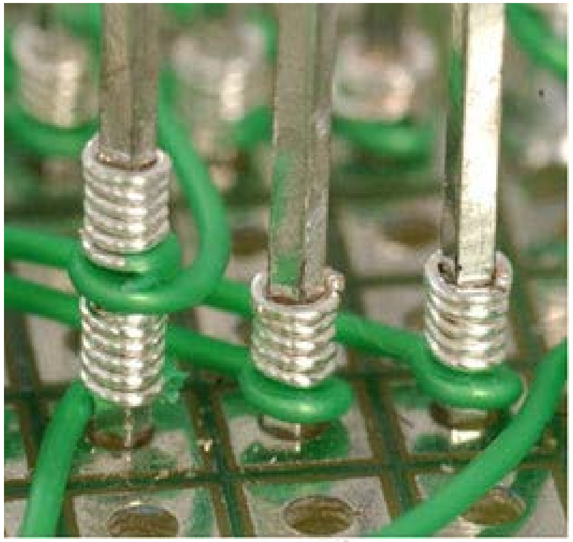
Other Prototyping techniques

- **"Perf board"**
  - Boards with "perforated" (punched) holes on 0.1" centers
  - Can put in sockets and solder wires to make connections



[Jameco]

- **Wire wrap**
  - Usually perf board, but with special sockets with long square pins
  - Wire wound around the square pins makes the connections
  - Pins are long enough to fit three wrapped wires



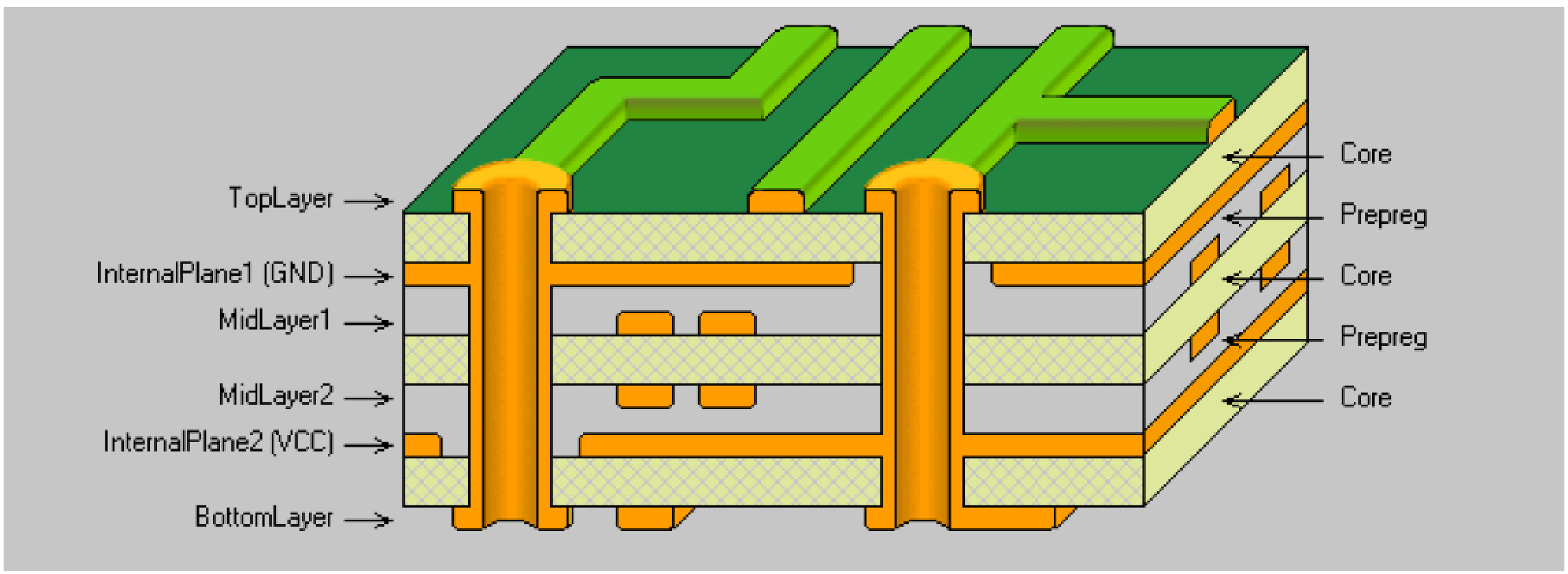
[Jameco]

- **Printed circuit boards**
  - You can get 'quick turn' boards in small numbers fairly inexpensively
  - But, making changes is painful

Printed circuit boards

- **One or more sheets of thin fiberglass coated with copper on both sides**
  - Copper is etched away to leave circuit traces and “pads”
  - Holes are drilled through to make “vias” and places for DIP pins
  - Insulation between fiberglass is “prepreg” – pre-impregnated bonding layers
- **Good idea to have plenty of power and ground**
  - Usually want dedicated ground layer & dedicated power layer

Multi layer Design

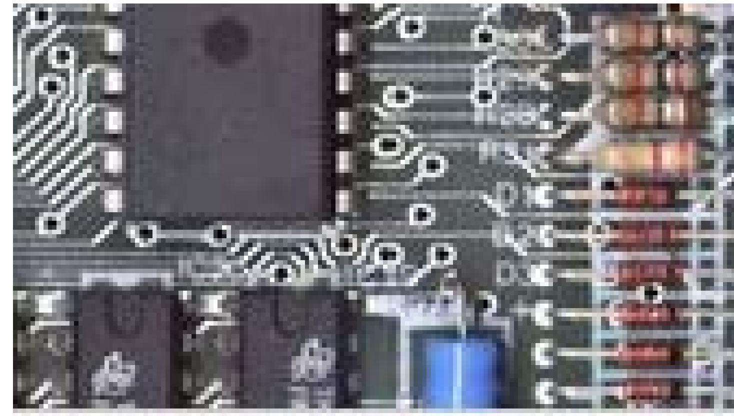


Typical 6 Layer PCB Construction

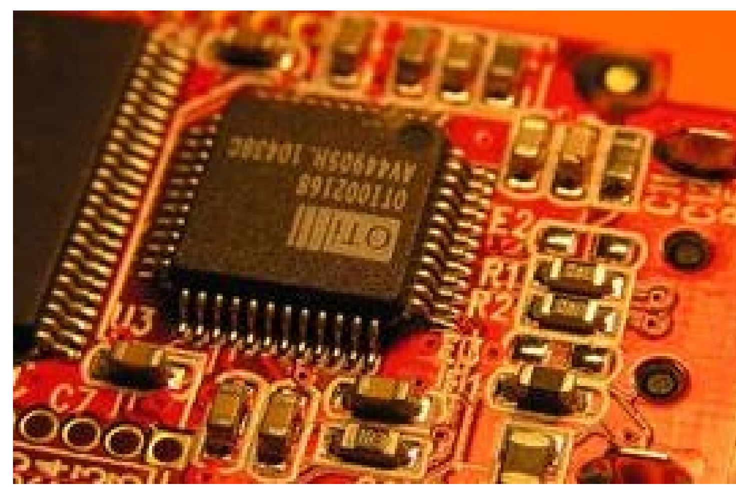
[Jones94]

Through-hole vs. surface mount

- **Through-hole**
  - DIP pins and resistor leads, etc. go all the way through the PCB
  - Each pin eats up space on every layer of the board
  - Older technology – requires wide pin spacing and works poorly with more than about 8 layer PCBs



- **Surface mount**
  - Pins only attach on top layer
  - Finer pitch pins, higher density
  - Newer technology
  - Difficult (or with Ball Grid Array pretty much impossible) to hand-solder prototypes without using sockets.

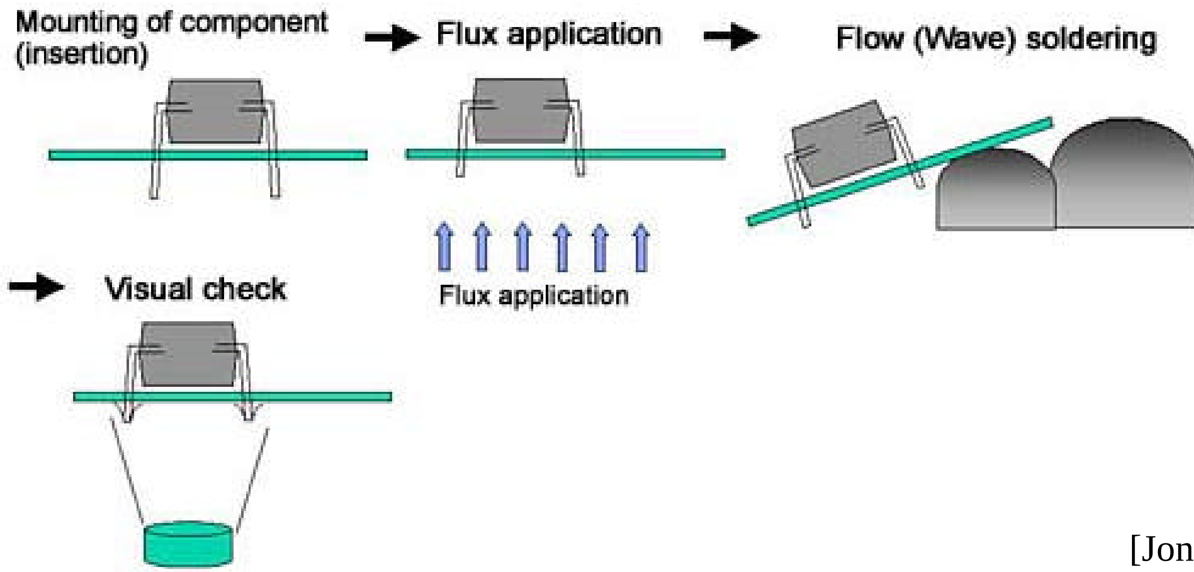


[Wikipedia]

Getting Components On To The Board

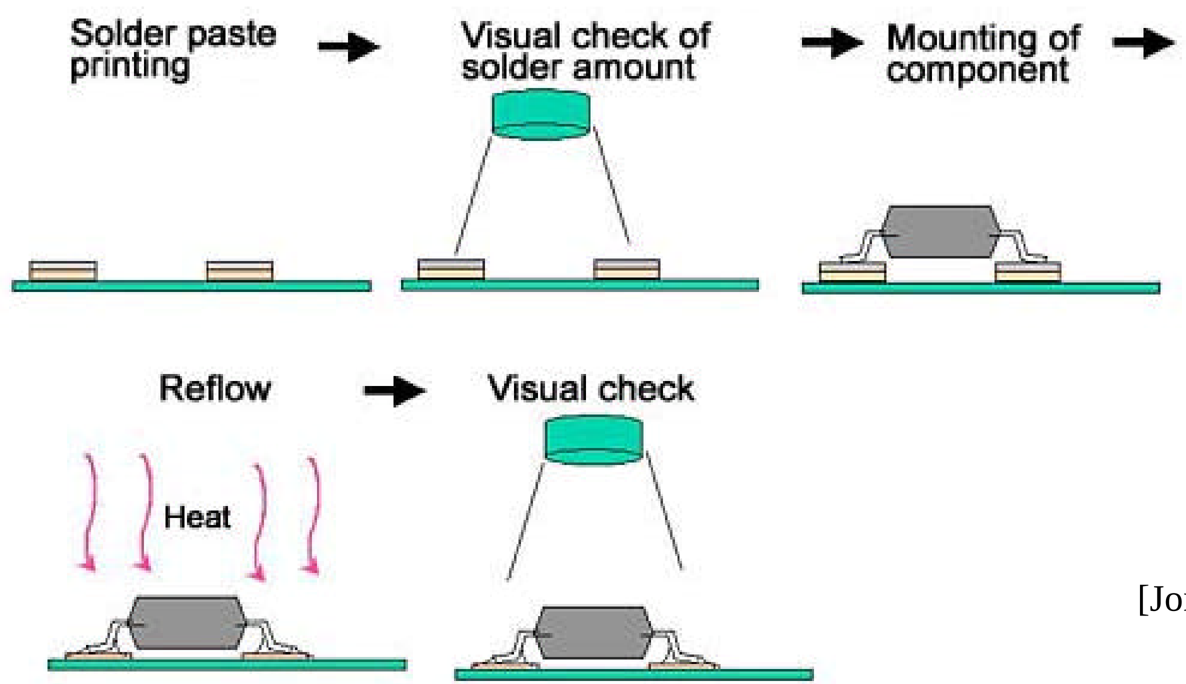
- **Wave soldering:**

RoHS: Restriction of Hazardous Substances (get the lead out of solder)



[Jones94]

- **Reflow Soldering:**

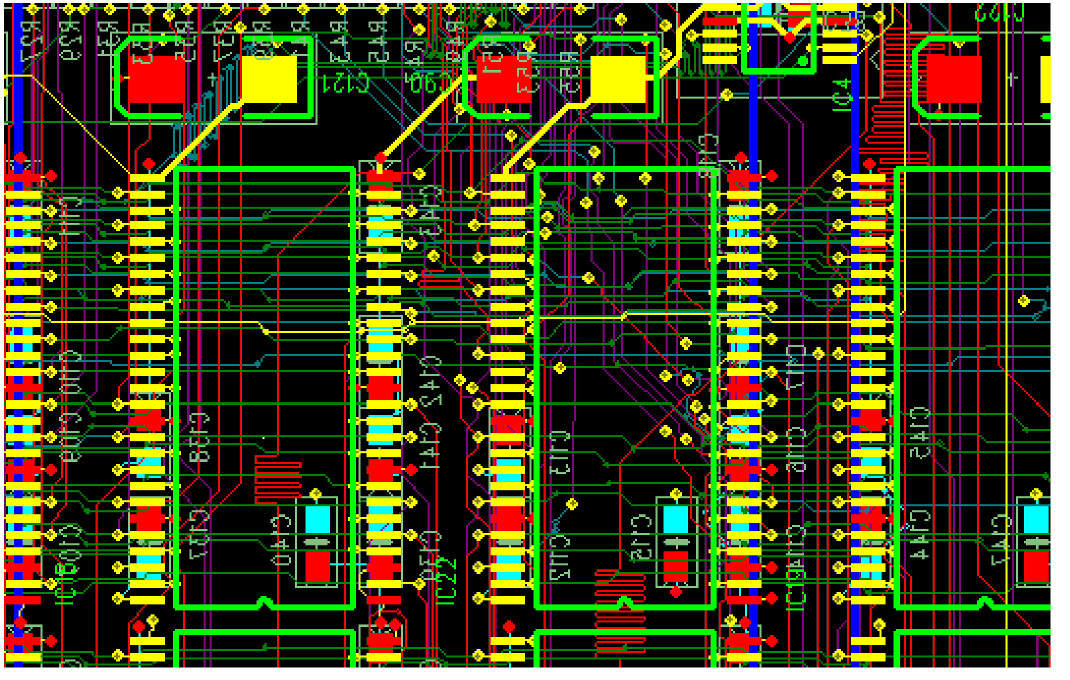


[Jones94]

Layout tools & challenges

- **Layout is a difficult 2.5-dimension puzzle**
  - K layers, where K is usually even
  - Pretty much like IC layout – very similar algorithms
  - Auto-routers have gotten better over time, but still some hand-assist
  - Using a CAD tool, each layer is a different color

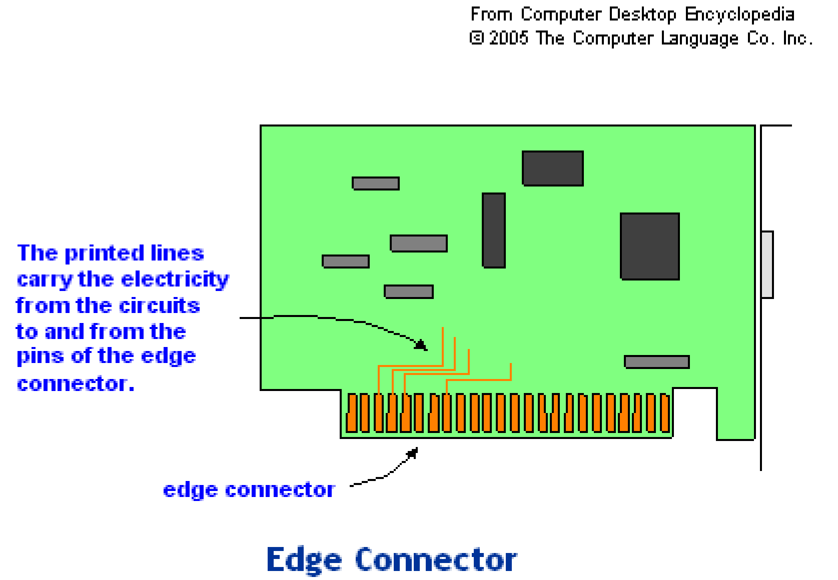
- **Common design strategies**
  - Dedicated layer for power and for ground (helps with noise)
  - Even layers are mostly horizontal, odd layers are mostly vertical



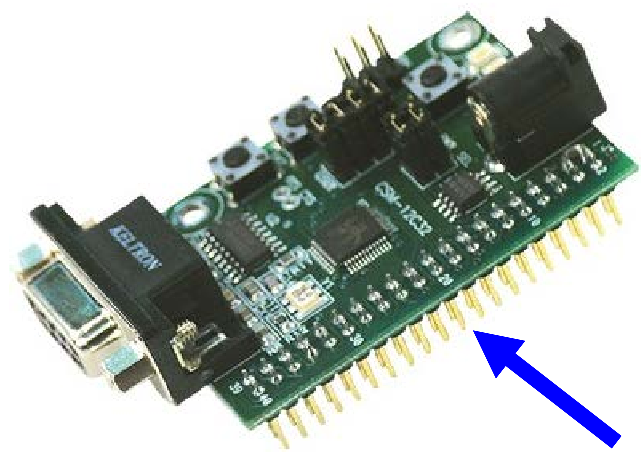
[eeinternational.net]

External connectors: headers; edge connectors

- **Edge connectors**
  - Plated areas of circuit board
    - Usually gold or copper
    - Tin tends to corrode – unreliable
  - Old-style PCs used these to connect onto motherboard (ISA bus)



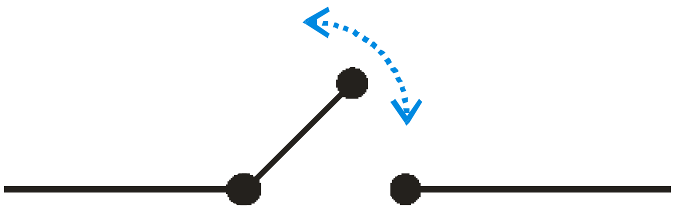
- **Headers**
  - A set of posts for connecting
  - Posts insert into sockets or can be clipped, wire-wrapped, soldered to, etc.
  - Especially popular – ribbon cable (caution, most ribbon cables only good for a half-dozen insertions before becoming unreliable!)



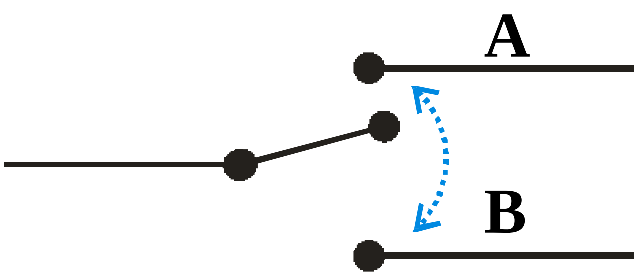
[Freescale]

Switches

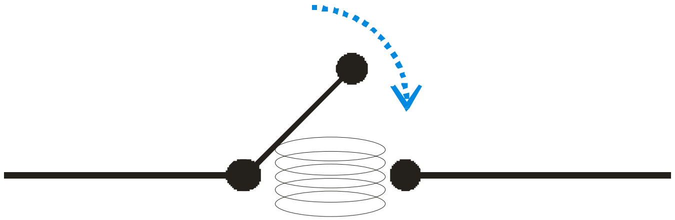
- **Single pole, single throw switch**
  - E.g., ordinary house lighting switch
  - It's "on" or "off" and switches a single line
  - Stays "on" or "off" unless moved



- **Double pole, single throw switch**
  - 3-way house lighting switch
  - Either "side A on" or "side B on"
  - Stays on A or B once there, unless moved



- **Momentary switch**
  - "normally open" – "off" normally, "on" when pressed
    - These are the switches on the lab project board
  - "normally closed" – "on" normally, "off" when pressed
    - The brake pedal on your car is this type of switch



Data sheets overview

- **Data sheets are the roadmap to a chip**
  - Vary between 1 sheet and 500+ sheets
  - Every circuit part has a data sheet – even a resistor or socket
  - In industry, there is a library of data sheets for approved parts (and getting a new part approved is a huge deal – so you use parts that are already approved)

- **Data sheet content**
  - Pinout
  - Physical characteristics (package size, pin type, etc.)
  - Electrical characteristics
  - Thermal limits
  - Etc.

- MC9S12C data sheet Appendix A has electrical characteristics

Key items in data sheet: speeds

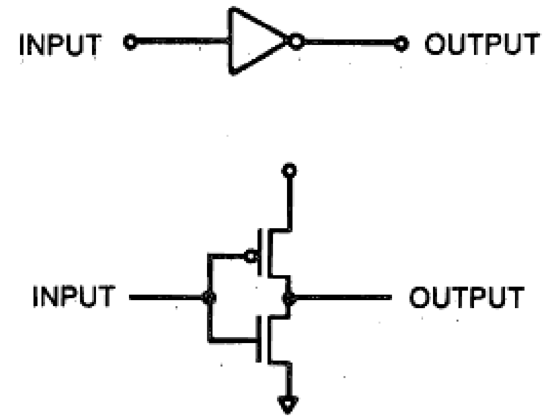
- **Propagation delays**
  - Low to high and high to low are sometimes different speeds
  - Speeds depend on operating conditions

PARAMETER	SYMBOL	TEST CONDITIONS	V_{CC} (V)	25°C MIN	25°C TYP	25°C MAX	-40°C TO 85°C MIN	-40°C TO 85°C MAX	-55°C TO 125°C MIN	-55°C TO 125°C MAX	UNITS
HC TYPES											
Propagation Delay Clock to Output	t_{PLH}, t_{PHL}	C_L = 50pF	2	-	-	165	-	205	-	250	ns
			4.5	-	-	33	-	41	-	50	ns
		C_L = 15pF	5	-	15	-	-	-	-	-	ns
		C_L = 50pF	6	-	-	28	-	35	-	43	ns
Output Disable to Q	t_{PLZ}, t_{PHZ}	C_L = 50pF	2	-	-	135	-	170	-	205	ns
			4.5	-	-	27	-	34	-	41	ns
		C_L = 15pF	5	-	11	-	-	-	-	-	ns
		C_L = 50pF	6	-	-	23	-	29	-	35	ns

[TI]

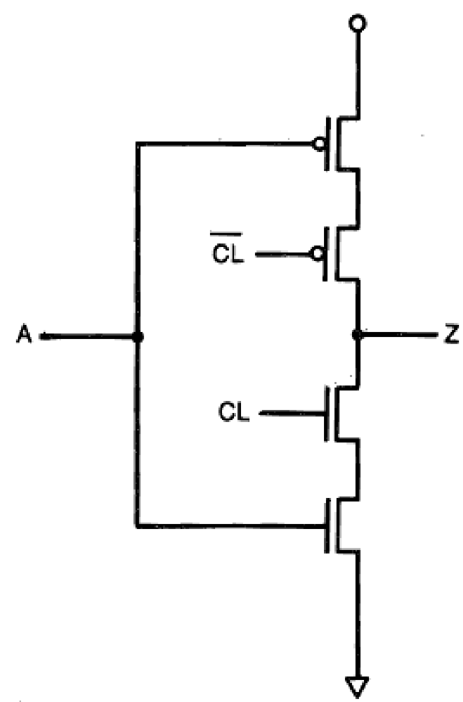
Outputs & Inputs

- **Regular output driver and input buffer:**
  - Amplifies on-chip to off-chip current capability
  - Usually just an inverter with big (high drive) transistors
    - (real chip implementations more complex; but that's the basic idea)



[Weste95]

- **Tri-state output drivers:**
  - Has ability to output "0", "1", or "Hi-Z" (off)
    - CL high turns it on, propagating input A
    - CL low turns output off (Hi-Z)
  - Allows multiple chips to drive the same signal



Key items in data sheet: electrical specifications

- **Be sure to look for**
  - Power consumption when running
  - Input and output parameters, especially
    - Input switching thresholds: V_{IH}, V_{IL}
    - Output drive currents: I_{OH}, I_{OL} (in mA or ‘standard loads’)

DC Electrical Specifications (Continued)

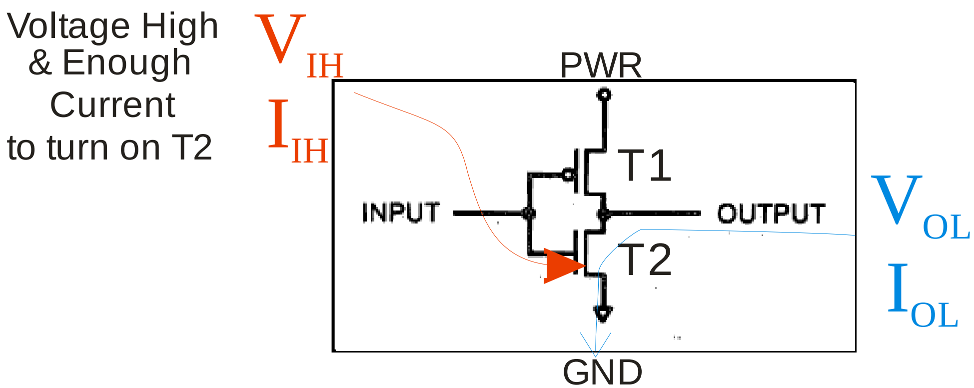
PARAMETER	SYMBOL	TEST CONDITIONS		V_{CC} (V)	25°C			-40°C TO 85°C		-55°C TO 125°C		UNITS
		V_I (V)	I_O (mA)		MIN	TYP	MAX	MIN	MAX	MIN	MAX	
Quiescent Device Current	I_{CC}	V_{CC} or GND	0	6	-	-	8	-	80	-	160	µA
Three- State Leakage Current	V_{IL} or V_{IH}	$V_O = V_{CC}$ or GND	-	6	-	-	±0.5	-	±5.0	-	±10	µA
HCT TYPES												
High Level Input Voltage	V_{IH}	-	-	4.5 to 5.5	2	-	-	2	-	2	-	V
Low Level Input Voltage	V_{IL}	-	-	4.5 to 5.5	-	-	0.8	-	0.8	-	0.8	V

[TI]

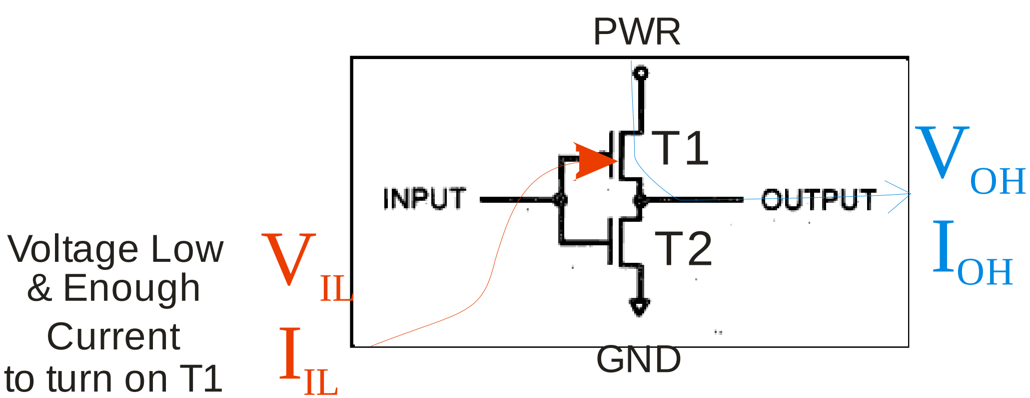
Key Voltage & Current Specifications

Input switching thresholds:

- V_{IH} = Input Voltage that is seen as a "high" input
  - For example, any input above 2 Volts is High; V_{IH} = 2V



- V_{IL}= Input Voltage that is seen as a "low" input
  - For example, any input below 0.8 Volts is Low; V_{IL} = 0.8V
  - In these examples: anything between 0.8V and 2.0V is indeterminate

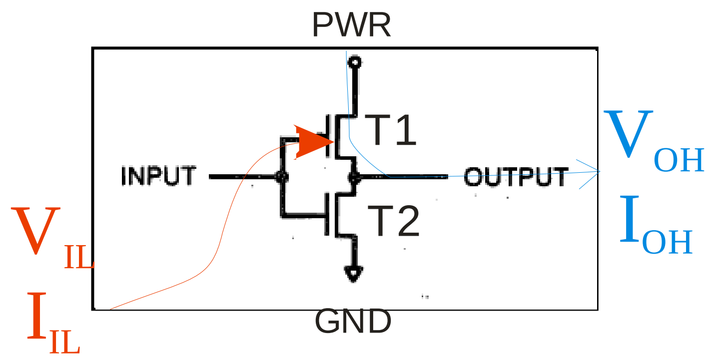


Key Voltage & Current Specifications

◆ Output drive currents:

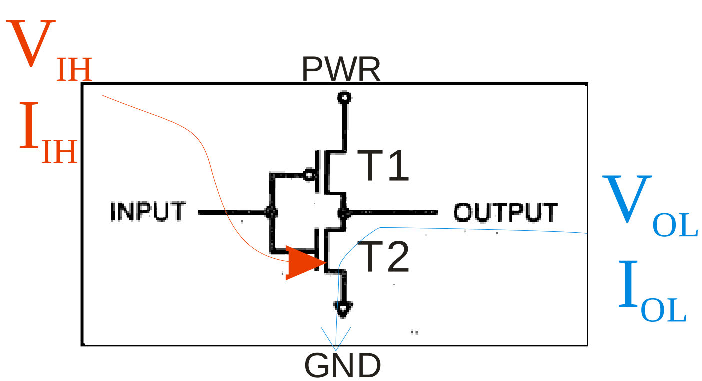
- I_{OH} = Current driven if output is high
  - For example, a high output at 4.5V might drive .5 mA

Voltage Low & Enough Current to turn on T1



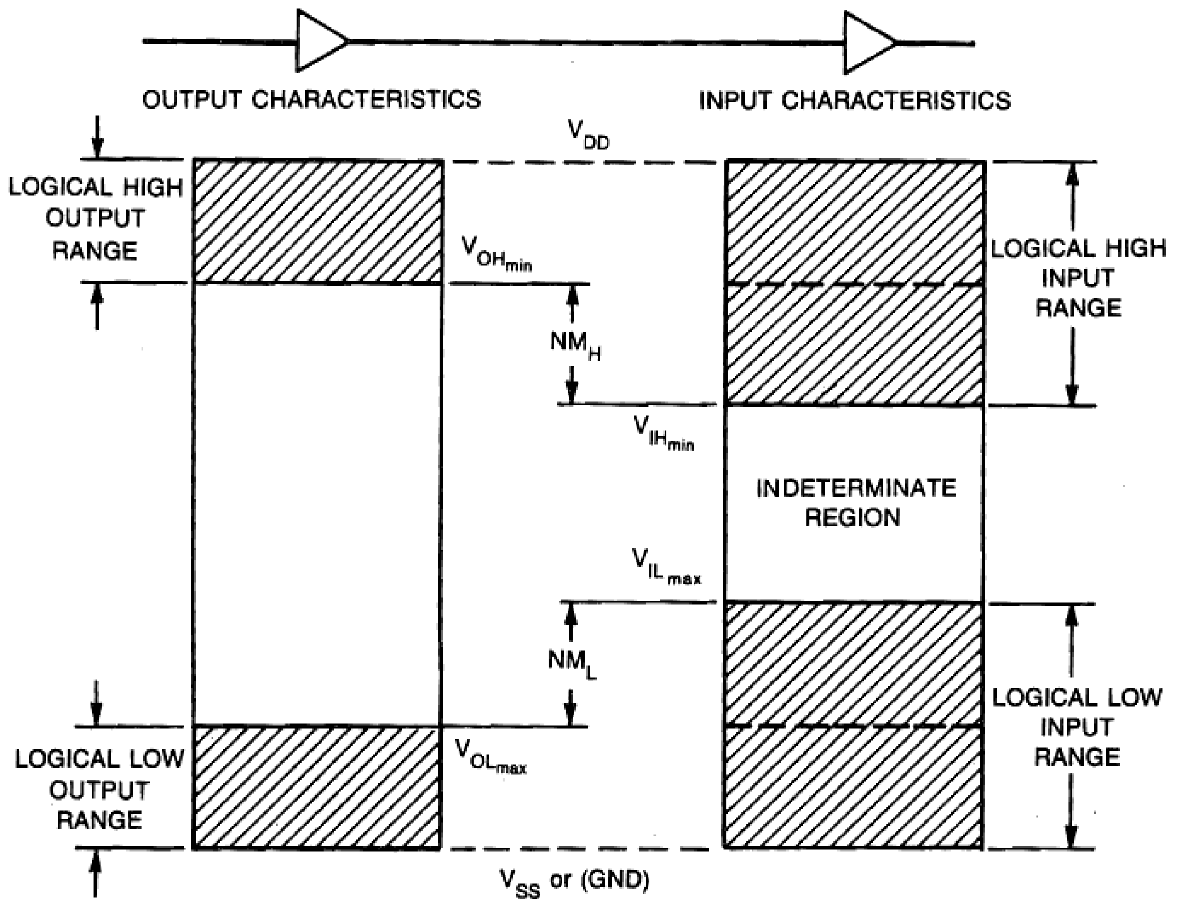
- I_{OL}= Current driven if output is low
  - For example, a low output at 0.5V might drive 25 mA
  - I_{OL} is often much higher than I_{OH}! And usually only a few mA for TTL chips
  - But, the course microcontroller has both at 25 mA

Voltage High & Enough Current to turn on T2



Noise Margin: Input vs. Output Voltage

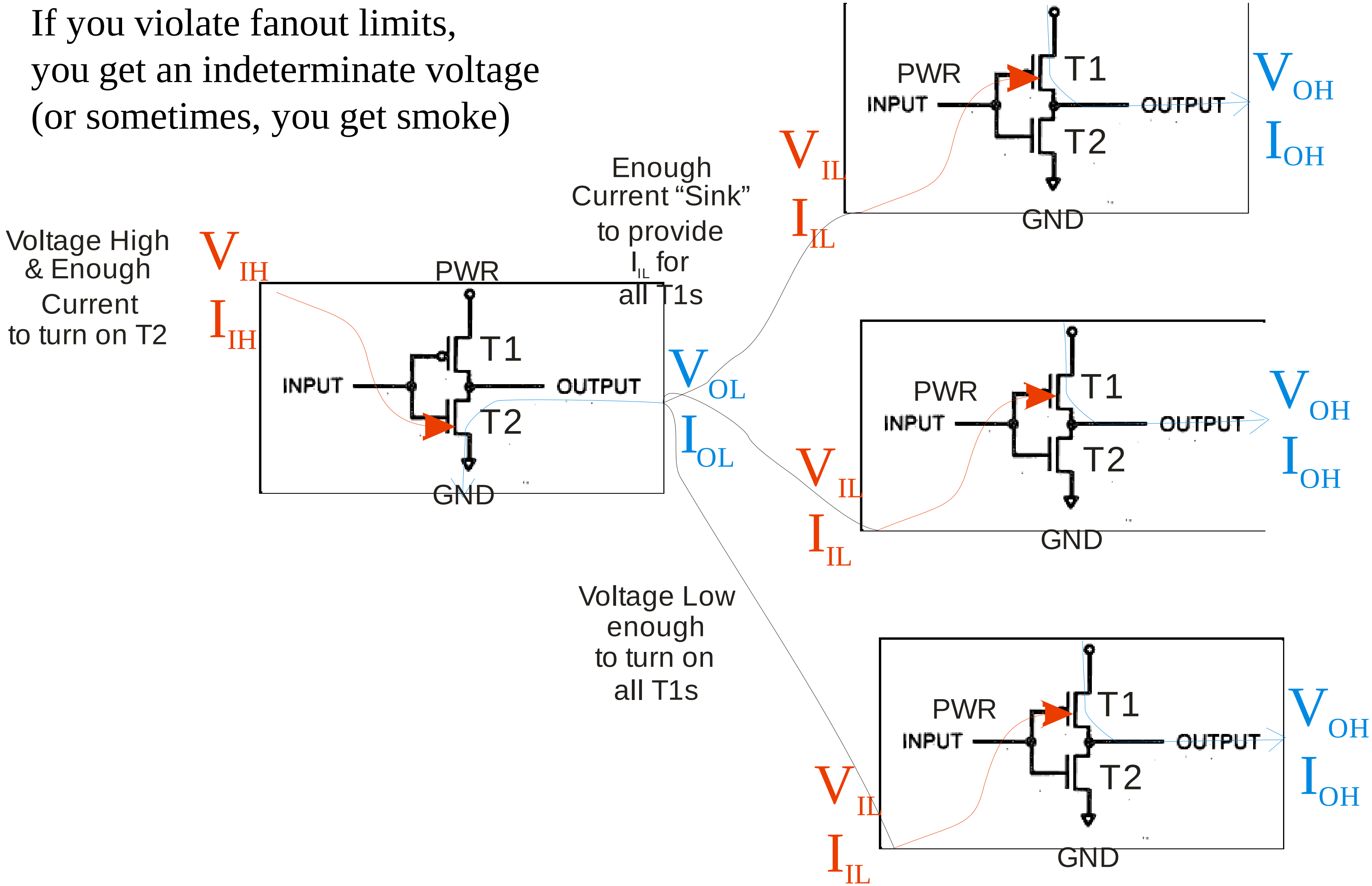
- **Real chips have three output voltages that matter:**
  - High enough to be a "1" -- Voh > Vih
  - Low enough to be a "0" -- Vol < Vil
  - Something in between – a "I'm not sure if I'm a 1 or a 0" voltage (this is **Not Good**)



[Weste95]

Fanout – How Many Gates Can You Drive?

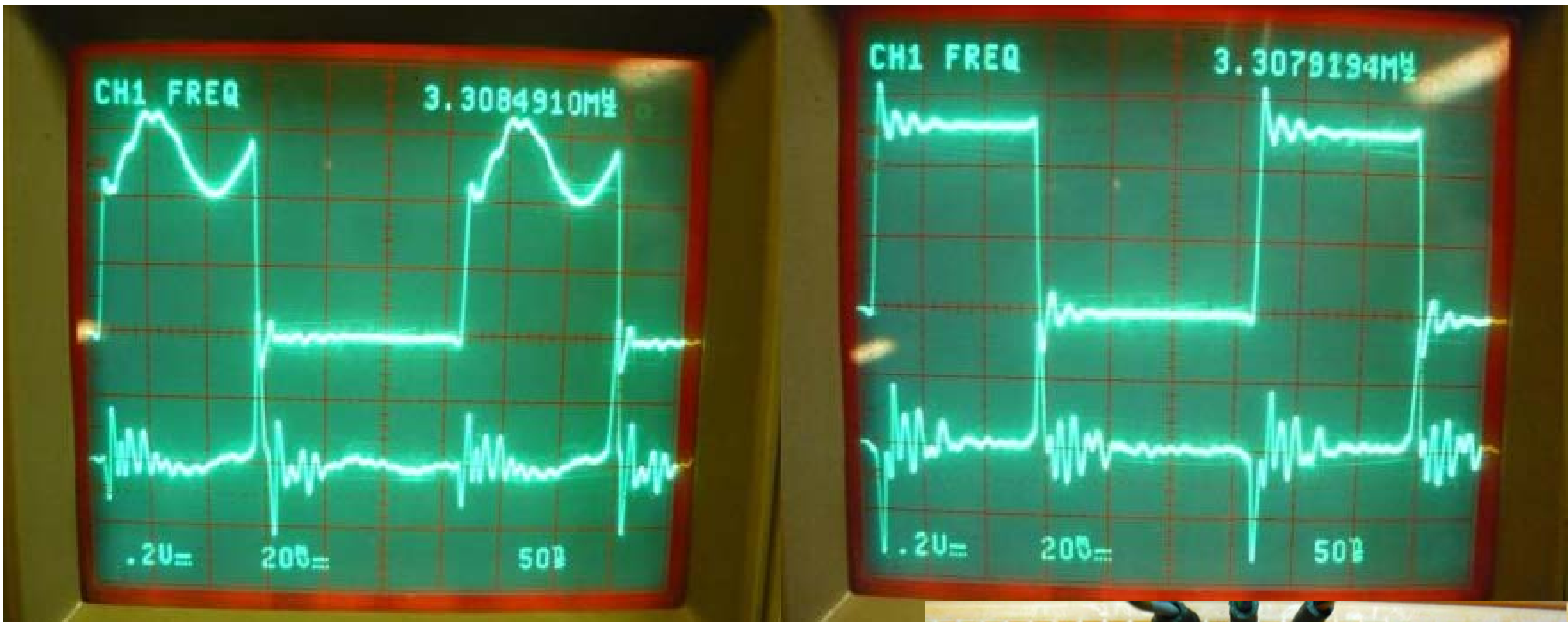
- **Fanout of 3 means an output can drive at most 3 inputs**
  - E.g., $V_{OL} < V_{IL}$ and $sum(I_{IL}) < I_{OL}$
  - If you violate fanout limits, you get an indeterminate voltage (or sometimes, you get smoke)



Decoupling Capacitors

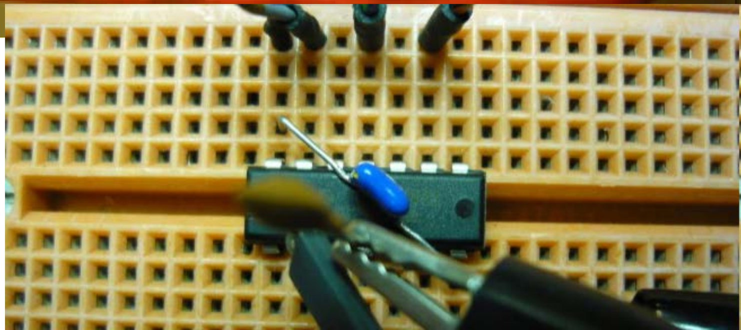
◆ Use decoupling caps to reduce switching noise

- Provides fast-response temporary power supply for switching
- Left: no cap   Right: with capacitor



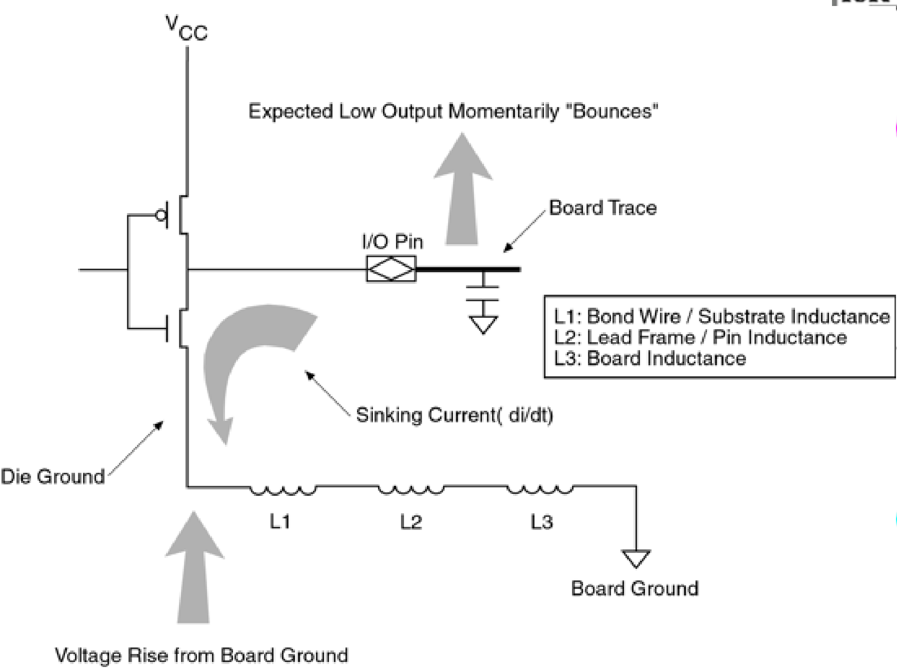
Top trace is voltage
Bottom trace is Current

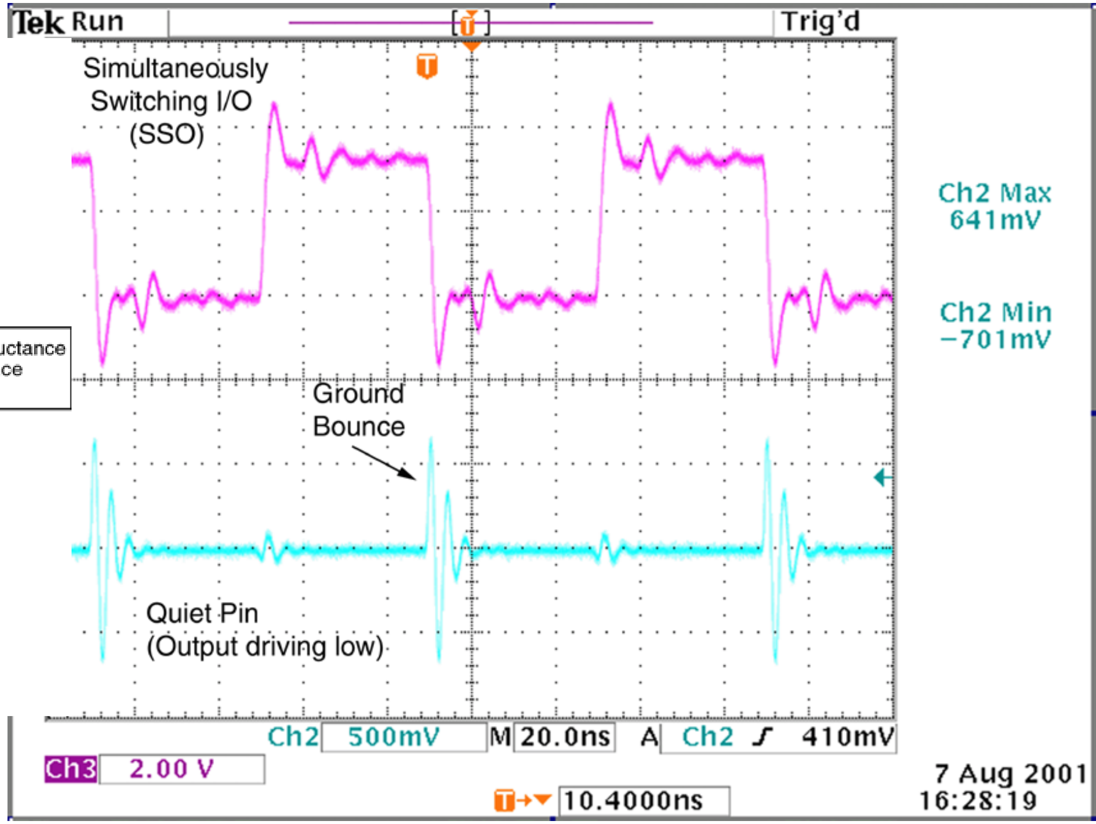
Source: http://www.vagrearg.org/?p=decoupling



Ground Bounce

- **CMOS power is largely consumed halfway through switch**
  - Momentary near-short between power and ground when switching – near zero resistance
  - This causes power to be pulled down and ground to be pulled up
    - Decoupling caps help with this too!
  - Note that ground bounce of $>V_{IL}$ on TTL causes "maybe" values

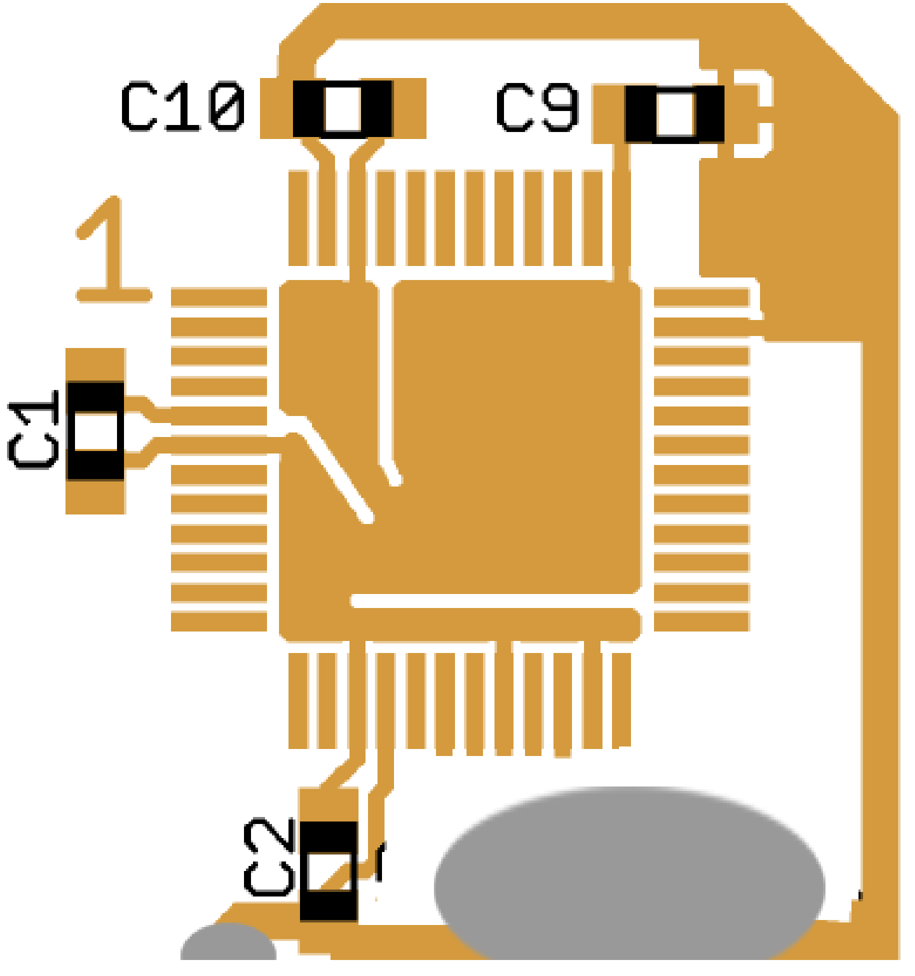




Source: http://www.altera.com/literature/wp/wp_grndbnce.pdf

Decoupling ("bypass") capacitor placement

- **Put capacitors as close to chip as possible**
  - Minimize total wire length between power and ground pins
  - (picture is suggested layout for course CPU – note extra-wide ground trace!)



[Freescale]

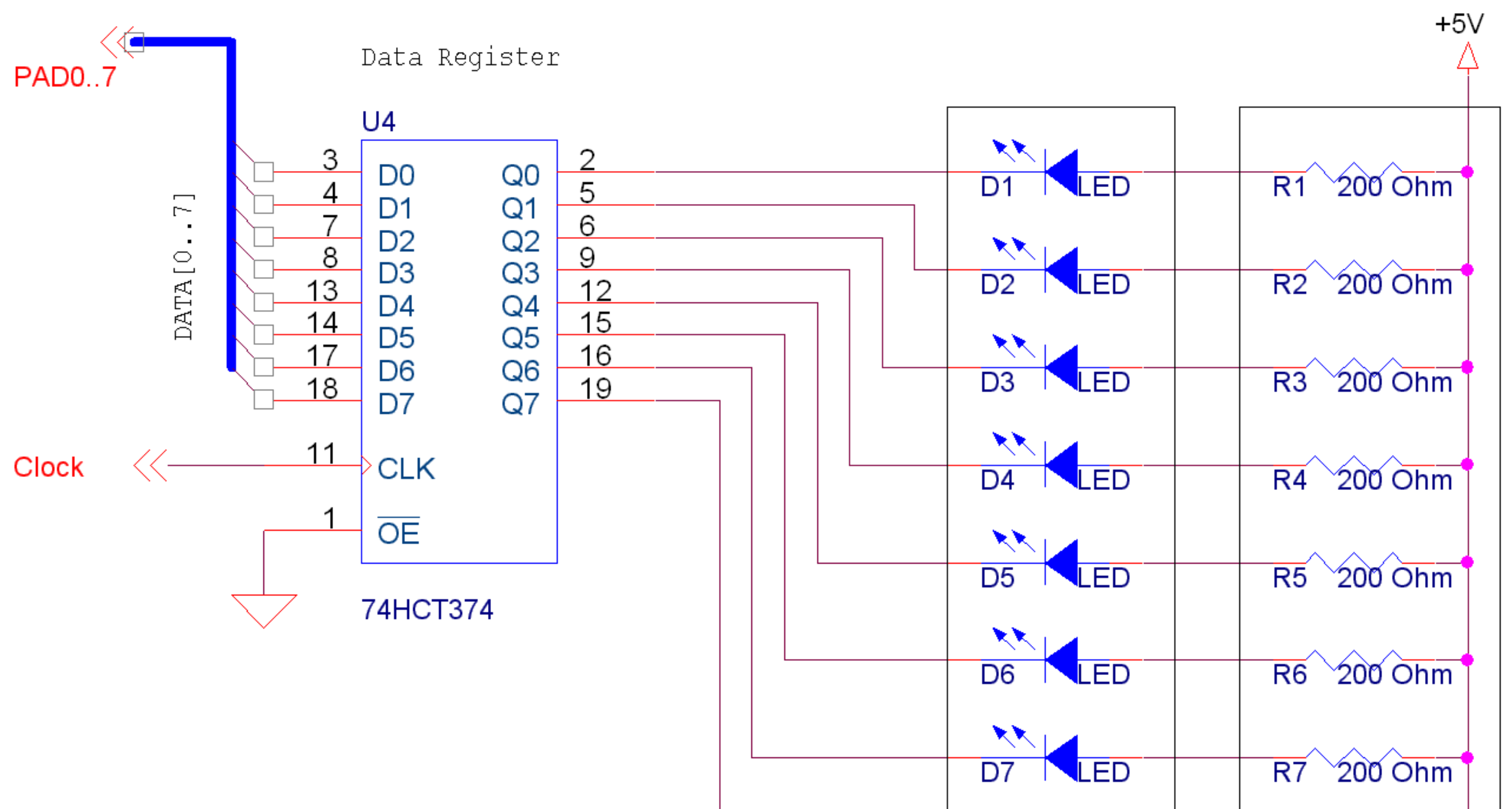
Noise issues

- **Electronic "noise" is a fact of life**
  - Digital signals are a nice fiction; real signals are analog
  - Inductive/capacitive coupling among circuit traces
  - Switching transients affecting power supplies

- **Good design practices (for noise and other matters):**
  - Use decoupling capacitors to act as mini-power-supplies for chips
    - Use a capacitor as close as possible to power/ground pin pair on a chip
    - Generally this is enough under 50 MHz (usually 0.01 to 0.1 uF)
    - Above 50 MHz more care is required (but most small embedded systems are slow)
  - Separate analog and digital portions of the PCB (don't intermix traces)
    - Video, radio, and backlight power traces are especially nasty radiators of noise
    - Audio is especially sensitive to picking up interference from other traces
  - Run ground traces on all sides of critical lines
  - Dedicated layers for power and ground planes or grids
  - Socket external interface chips that could get burned out via transients
  - Put power on an un-populated PCB to check for power/ground faults

How Much I_{OL} is Enough?

- Assume 2V drop across LED – how much current is drawn?
  - Assume $V_{OL} = 0.5V$
  - Reminder – Ohm's Law: V=IR
  - What is I_{OL}?
- Does I_{OH} matter for this circuit?



Course Microcontroller Data Sheet Contents

- Chapter 1 MC9S12C and MC9S12GC Device Overview (MC9S12C128)
- Chapter 2 Port Integration Module (PIM9C32) Block Description
- Chapter 3 Module Mapping Control (MMCV4) Block Description
- Chapter 4 Multiplexed External Bus Interface (MEBIV3)
- Chapter 5 Interrupt (INTV1) Block Description
- Chapter 6 Background Debug Module (BDMV4) Block Description
- Chapter 7 Debug Module (DBGV1) Block Description
- Chapter 8 Analog-to-Digital Converter (ATD10B8CV2) Block Description
- Chapter 9 Clocks and Reset Generator (CRGV4) Block Description
- Chapter 10 Freescale's Scalable Controller Area Network (S12MSCANV2)
- Chapter 11 Oscillator (OSCV2) Block Description
- Chapter 12 Pulse-Width Modulator (PWM8B6CV1) Block Description
- Chapter 13 Serial Communications Interface (S12SCIV2) Block Description
- Chapter 14 Serial Peripheral Interface (SPIV3) Block Description
- Chapter 15 Timer Module (TIM16B8CV1) Block Description
- Chapter 16 Dual Output Voltage Regulator (VREG3V3V2) Block Description
- Chapter 17 16 Kbyte Flash Module (S12FTS16KV1)
- Chapter 18 32 Kbyte Flash Module (S12FTS32KV1)
- Chapter 19 64 Kbyte Flash Module (S12FTS64KV4)
- Chapter 20 96 Kbyte Flash Module (S12FTS96KV1)
- Chapter 21 128 Kbyte Flash Module (S12FTS128K1V1)
- Appendix A Electrical Characteristics
- Appendix B Emulation Information
- Appendix C Package Information
- Appendix D Derivative Differences
- Appendix E Ordering Information

Lecture 2 Review

- **General pinout of course microcontroller**
  - Types of pins
    - But not “what does pin 17 do” without a pinout diagram
  - General voltages, speeds, packaging

- **General electronic hardware**
  - Packaging types
  - Where’s pin 1 on a package?
  - Printed circuit board construction and related topics
  - Circuit parameters and meanings (e.g., what does “I_{OH} = 4 mA” really mean?)
  - Be able to compute current through an LED
    - LED components are most expensive after CPU – almost $5 apiece
    - Over-driving CPU outputs can easily burn out CPU module (about $75)
    - Use resistors with LEDs – and get resistor value right!
  - Good design practices

Lab Skills

- **Be able to hook a simple circuit on a proto-board**
  - D-register (including chip insertion into the proto-board)
  - LEDs
  - Resistors