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

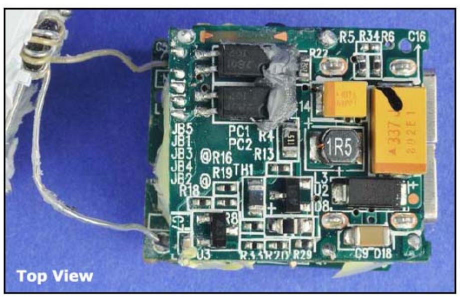
- **Lab board handouts in progress**
  - See Blackboard/admin page for TA office hours
  - OK to go to any scheduled lab section (but, give priority to scheduled students)
  - For Friday prelab give a good faith attempt to get things working by the deadline
    - If you hit a showstopper get it fixed on Tuesday so you can do Prelab 2 on time.

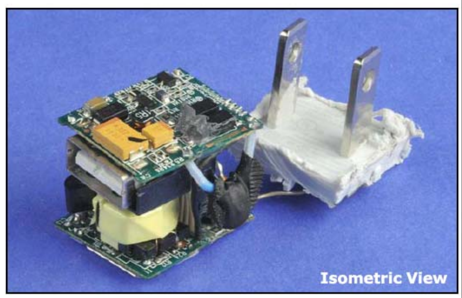
Design Example: Rack-Mount Power Supply

- **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"**

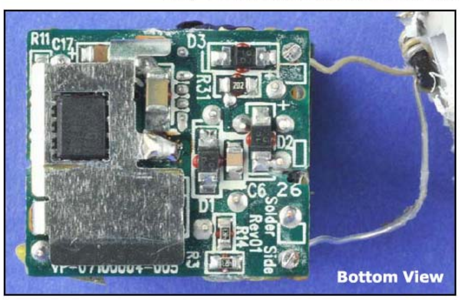
http://accessories.us.dell.com
Dell 870W Power Supply for PowerEdge R710 Server

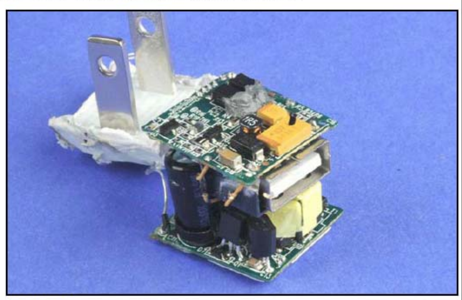
Portelligent **AC Adapter** (Internal Components) **iPhone 3G**





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?

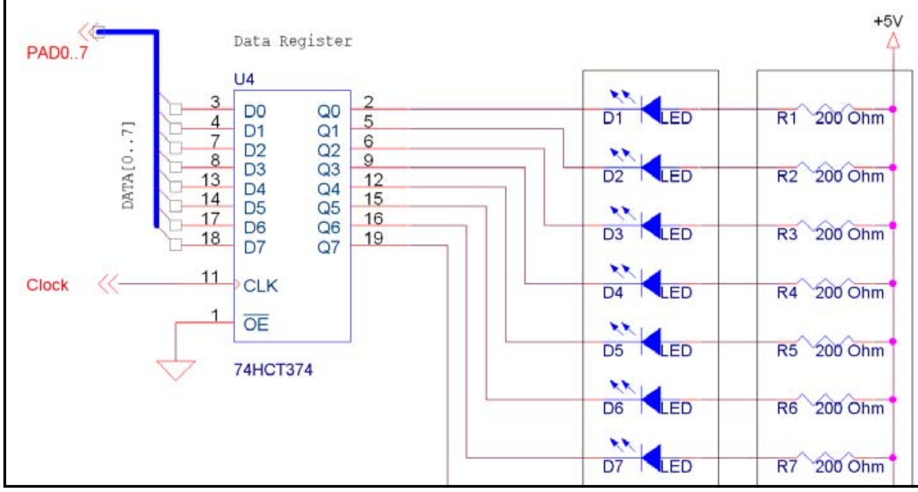
- **Where we've been:**
  - Course Intro
- **Where we're going today:**
  - Embedded system hardware
- **Where we're going next:**
  - Microcontroller assembly language
  - Engineering design approaches
  - Embedded-specific C
  - …

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)



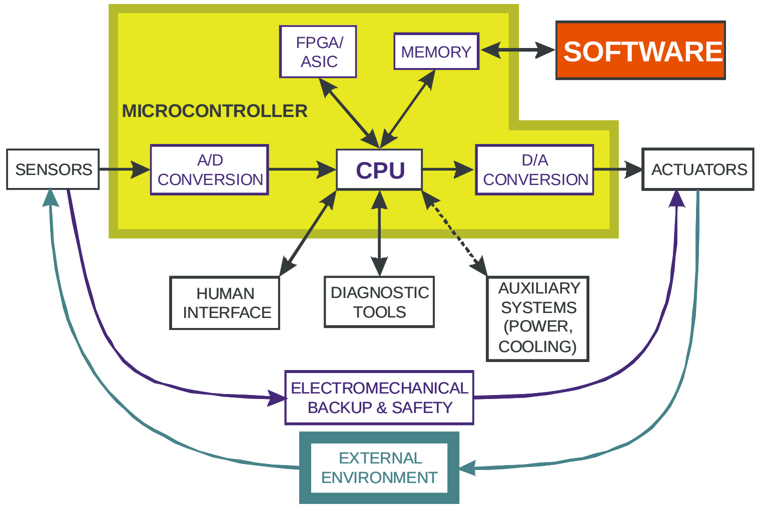
Schematic Capture Tools

- **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

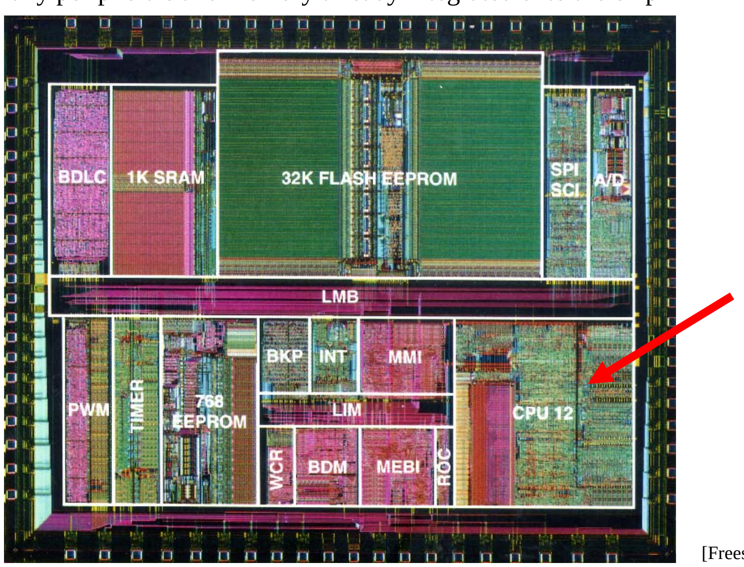
Stuff that goes around a microcontroller/overview

- **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

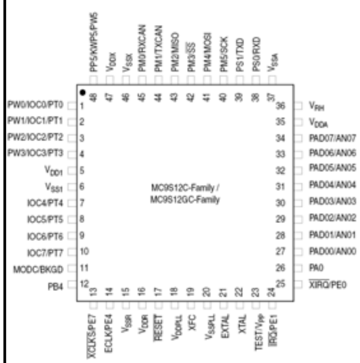


Figure 1-9. Pin Assignments in 48-Pin LQFP

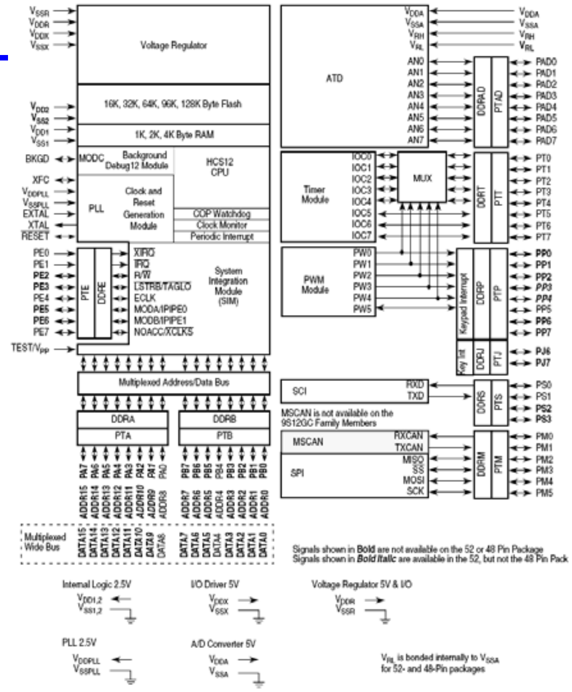
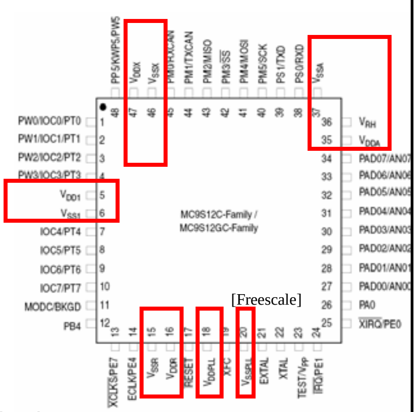


Figure 1-1 MC9S12C-Family / MC9S12GC-Family Block Diagram

[Freescale]

Power

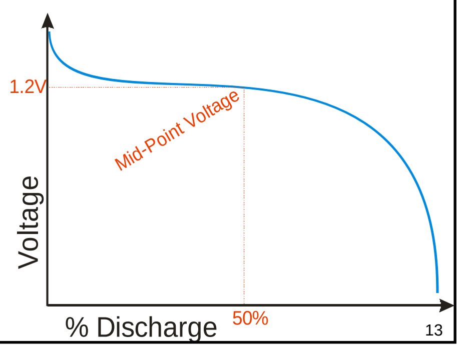
- **DC electrical power to run the CPU and power I/O circuits**
- **Some standard voltages**
  - 5V DC – old style from the first commercial logic chips, but still in common use ("TTL logic levels")
  - 3.3V DC – common in newer designs
  - Lower voltages often used for low power
- **MC9S12C family:**
  - 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



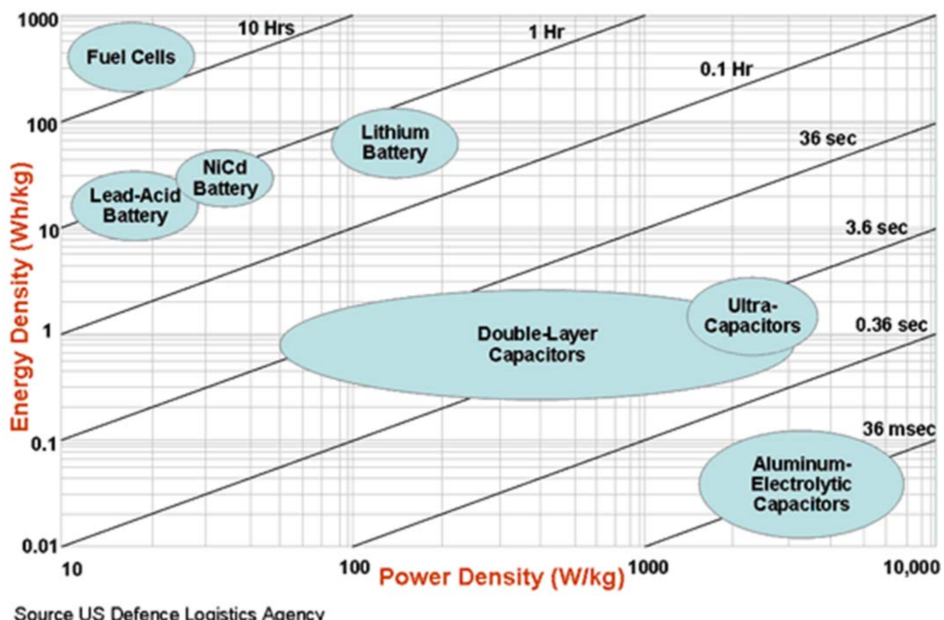
- **Actual voltages used depend on power strategy**
  - **Will this chip run on two NiCd or NiMH batteries? Does that provide 3V?**

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



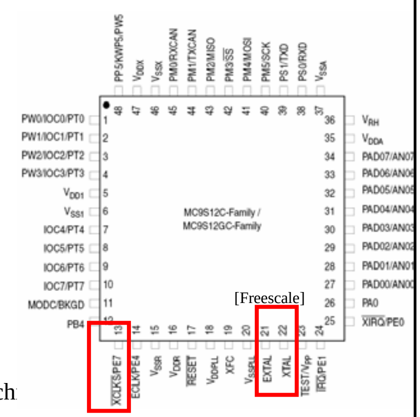
High Power or High Energy (but not both)



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

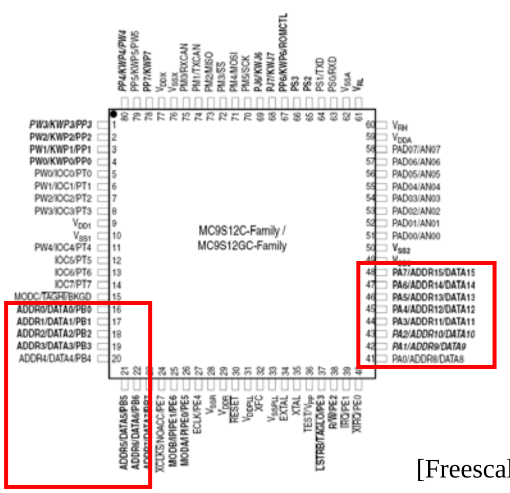
Oscillator/“clock”

- **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

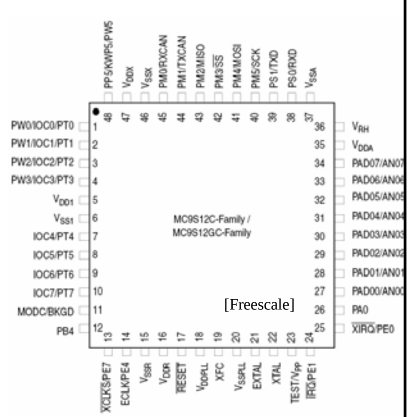
- **We’re using a smaller package (48 pin) to reduce costs**
  - That package doesn’t put the memory bus on the pins



[Freescale]

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

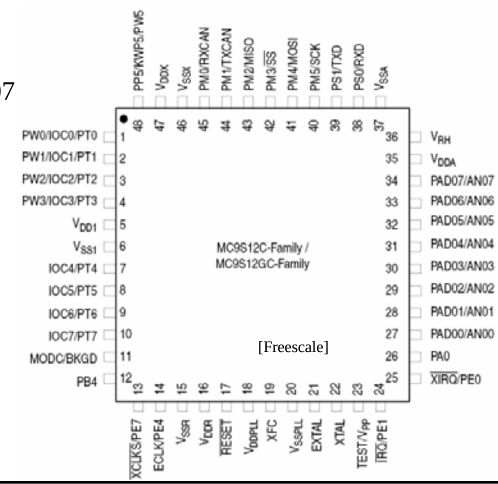


Available I/O pins

- **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

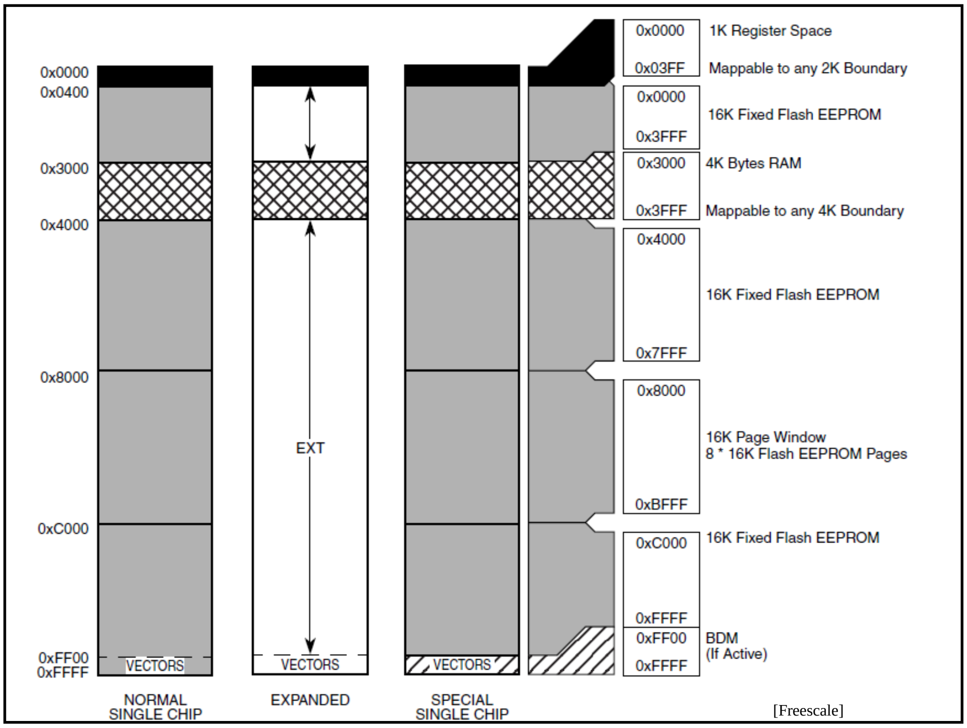
- **Most important pins:**
  - PAD00..PAD07 // AN00 .. AN07 provides digital and analog I/O
  - PT0..PT7 provides additional digital I/O
  - PW0..PW3 provides hardware-assisted pulse generation

- **Data sheet lists all the signals**



Registers & Memory Maps

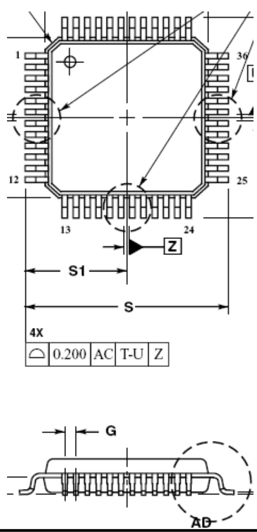
- **How do you get data on and off the pins?**
  - Interface to I/O is done via **<u>"registers"</u>** (a set of flip-flops on the chip)
  - Write to registers to configure the pins – e.g., is it digital or analog?; in or out?
  - Read/write other registers to actually do I/O
    - Read a byte from switches 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 **<u>"memory mapped"</u>**
    - 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

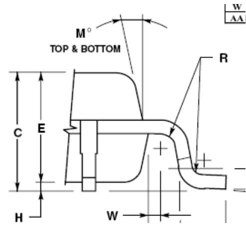


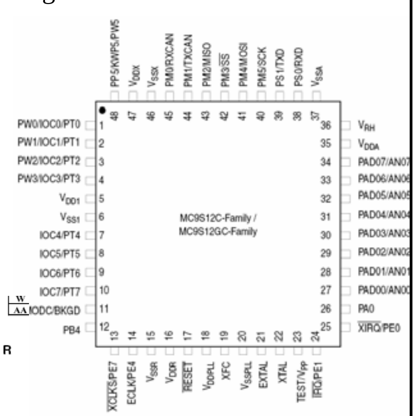
[Freescale]

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



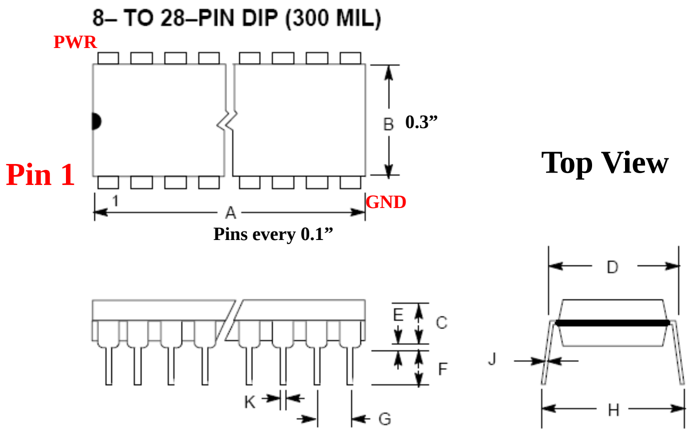




[Freescale]

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; <u>smoke ensues</u>***



[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)

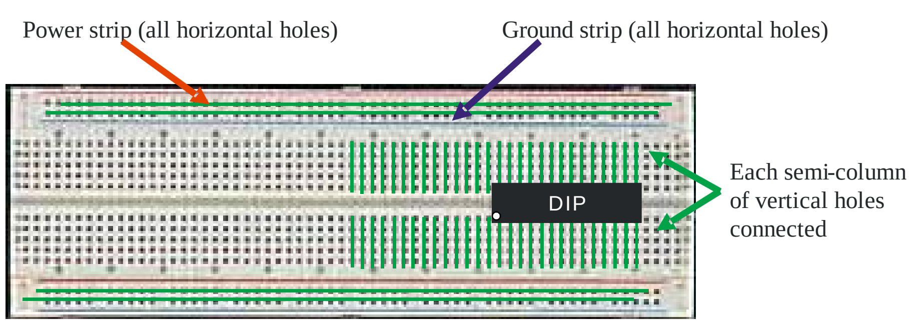
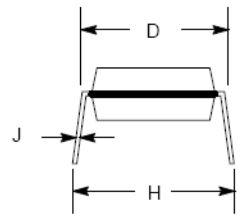


Photo portion: [Axiom]

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

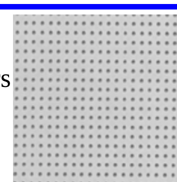


[maxim-ic]

- **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

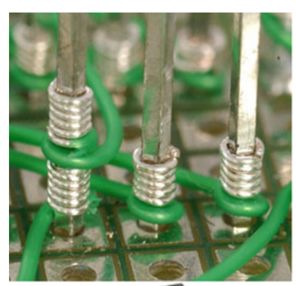
Other Prototyping techniques

- **"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



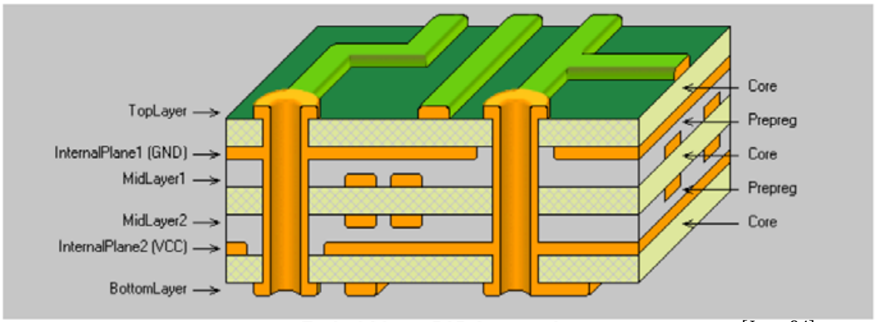
[Jameco]

- **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

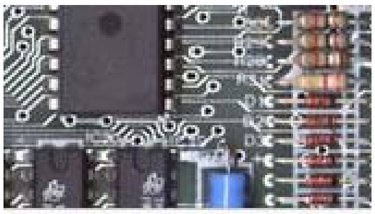


Typical 6 Layer PCB Construction

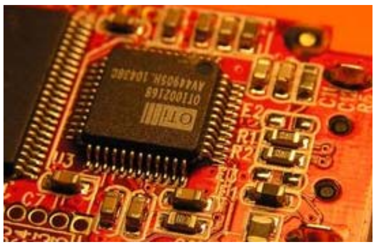
[Jones94]

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



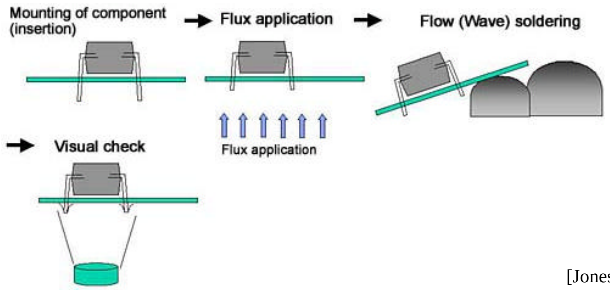
- **Surface mount**
  - Pins only attach on top layer
  - Finer pitch pins, higher density
  - Newer technology
  - Difficult (or with Ball Grid Array pretty much impossible) to hand-solder prototypes without using sockets.



[Wikipedia]

Getting Components On To The Board

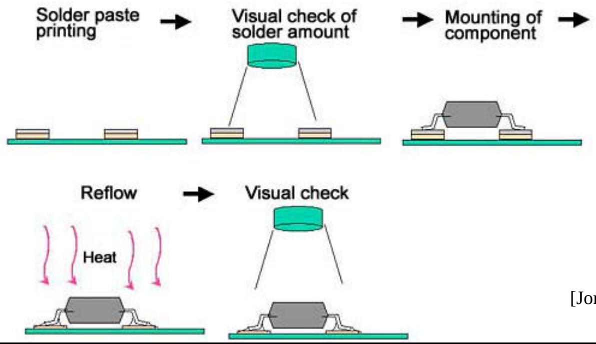
- **Wave soldering:**



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

[Jones94]

- **Reflow Soldering:**

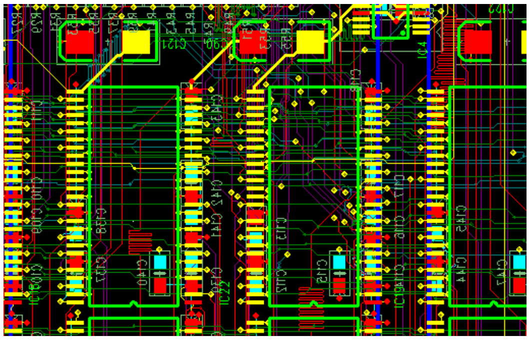


[Jones94]

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

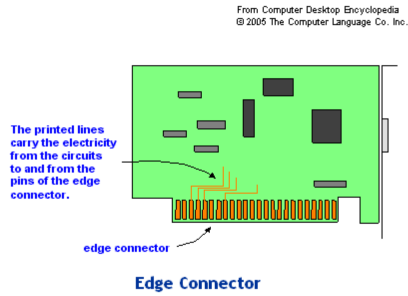
- **Common design strategies**
  - Dedicated layer for power and for ground (helps with noise)
  - Even layers are mostly horizontal, odd layers are mostly vertical



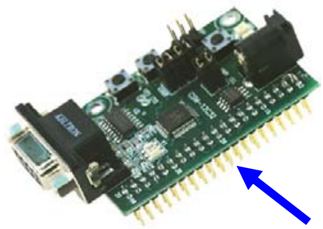
[eeinternational.net]

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)



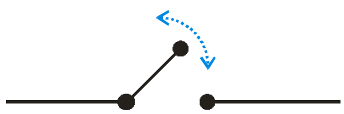
- **Headers**
  - A set of posts for connecting
  - Posts insert into sockets or can be clipped, wire-wrapped, soldered to, etc.
  - Especially popular – ribbon cable (caution, most ribbon cables only good for a half-dozen insertions before becoming unreliable!)



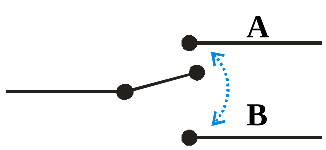
[Freescale]

Switches

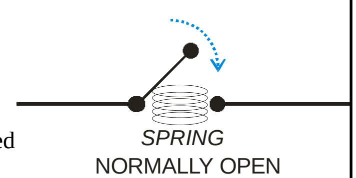
- **Single pole, single throw switch**
  - E.g., ordinary house lighting switch
  - It's "on" or "off" and switches a single line
  - Stays "on" or "off" unless moved



- **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

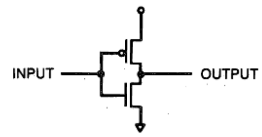
- **Propagation delays**
  - Low to high and high to low are sometimes different speeds
  - Speeds depend on operating conditions

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]

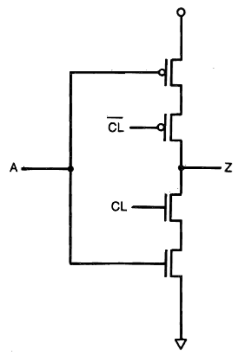
Outputs & Inputs

- **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')

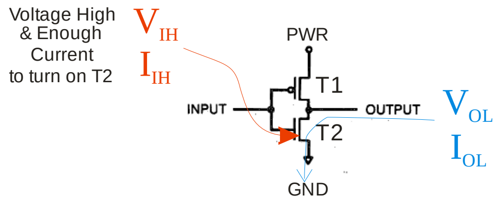
DC Electrical Specifications (Continued)

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

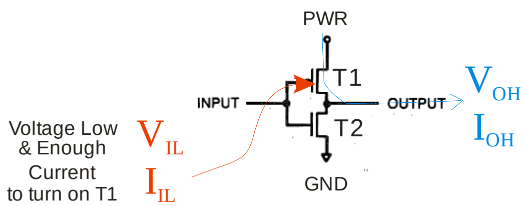
[TI]

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

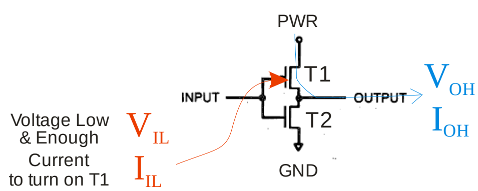


  - V_{IL} = Input Voltage that is seen as a "low" input
    - For example, any input below 0.8 Volts is Low; V_{IL} = 0.8V
    - In these examples: anything between 0.8V and 2.0V is indeterminate

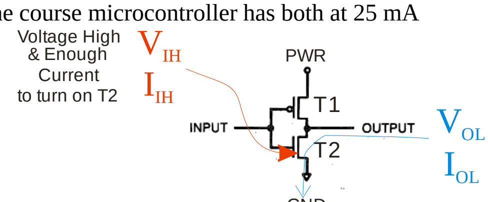


Key Voltage & Current Specifications

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

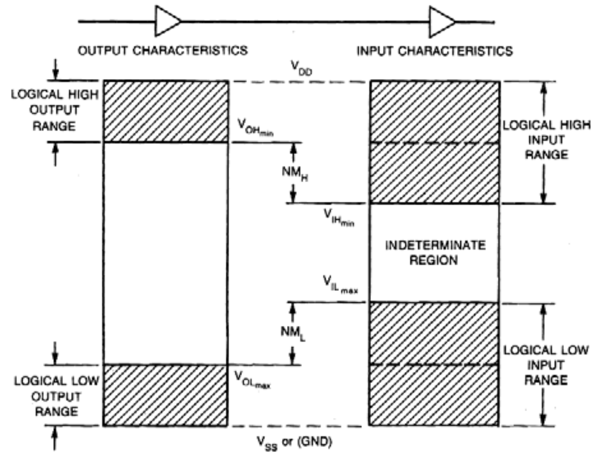


  - I_{OL} = Current driven if output is low
    - For example, a low output at 0.5V might drive 25 mA
    - I_{OL} is often much higher than I_{OH}! And usually only a few mA for TTL chips
    - But, the course microcontroller has both at 25 mA



Noise Margin: Input vs. Output Voltage

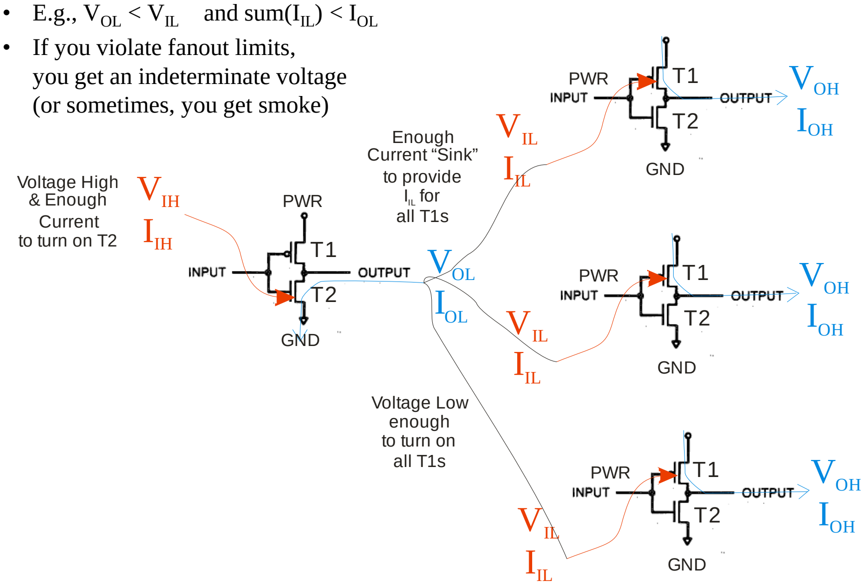
- **Real chips have three output voltages that matter:**
  - High enough to be a "1" -- Voh > Vih
  - Low enough to be a "0" -- Vol < Vil
  - Something in between – a "I'm not sure if I'm a 1 or a 0" voltage (this is **Not Good**)



[Weste95]

Fanout – How Many Gates Can You Drive?

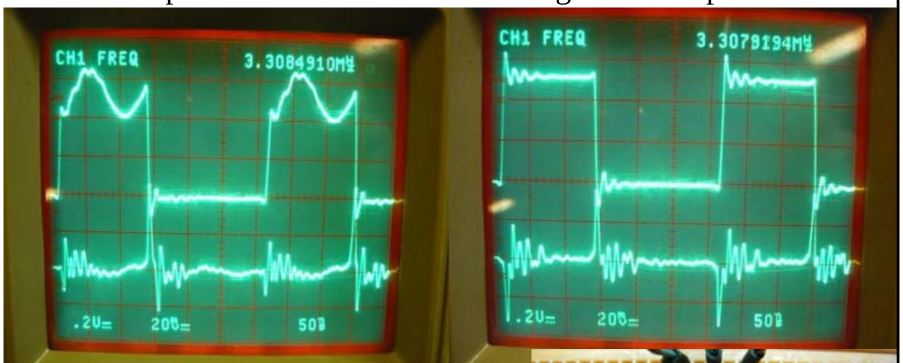
- **Fanout of 3 means an output can drive at most 3 inputs**
  - E.g., $V_{OL} < V_{IL}$ and $\text{sum}(I_{IL}) < I_{OL}$
  - If you violate fanout limits, you get an indeterminate voltage (or sometimes, you get smoke)



Decoupling Capacitors

◆ **Use decoupling caps to reduce switching noise**

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



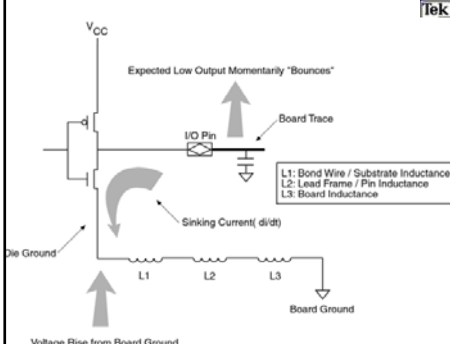
Top trace is voltage
Bottom trace is Current

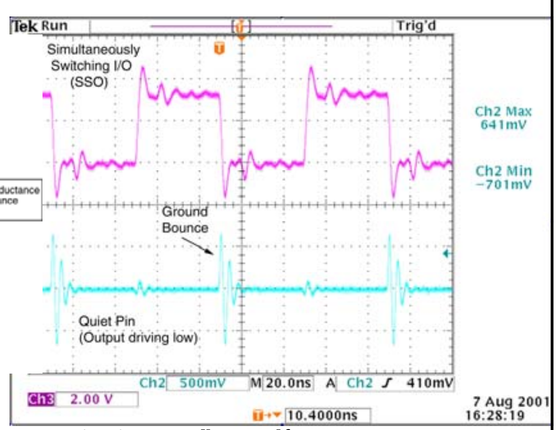
Source: http://www.vagrearg.org/?p=decoupling

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

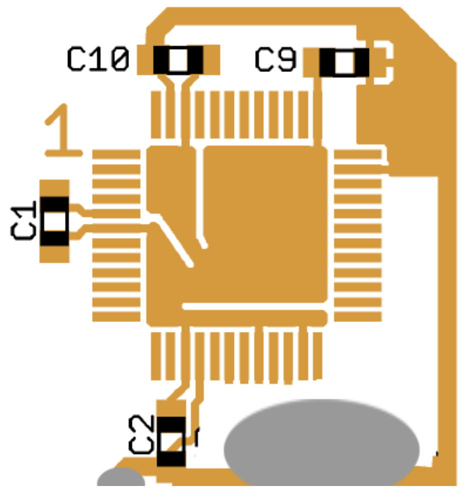




Source: http://www.altera.com/literature/wp/wp_grndbnce.pdf

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]

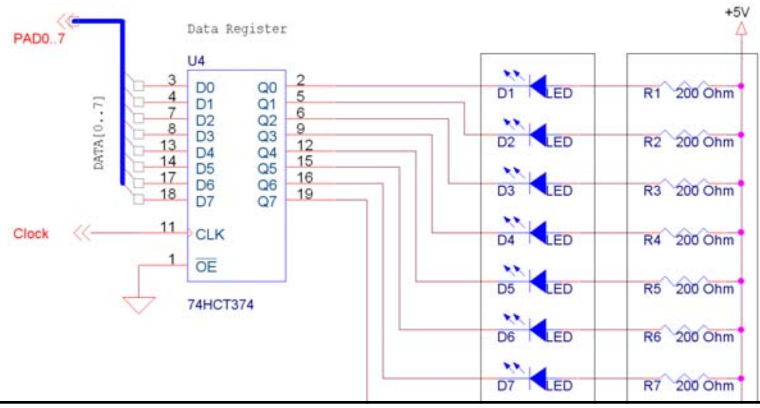
Noise issues

- **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

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