Systems Engineering and Management for Robotics:

Printed Circuit Board Design and Fabrication

Questions to Answer

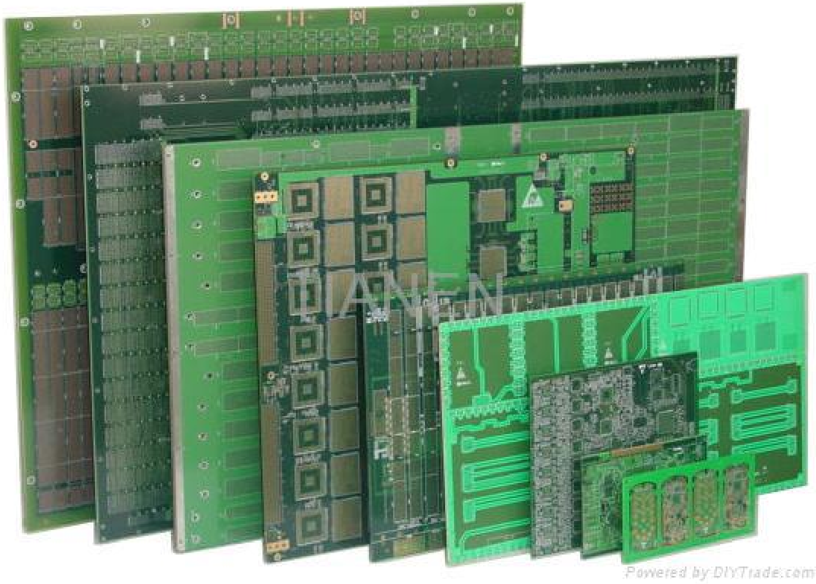
- **What is a Printed Circuit Board (PCB) and why are they instrumental to electronic devices?**
- **How do I design a PCB?**
  - What's an electrical schematic good for?
  - What's a "Layout"?
  - Where do parts come from?
- **How do I convert a system diagram into an electrical schematic?**
- **What are some important design considerations?**

Who is this man?

- **Paul Eisler (1907-1995)**
- **Invented the PCB in 1936**
- **Used it in his radio**
  - Also used in proximity fuse
- **Also invented...**
  - Rear-window defroster
  - Pizza warmer

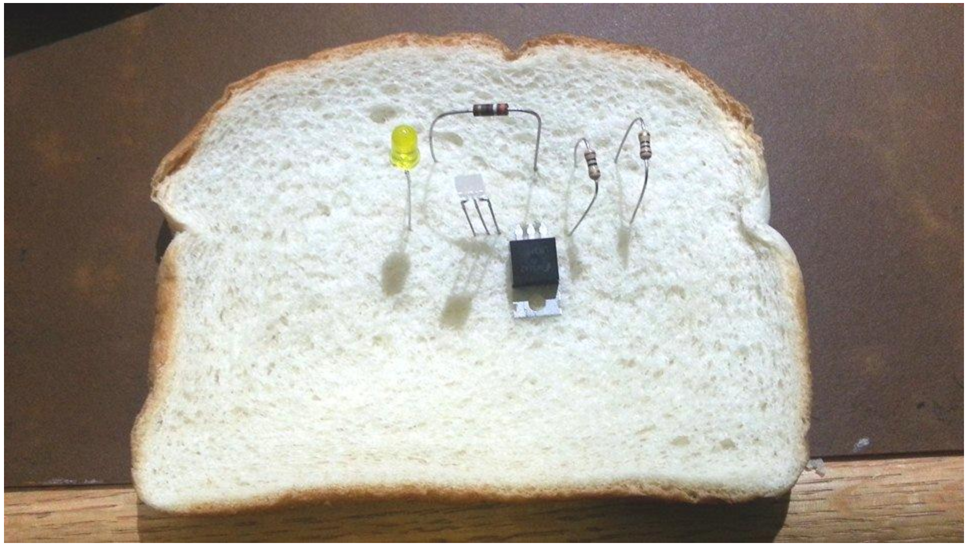
The Printed Circuit Board (PCB)

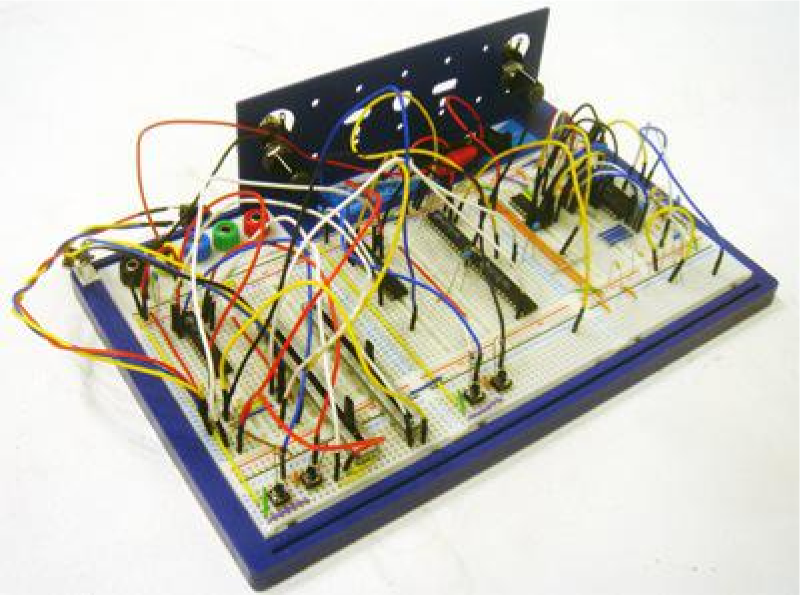
- **Essential Component**
- **Mechanical Mounting**
- **Electrical Connectivity**
  - Traces can also form components
- **Many flavors**
  - Color, flexibility, temperature rating, density



Which is Better?

This???





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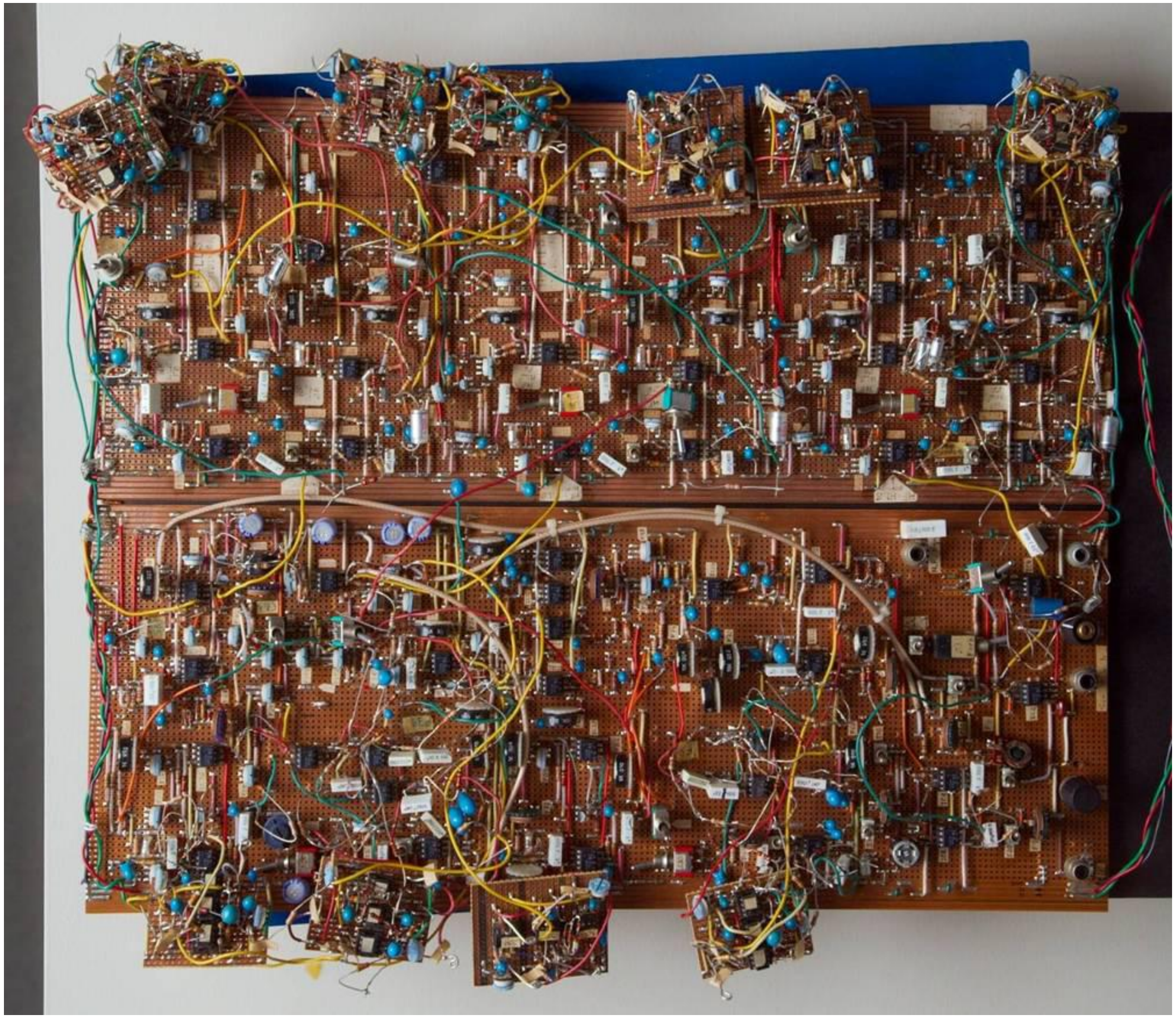
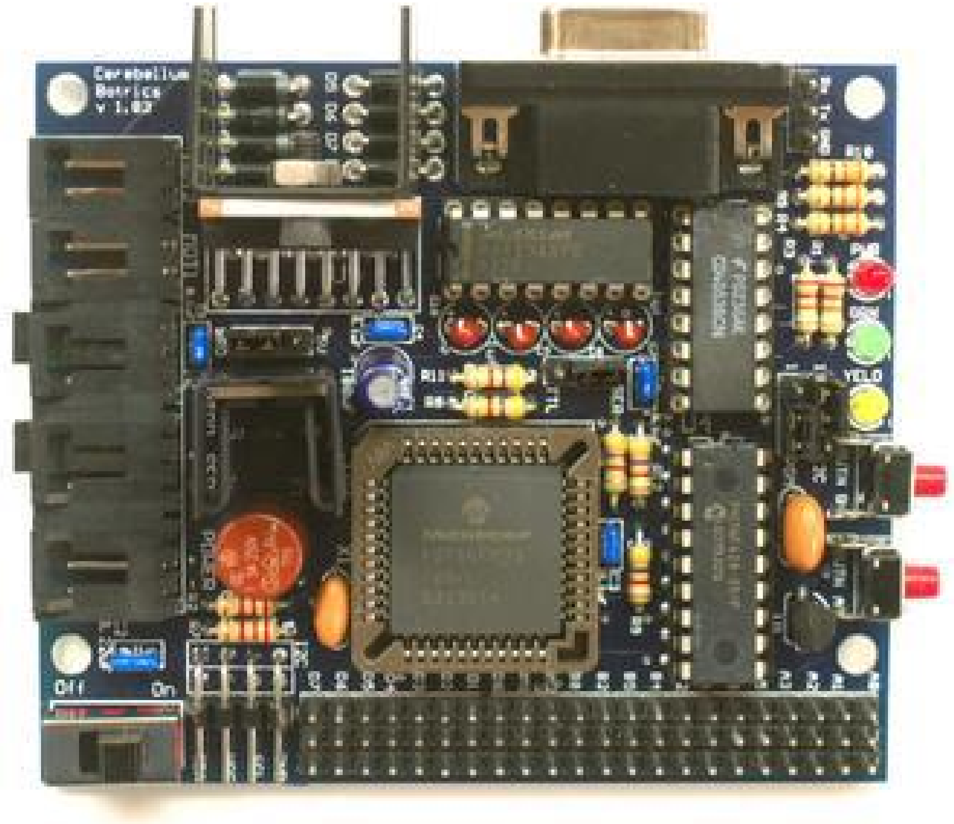
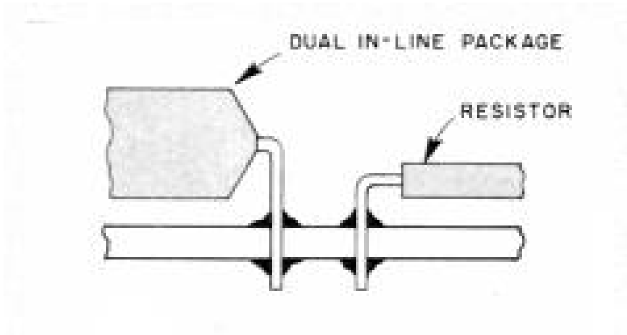


This is Better

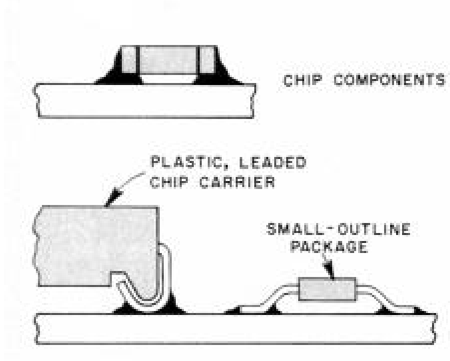


Through-hole



This is Even Better *

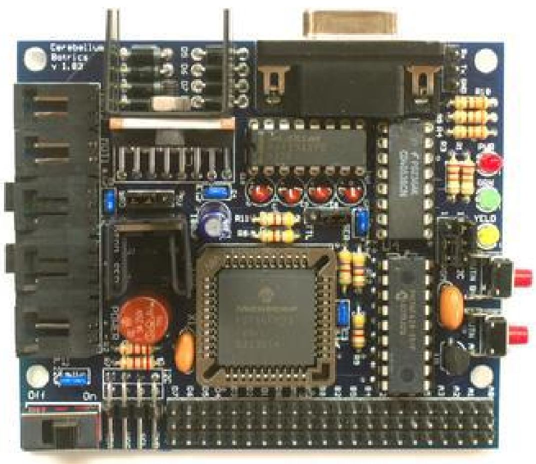
Surface mount



* see next slide

Through-Hole Vs. Surface Mount

Through-Hole:
- Easy to solder
- Easier to fix circuits
- You don't lose components on the floor

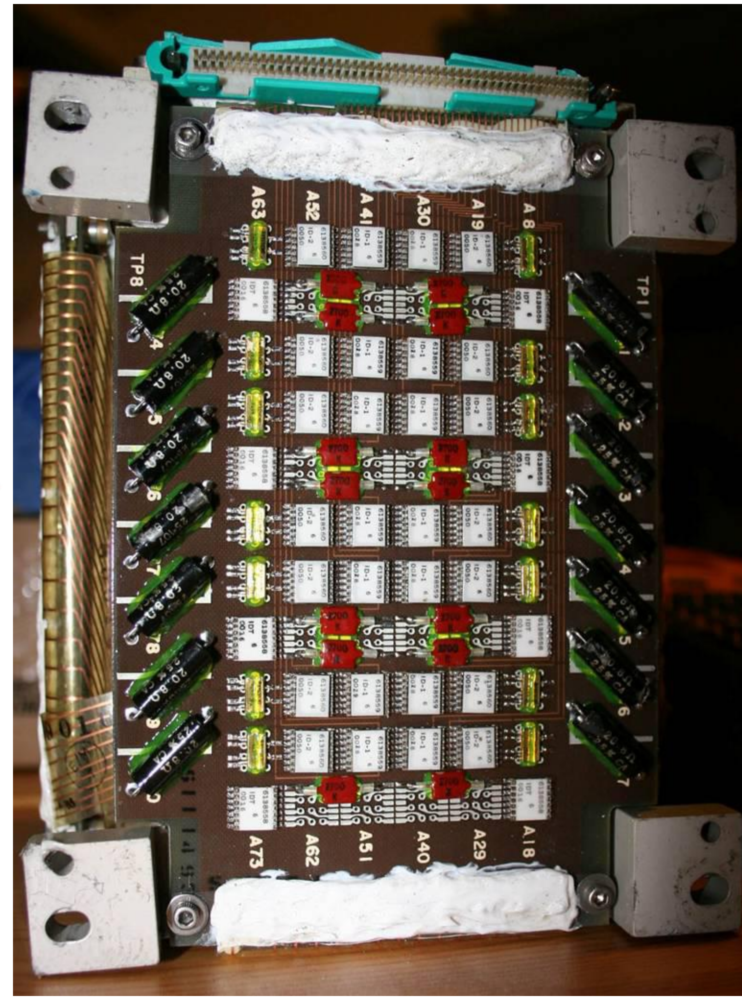


Surface Mount:
- Miniaturization
  - From *small* to *ridiculous*
- Easier Automated Assembly
- PCB Fabrication is easier
  - fewer holes to drill
  - shorter manufacturing time
- Most cool/advanced parts are only Surface Mount

Another Historical Digression

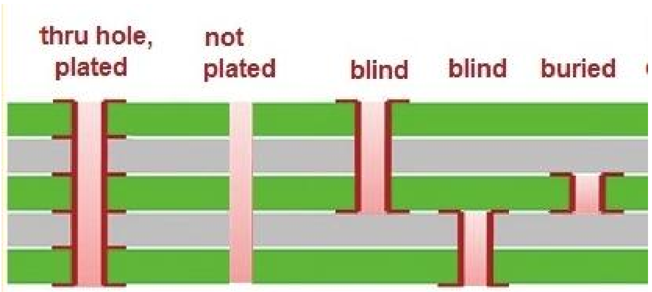
- **First *surface mount boards* were developed for Saturn V flight computers**
  - In 1964
  - By IBM

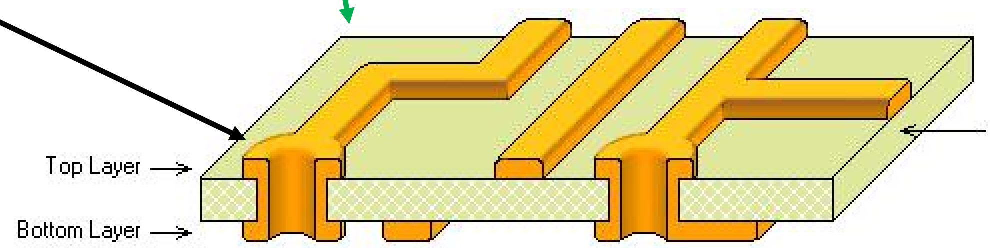
- **This module can hold 14,336 bytes**
  - The Saturn V had 8 of them



Multi-layer Construction

- **PCBs have many layers:**
  - **The dielectric**
  - **Copper layers**
  - **Vias**





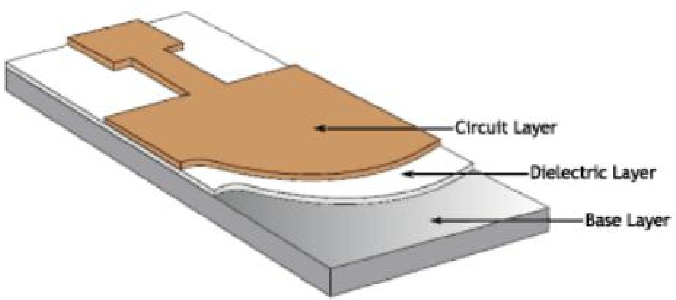
- **Other Common Features**
  - **Soldermask**: [usually green] overlay that insulates copper
  - **Silkscreen**: [usually white] with text, logos, etc.
  - **Multi-layer**: Many sandwiched copper/dielectric layers "planes" are often implemented this way. Complex PCBs like motherboards might have 16 copper layers—or even more

PCB Materials

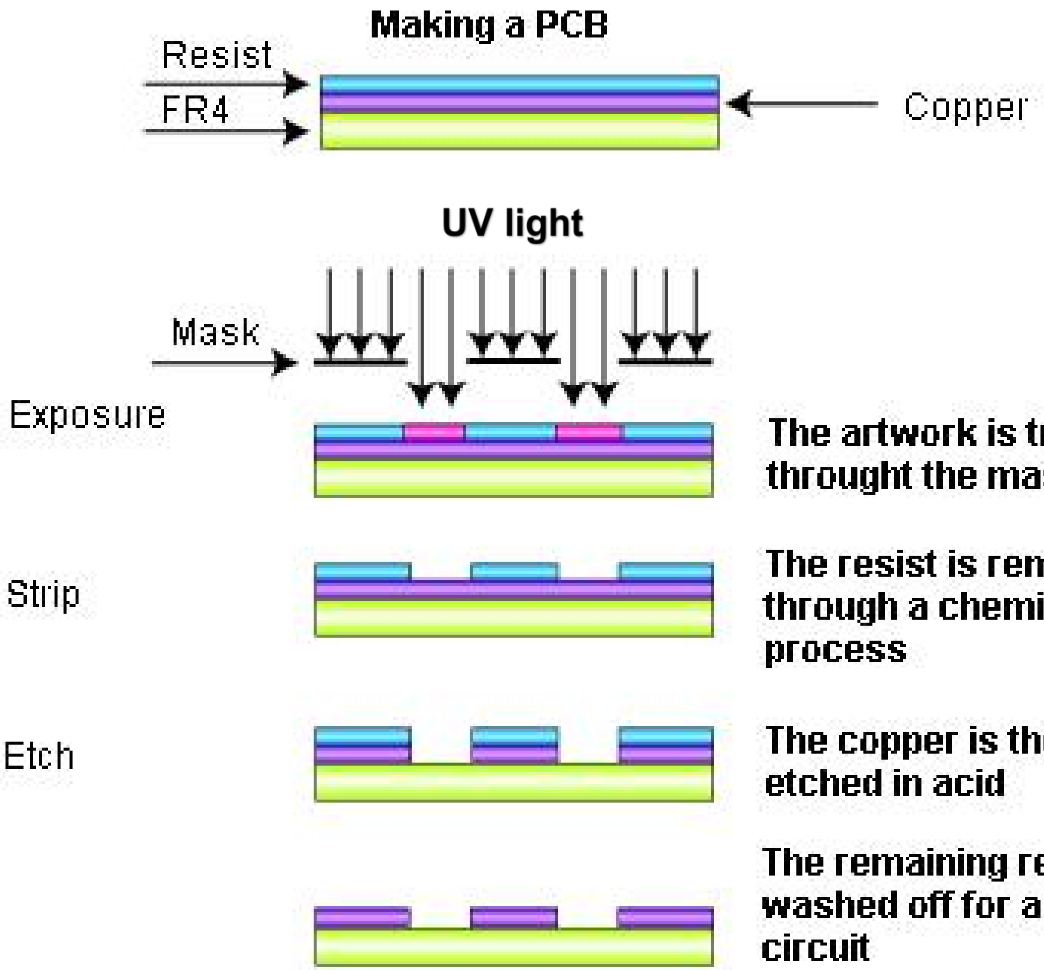
- **PCBs are available in several grades**

GRADE DESIGNATION	MATERIAL/COMMENTS
FR–1	Paper/phenolic: room temperature punchable, poor moisture resistance.
FR–2	Paper/phenolic: suitable for single-sided PCB consumer equipment, good moisture resistance.
FR–3	Paper/epoxy: designed for balance of good mechanical and electrical characteristics.
FR–4	Glass cloth/epoxy: excellent mechanical and electrical properties.
FR–5	Glass cloth/epoxy: high strength at elevated temperatures, self-extinguishing.
G10	Glass cloth/epoxy: high insulation resistance, highest bond strength of glass laminates, high humidity resistance.
G11	Glass cloth/epoxy: high flexural strength retention at high temperature, extreme resistance to solvents.

Aluminum PCB
- Higher heat transfer
- More expensive than FR-4
- Widely used in LED industry



Modern PCB Fabrication

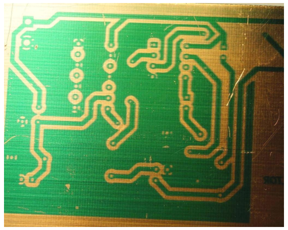


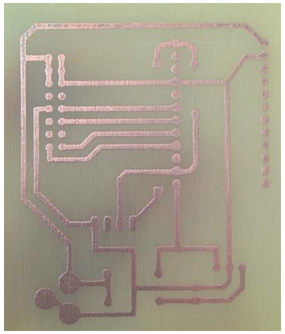
The artwork is transfered throught the mask

The resist is removed through a chemical process

The copper is then etched in acid

The remaining resist is washed off for a finished circuit





Implementing Systems with PCBs

- **PCBs are a good way to implement *Interconnect***
  - Mechanical Mounting
  - Electrical Connectivity

- **Many parts are designed to operate solely on PCBs**
  - ICs (microcontrollers, regulators, motion controllers, modern sensors, etc.)
  - Discrete components shaped to fit

- **Standalone devices interact with PCBs via electrical *connectors***
  - *Never underestimate the power of connectors to foil your project*

Custom PCBs in System Design: Benefits

- **Interconnect organization**
  - Put all your electronic subsystems **in one place**
    - **Combine** many “breakout boards” into single PCB
  - **Eliminate** unnecessary electrical connectors
  - **Increase** reliability
- **Form Factor**
  - Extreme miniaturization is possible
  - PCB shape and part placement is definable
  - Can fit very small or unusual shapes
- **Greater choice in component selection**
  - Most modern parts not designed for standalone use
  - Not limited to breakout boards, dev kits, or hobby parts
  - Some electrical designs (high speed or analog) not possible or reliable using breadboards and development kits

Custom PCBs in System Design: Drawbacks

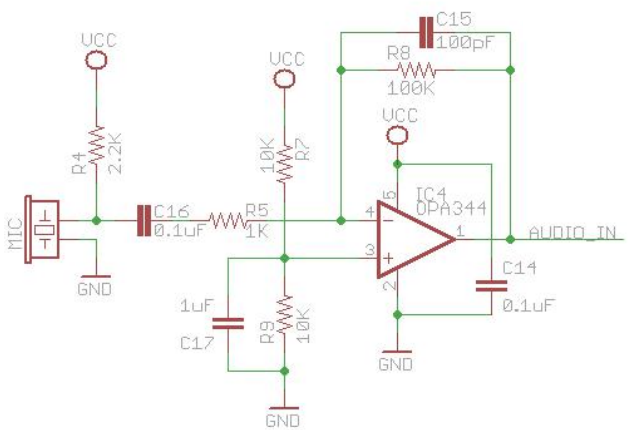
- **Learning Curve**
  - Takes a little more time to implement than COTS
  - Requires knowledge of electronics to implement
  - May require more testing/validation
    - Iterating PCB design 2-3 times (or more) is not uncommon

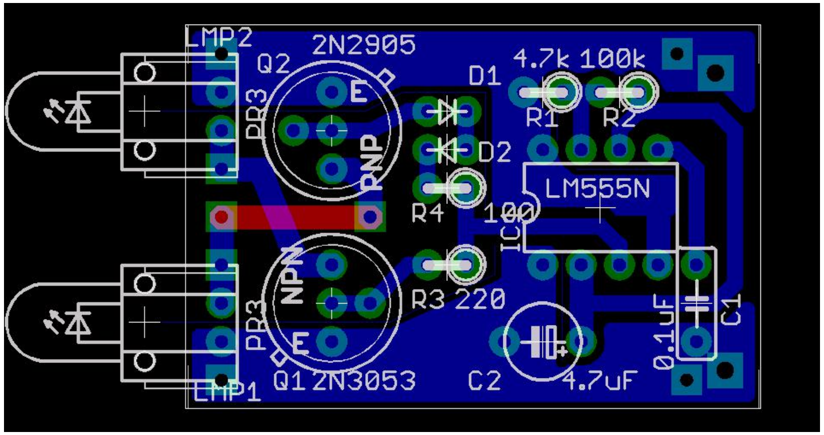
- **Failure may be harder to mitigate if entire system is on a single PCB!**
  - Can add additional, optional connectors to salvage
  - Test complex subsystems beforehand if possible

- **Balancing cost/effort against a COTS system**
  - For small design houses, turnaround on a design is generally 1-2 weeks
  - More effort in design, less effort in assembly / wiring
  - A single custom PCB may end up cheaper than 5 breakout boards

Designing PCBs with CAD tools:

Schematic Capture
and
Layout Design





PCB Design Software

- **PCB CAD provides two separate (but linked) tools:**
  - **Schematic** capture / verification
  - **Layout** artwork / verification

- **Also provides ability to create parts libraries**
  - Basic building block links logical (schematic) diagrams to physical (layout) parts

- **Some common software packages:**
  - Eagle (Easily Accessible Graphical Layout Editor)
  - OrCAD
  - Altium CircuitMaker
  - PADs
  - Many others!

Eagle CAD

- **In this class we'll be using EagleCAD**
  - Available from https://www.autodesk.com/products/eagle/free-download
  - Used by many—including Arduino designers
  - Commercial software
    - "free" version for non-commercial use
    - "free" restricted: 2-layer, 100mm x 80mm size

- **Also worth considering:**
  - *DIPTRACE*, available from http://www.diptrace.com at
    - Free, restricted version is also available
  - *KiCad EDA*, from http://kicad-pcb.org
  - *Altium CircuitMaker* http://circuitmaker.com/
    - MRSD Wiki: http://cmumrsdproject.wikispaces.com/Altium+Circuitmaker

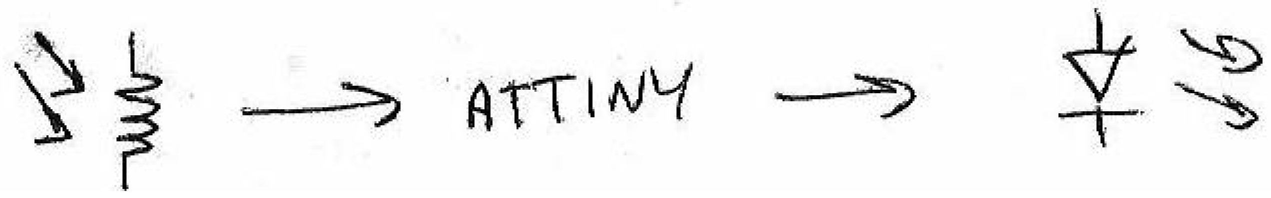
Schematics: A Picture is Worth a Thousand Words

- **Schematics represent circuits graphically**
- **Consider one very basic system:**

- **A little vague, but still a schematic**
- **A good schematic shows *what* and *how***

Adding Detail with Symbols

- **Using specific symbols tells more information**



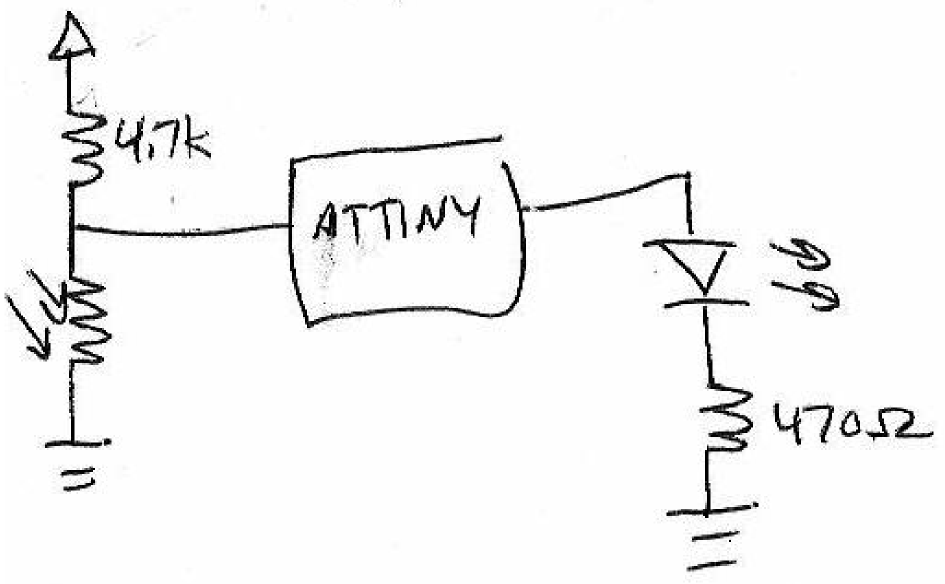
A photocell is read by an ATTiny microcontroller which lights an LED

- **Shows you've thought about *what* you're using**
- **But**  **is not really a valid electrical device**

Adding Detail with Basic Circuits

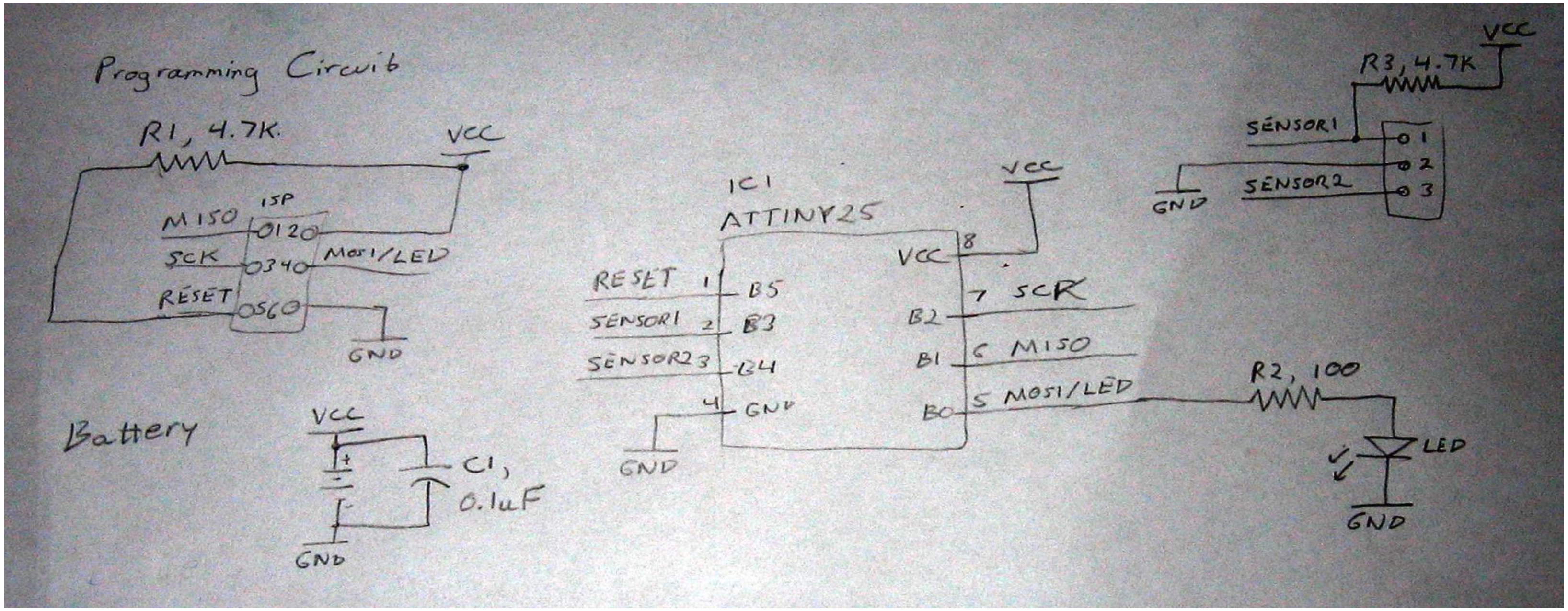
- **Explaining *how* requires circuit diagrams**

A photocell in a voltage divider is read by an ATTINY which outputs to an LED with a current-limiting resistor



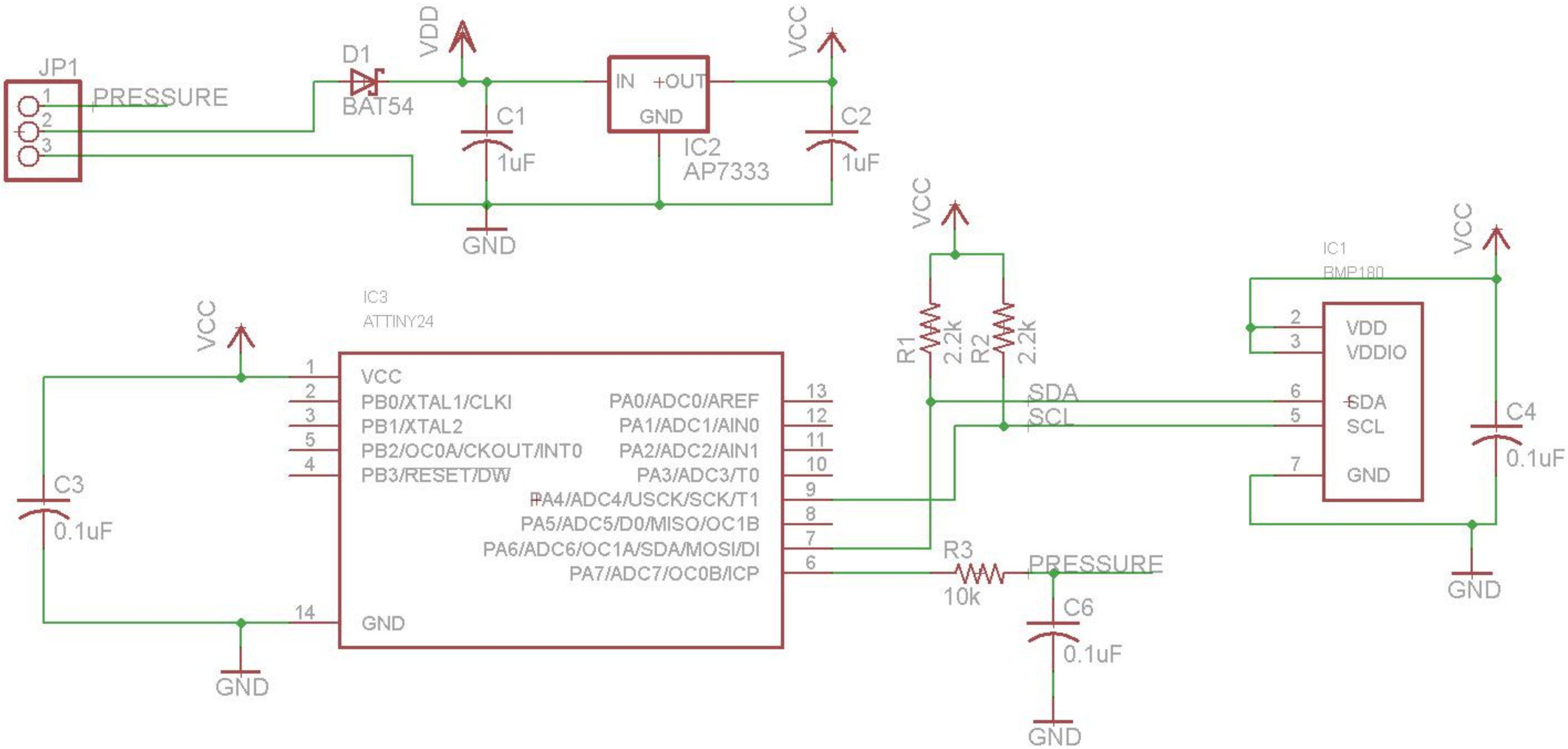
But... is this enough?

A complete schematic



- **Lots going on! A *complete schematic.***
- **However, *layout* is not apparent**

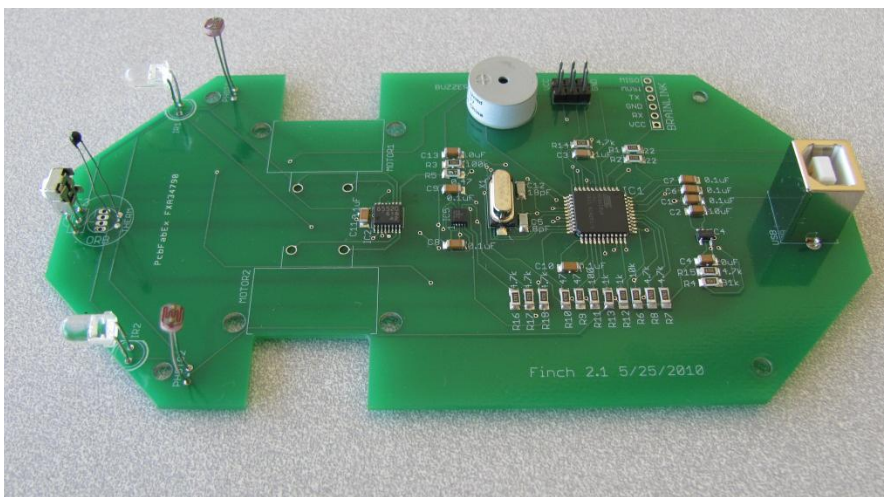
A Complete Schematic in Eagle

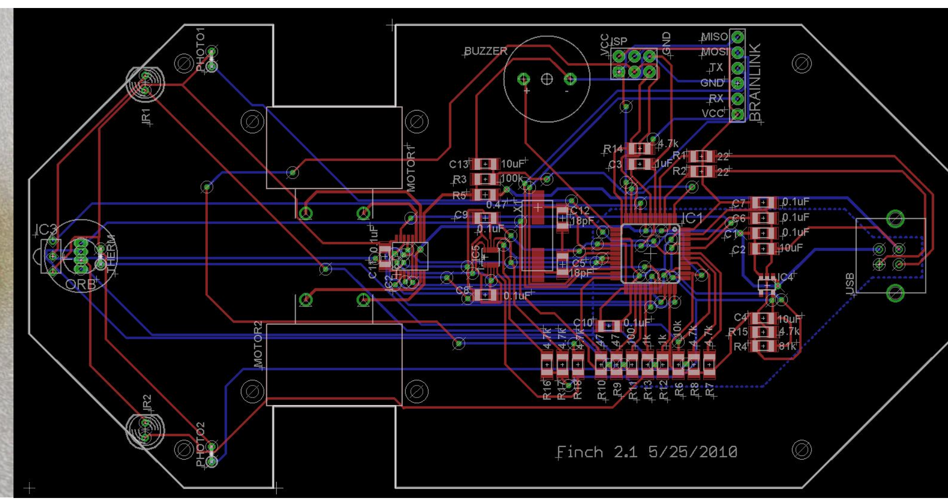


So I’ve Got my Schematic…

- **Time to make a “Layout”**
  - Scale representation of your PCB

- **Layers**
  - Copper in red and blue
    - Around holes it’s in green
  - Designators in white
  - Holes marked with **x**’s





Real World Layout Considerations

- Design Rules
- Surface Mount and Through-hole
- Heat sinks
- Shape, mounting, and 2D representations of 3D parts
- Routing

Design Rules

- **Design Rules – "*Thou shalt nots*" for your circuit board**

- **Adjustable, but…they come from reality:**
  - **Advanced Circuits Capabilities**

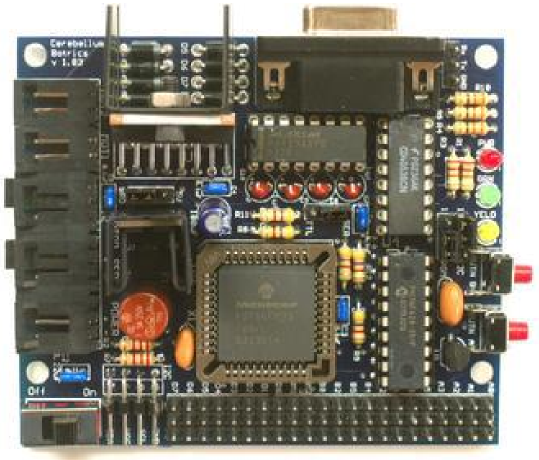
- **Tell you things like:**
  - How small traces can be
  - How small holes can be
  - Minimum distance between part, pad, trace, and the board's edge
  - Minimum distance between traces
  - And much more!

- **You must *always* address *any* violations *and* warnings flagged by the CAD software**

Through-hole Vs. Surface Mount

Through-Hole:

- Easy to solder
- Easier to fix circuits
- You don't lose components on the floor
- Better for large connectors



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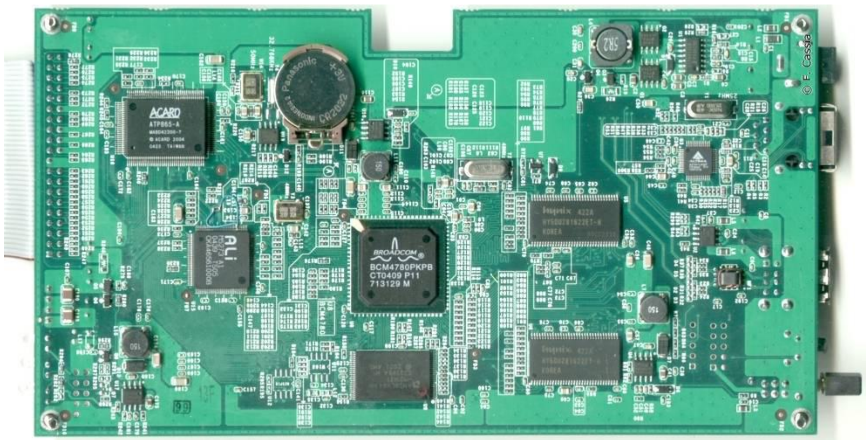
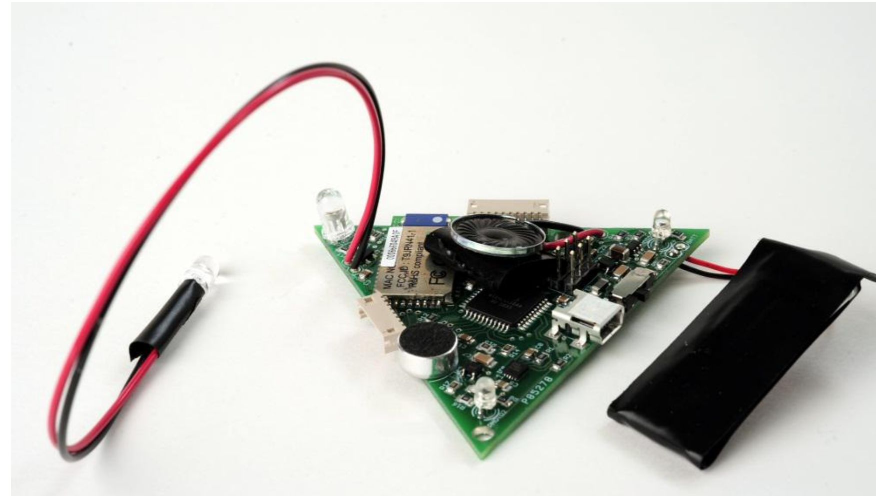
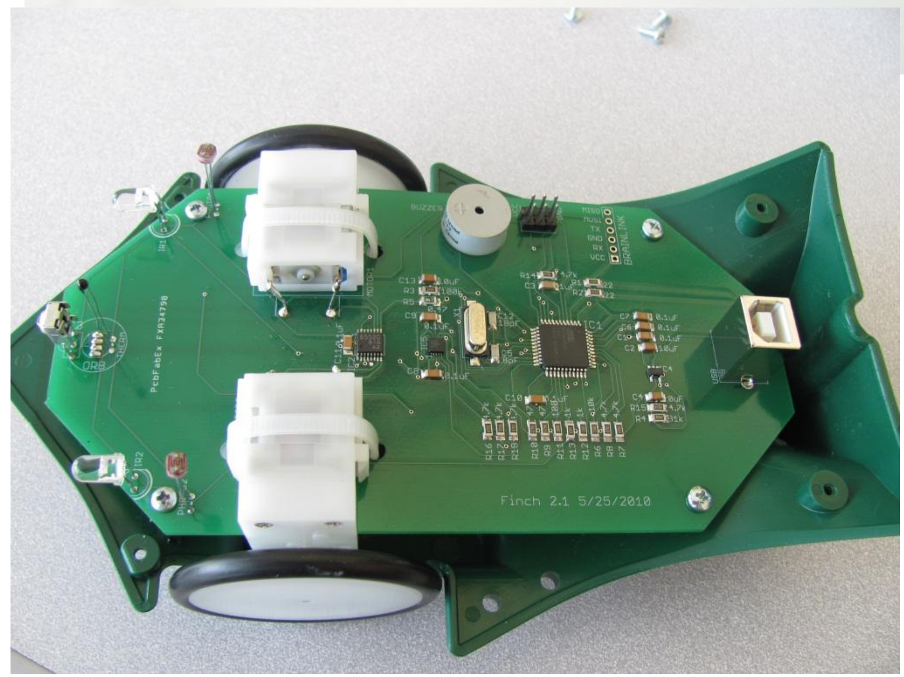


Shape, Mounting

- **PCB does not need to be a rectangle**
  - Not always a choice, though
  - Service used in this class requires <u>rectangular shapes</u>
- **Make sure you allow for a way to mount the board**
- **Keep in mind: it's a 2D representation of a 3D part!**





Heatsinking

- Some high power parts may require a heat sink
- Often much bigger than part
- Specified in datasheet
- Make sure to factor size of heat sink into your layout
- Location is also important

- Insulate electrically !!!

Routing

- **Definition:** ***The process of making electrical connections between the different components by editing the physical (copper) representation of the nets created in your schematic***

- **Your "frenemy," the autorouter**
  - Computers do the darnedest things
  - Fixing things may take as long as routing by hand

- **Routing by hand creates a much cleaner looking design**
  - However, it's invaluable for large projects!

Trace Widths and Power

- **All traces/wires have resistance**

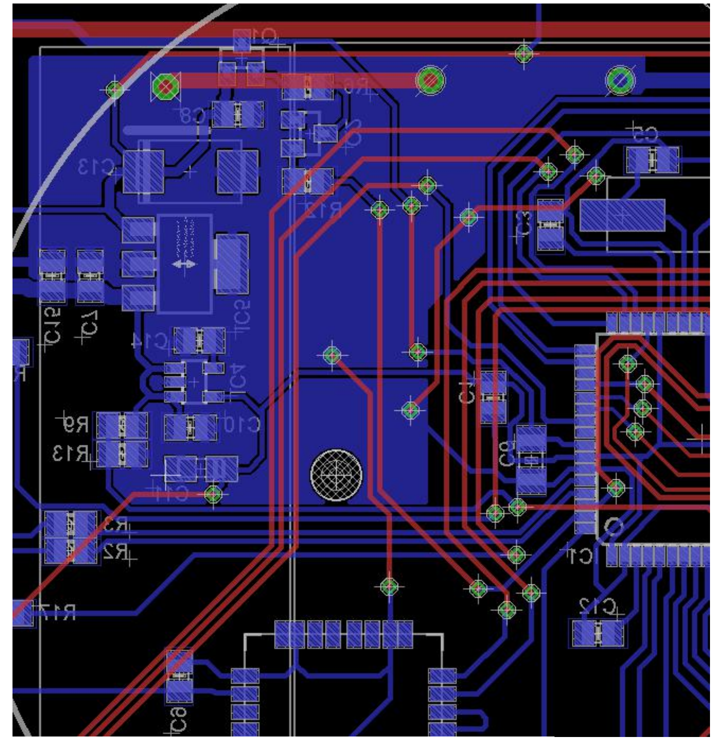
- **Car jumper cables vs. Christmas lights**

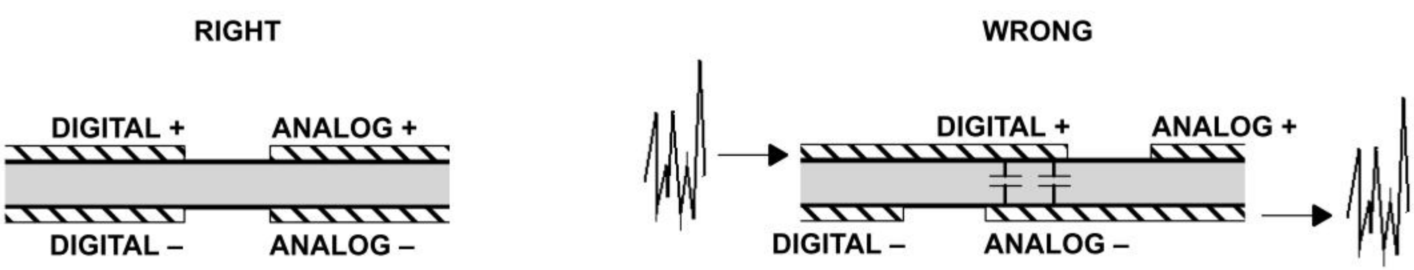
- **Some traces need to be wider than others**
  - Wider traces carry more current (necessary for driving high-current devices, like motors).
    - Thin trace carrying lots of current = FIRE
  - Wider traces have less noise (good for analog signals)

- **Handy tool:**
  - **http://www.4pcb.com/trace-width-calculator.html**
  - Understand issues with temperature

Planes

- **Cover a large part of your board with copper connected to a net (typically ground)**
- **Used for:**
  - Heat-sinking
  - Noise reduction
  - Simplify routing (one less net)

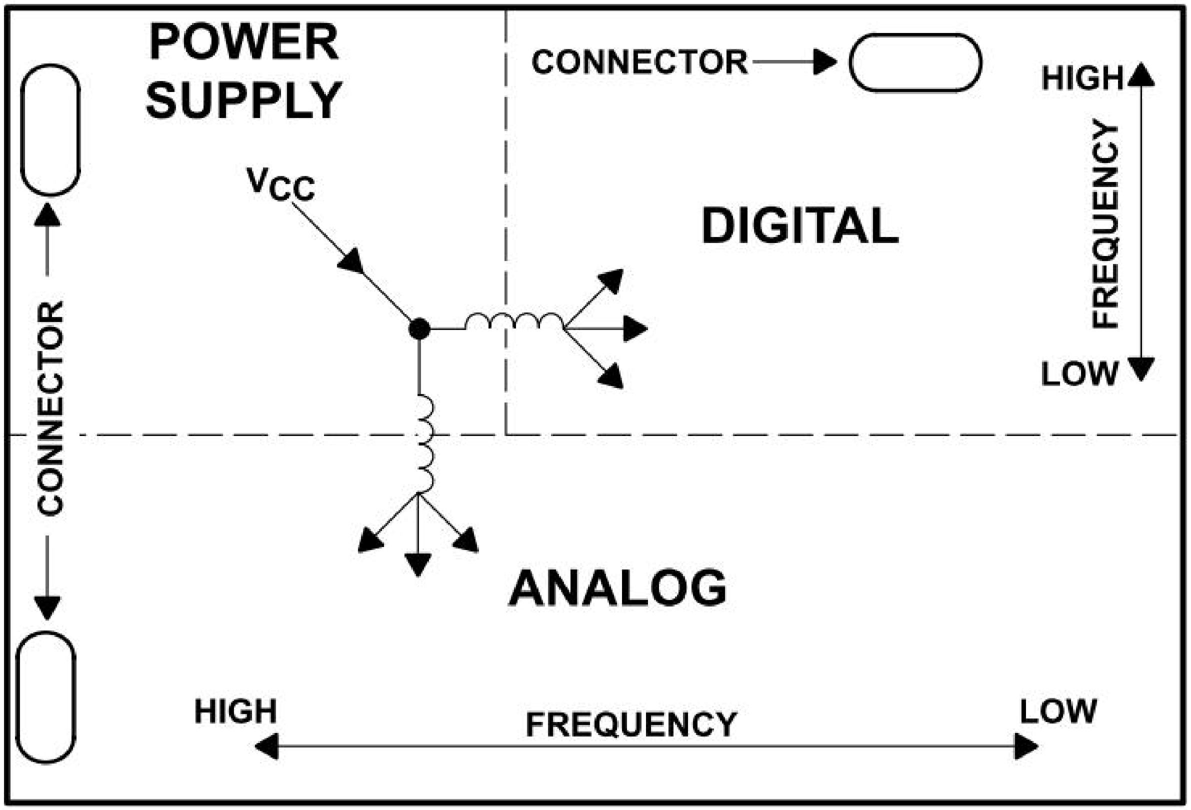




Avoid coupling high-frequency digital noise into analog circuitry

Board Layout

- Careful placement prevents a lot of problems



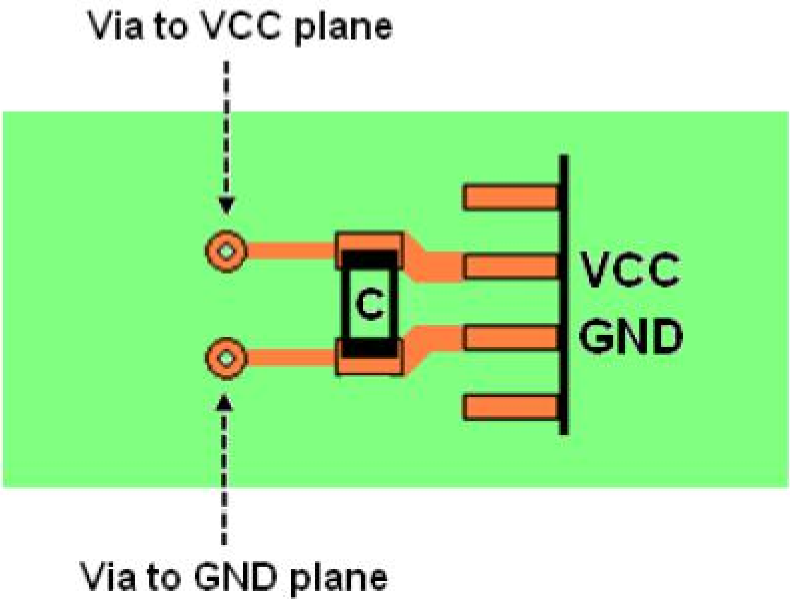
- Keep grounds separate!!
  - But they must be common at a single, low-impedance point

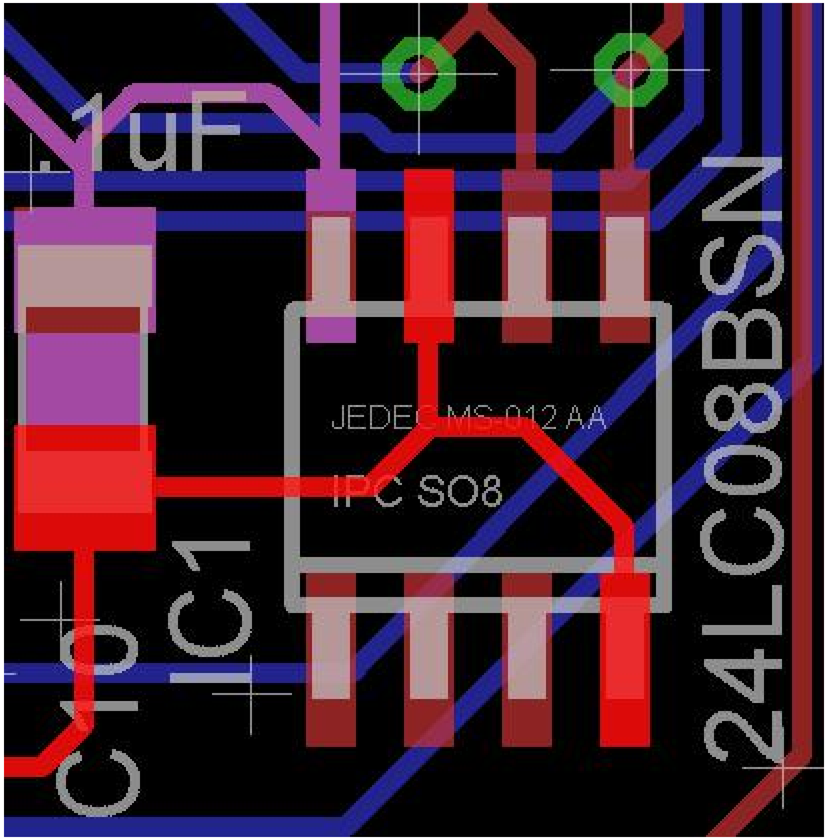
Slight Detour: Decoupling Capacitor Placement

- **Short traces (less than 0.5”)**
- **At least one per IC**
  - Usually one per pair of VCC/GND terminals on IC
- **Can be on underside if you want to save space**
- **Following slides – a few examples of good capacitor placement**

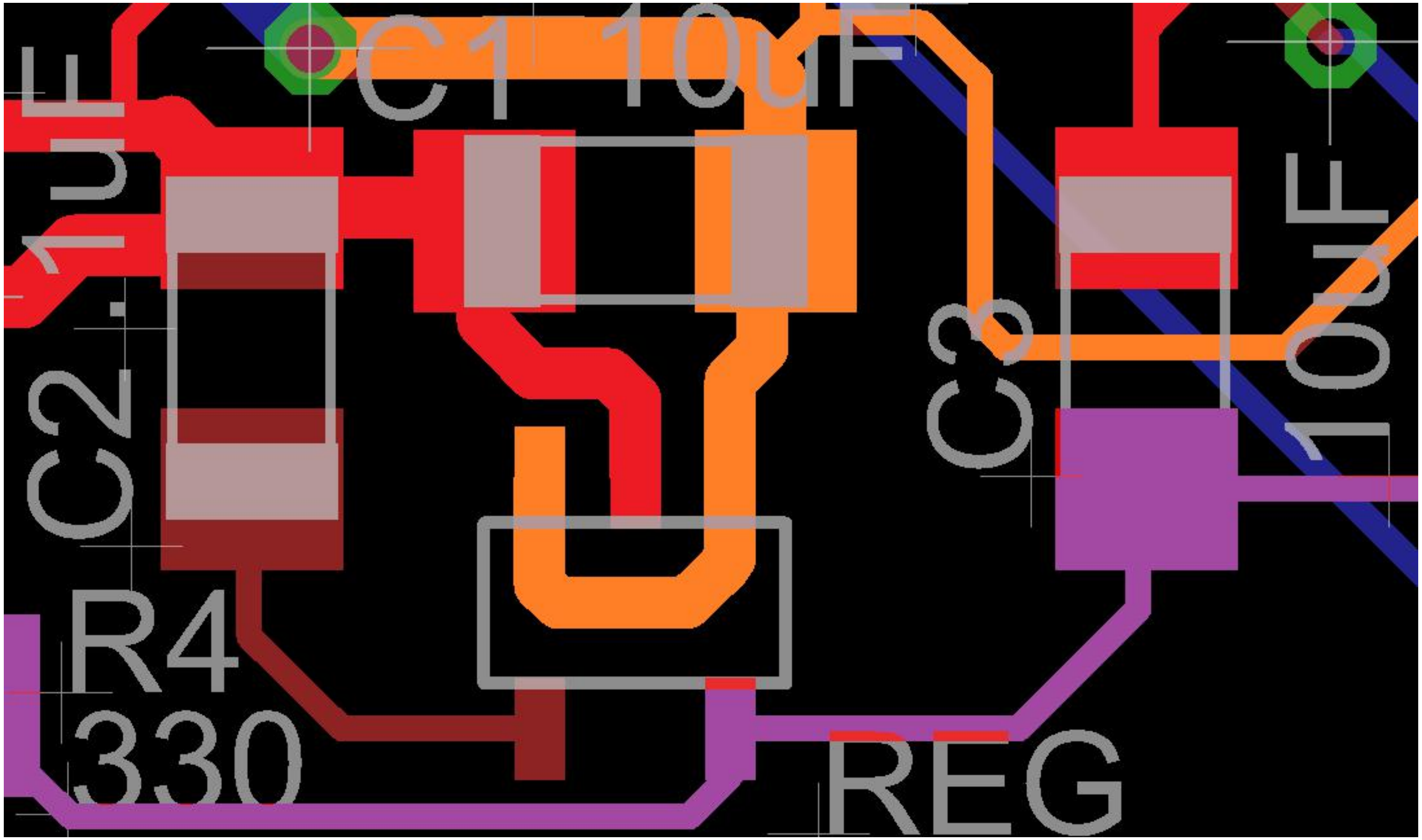
Good IC Decoupling

- VCC = PURPLE
- GND = RED





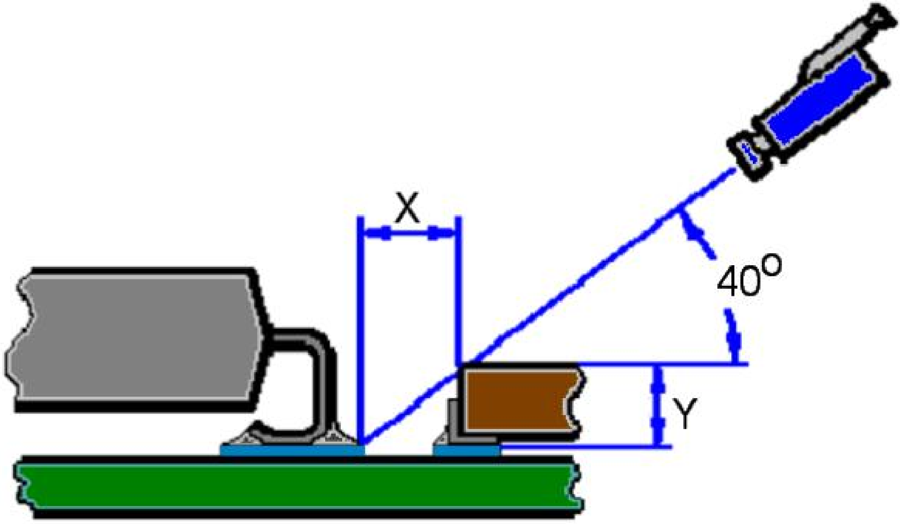
Good Input Capacitors for a Voltage Regulator



GND = Red, VDD = Orange, VCC = Purple

Design for Testing, Inspecting, and Assembling

- **Test points**
- **Tooling pins**
  - Precise registration with test fixture
  - Push fingers
- **Clearances for inspection**
- **Simplify populating your board**

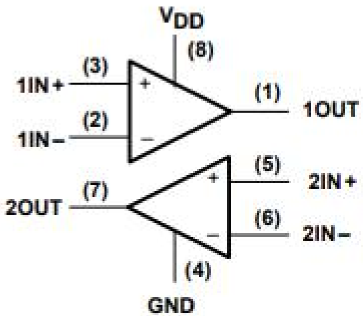


So where do parts come from?

- **Answer: Libraries!**
- **Every part is divided into three representations**
  - **Package**
    - The physical representation of the part
    - What you see in Layout view
  - **Symbol**
    - The logical representation of the part
    - What you see in Schematic View
  - **Device**
    - A place to tie the **package** to the **symbol**
    - Lets you re-use common packages on different parts
    - Lets you re-use common symbols on package variants

Device = Package + Symbol

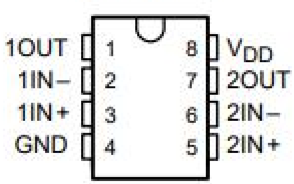
TLC272, TLC272A, TLC272B, TLC272Y, TLC277
LinCMOS™ PRECISION DUAL OPERATIONAL AMPLIFIERS

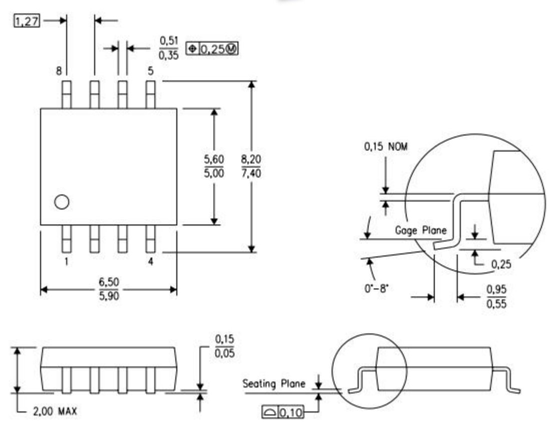


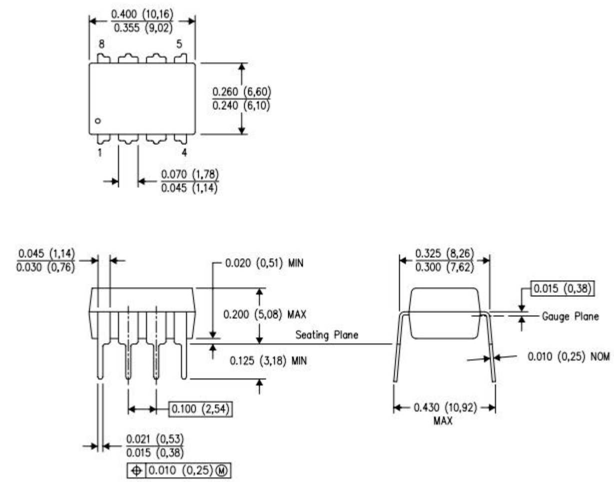
AVAILABLE OPTIONS

T_A	$V_{IO}max$ AT 25°C	PACKAGED DEVICES					CHIP FORM (Y)
		SMALL OUTLINE (D)	CHIP CARRIER (FK)	CERAMIC DIP (JG)	PLASTIC DIP (P)	TSSOP (PW)	
0°C to 70°c	500 μV	TLC277CD	—	—	TLC277CP	—	—
	2 mV	TLC272BCD	—	—	TLC272BCP	—	—
	5 mV	TLC272ACD	—	—	TLC272ACP	—	—
	10mV	TLC272CD	—	—	TLC272CP	TLC272CPW	TLC272Y
−40°C to 85°C	500 μV	TLC277ID	—	—	TLC277IP	—	—
	2 mV	TLC272BID	—	—	TLC272BIP	—	—
	5 mV	TLC272AID	—	—	TLC272AIP	—	—
	10 mV	TLC272ID	—	—	TLC272IP	—	—

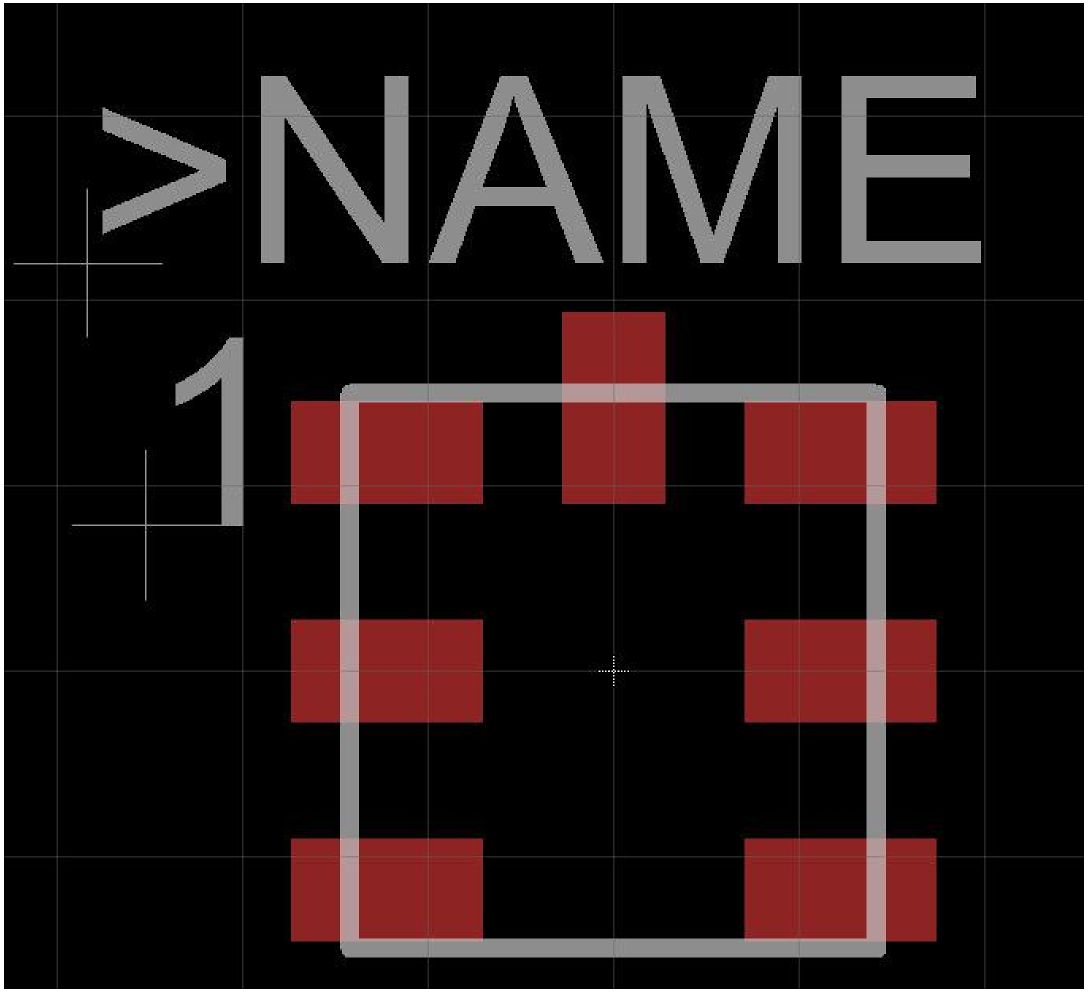
D, JG, P, OR PW PACKAGE
(TOP VIEW)



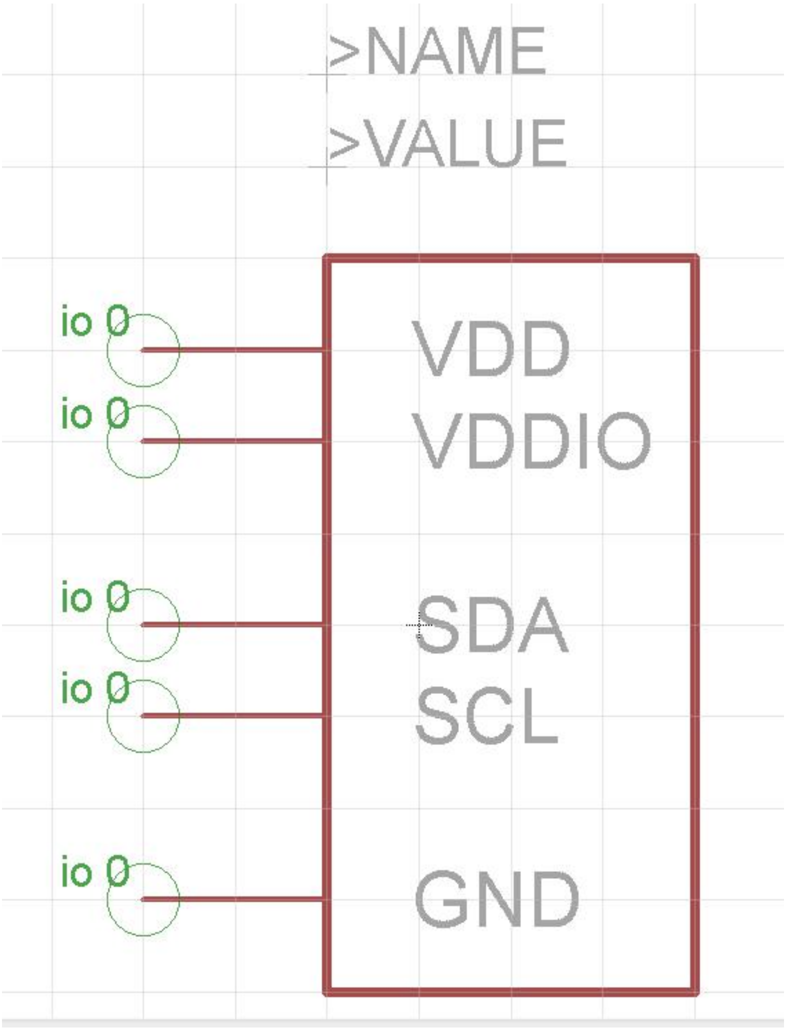




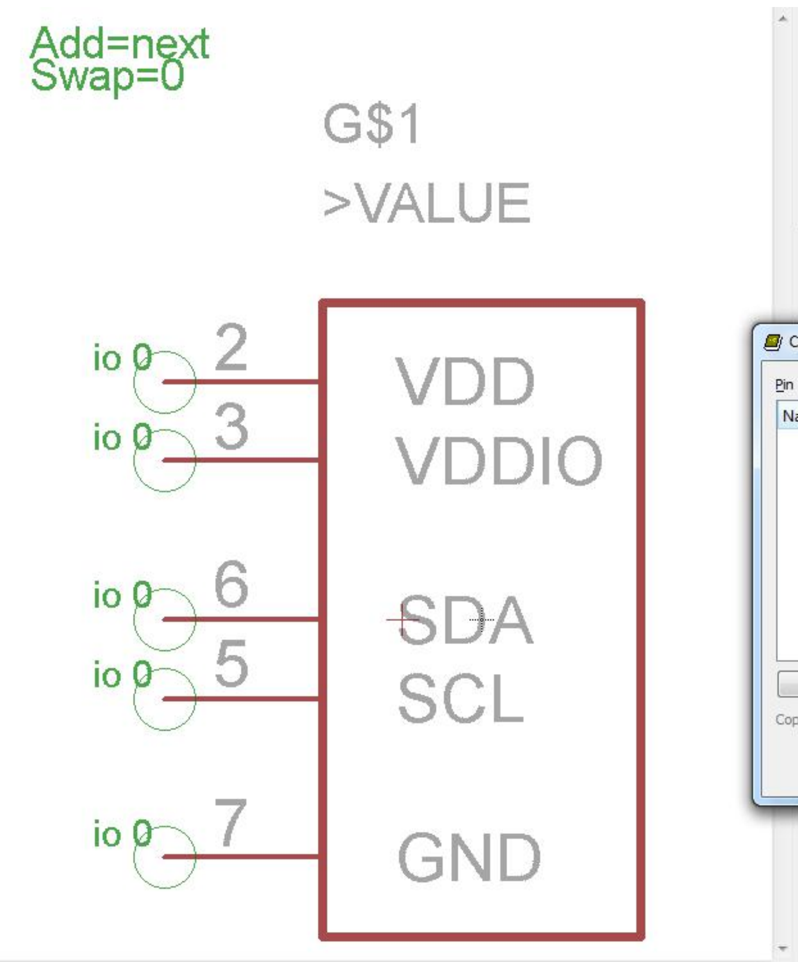
Sample Package View

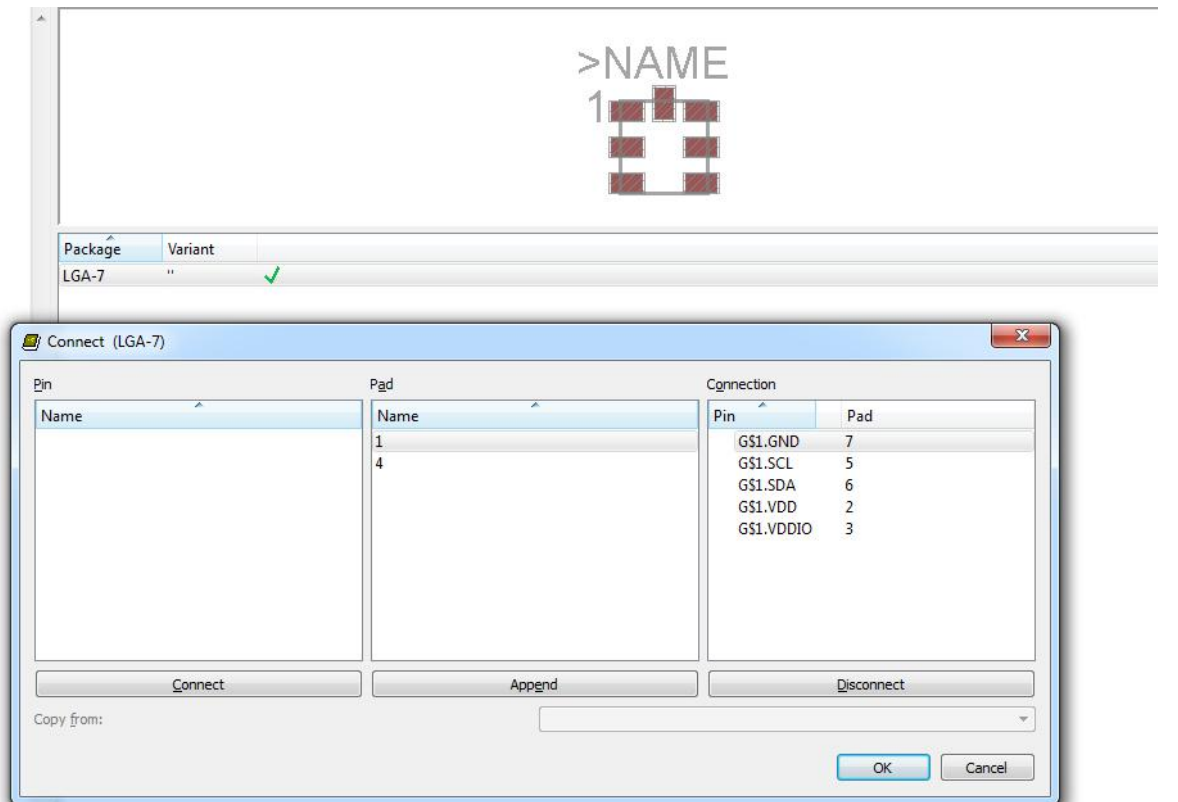


Sample Symbol View



Sample Device View





Always use meaningful names for devices, symbols, and packages

- Don't use the same name for everything!

Where do libraries come from?

- **EAGLE standard libraries**
  - Some are great, some are outdated
- **Online open-source libraries**
  - Contributed libraries on Eagle's site
  - Sparkfun, Adafruit, etc.
- **You!**
  - Complex or unusual parts are probably not in any library

Converting a System Diagram into an Electrical Schematic

Basic Implementation Guidelines

- Control
- Sensing/Actuation
- Power
- Interconnect

Implementing *Control*

- **Choosing a microcontroller**
  - AVR, PIC are popular choices
  - TI OMAP, Freescale, ARM7, ARM9…
  - Older architectures like 8051 or 16HC11

- **Also OK to plan on using a *microcontroller board* and interfacing to its connectors**
  - “Arduino shield”
  - Sensor/actuator boards (*e.g. L293 driver board)*

- **Others (higher degree of integration/capability)**
  - Raspberry PI, Beaglebone, Odroid, Jetson…

Implementing Control

- **Don't forget the baggage**
  - Usually specific programming infrastructure required ("toolchain")
  - A bunch of extra circuitry, specifically:
    - Required voltage regulation / decoupling
    - Programming connector (even if using a bootloader!)

- **For AVR consider availability of OSS `avr-gcc` compiler and `avr-dude` compiler.**
    - AVR Studio (windows only) also available free.

- **Arduino**
  - Uses AVR for the same reason
  - Also has bootloader / Processing interface for programming
  - If you like/need Arduino interface, consider making your own
    1. Download open source eagle files for your favorite Arduino version
    2. Modify design to add additional sensor/actuator interfaces to PCB
    3. Make PCB and re-release design files

Important Things to Remember on Control

- **Voltage Compatibility**
  - Modern ICs run at 3.3V or 1.8V, not 5V
  - If you need to hook up to a junky old sensor, may need level-shifting to prevent damage
- **Make sure to add debugging output**
  - Even a blinking LED helps iron out software kinks
  - A serial (or USB serial) port makes it even easier
- **Basic system testing – aim for a few simple milestones**
  - "Blink test" is a good first program (the "*Hello World*" of embedded systems)
  - Each subsystem should be able to be independently tested and verified, even if only in debugging mode

Sensing and Actuation

- **Sensing/Actuation lumps together subsystems that either:**
  - Measure the physical world and produce digital or analog values for a controller, or
  - Take digital or analog values from a controller and effect change on the physical world

- **Some sensors:**
  - Light sensors (photocells, cameras, photodiodes, etc.)
  - Temperature sensors (thermistors, thermocouples, etc.)
  - Contact sensors (buttons, limit switches, pressure pads, etc.)
  - Rangefinders (IR pairs, IR rangefinders, sonar, laser rangefinders, etc.

- **Some actuators:**
  - Light sources (LEDs, lamps, neon, etc.)
  - Motion (Motors, servos, steppers, solenoids, piezo elements, etc.)
  - Sound (speakers, buzzers, piezo elements, etc.)

Support Circuitry

- **Most sensors/actuators require additional circuit elements to operate, such as:**
  - Discrete components (capacitors, resistors)
  - Additional, non-logic level voltage sources (especially for motors)
  - Level translation
    - Communications protocols (e.g. RS232/485 to TTL)
    - Also commonly for old 5V components interfacing to modern ICs
  - Electrical connectors to connect off-board components

- **Most devices explicitly tell you what support circuitry is needed in their *datasheets* (more on future lecture)**

Actuators Brief: Motion Control

- **Always use the least amount of control needed!**
  - Only need to drive one direction? MOSFET/relay
  - Bi-directionality requires H-bridge & support circuits
- **Aim for reasonable voltage/current**
  - 5V/500mA is easier than 50V/50A
  - 24V@2A is easier than 2V@24A   [why?]
- **Many monolithic options available**
  - Driving 1-4 motors can be as simple as one IC, a few capacitors, and your connectors
  - L293 == L298 with integrated flyback diodes
  - Many MOSFET designs / ICs do not require flyback diodes
- **For high power (>10W), it may be easier to investigate hobby servos, off-board modules or motion control amps**

Implementing *Power Systems*

- **All electromechanical devices require power to operate**

- **All modern electronics perform logical operations while generating heat**

- **When implementing a power system, understanding the *bounds* is essential:**
  - Voltage ranges (min / max)
  - Current draw (quiescent / peak)
  - Storage capacity (mass / volume)
  - Runtime

Classifying Different Power Systems

Consider:

Voltage ***Current*** ***Capacity*** ***Runtime***

Different devices will have different requirements:

- Digital watch
- Wireless sensor node
- R/C Car
- R/C Quadrotor
- Computer performing video analysis
- Electric car

Implementing Power Systems

- **Regulation - switching, linear**
  - Low dropout
- **Banks of regulators**
- **Sizing loads for current at given voltages**
- **Sizing a battery for a given system**
- **Stability - capacitance, remote vs. local loads**
- **Recharging / power connections**
  - Power management systems

How Power Affects PCBs

- **May need multiple voltage sources**
  - Motors may need higher voltage than logic
  - Different logic may require different voltages
- **Current draw affects trace width and component size**
  - Big currents require big traces
  - Regulators for 100mA much smaller than for 2A

Voltage Regulation

- **Most systems designed to operate from a single source**
  - Wall (A/C) via AC/DC converter
  - Battery pack
  - Source voltage is usually optimized for largest power consuming subsystem (e.g. motors)

- **DC/DC converters used to create other subsystem voltages**
  - Logic voltage levels (frequently 1.8V, 3.3V, 5V)
  - Analog supplies (±5V, ±15V)
  - Other (500V photoflash bank, 5kV neon ballast)

- **DC/DC converters also used to *regulate* voltages**
  - Stable voltages are essential for logic ICs
  - Helps isolate subsystems from each other

Voltage Regulation

- **Linear Regulators**
  - Can only step-down voltages
  - Dissipates excess as heat [voltage drop X subsystem current]
  - Usually very clean signals
  - Low cost and complexity
  - Excellent for small voltage drops

- **Switching Regulators**
  - Allows output voltage to be above and/or below input voltage
  - Efficiencies typically 80-96%
  - Higher cost
  - Variable complexity – but Point of Load replacements available!
  - Excellent for large voltage differences

Minimizing current can minimize power losses / regulator size

Linear vs. Switching Efficiency

- **Desired Output Voltage: 5V**

Input Voltage	Linear Efficiency	Switching Efficiency
5.5V	91%	80-90%
6V	83%	80-90%
12V	42%	80-90%
24V	21%	80-90%
3.3V	Not possible	80-90%

- **Efficiency is not everything. 21% efficiency might be just fine if you're drawing 500µA.**

Assembling a Power System

- **Determine source voltage and current requirements**
  - Optimize for primary power using subsystems
  - **Add current** to account for other subsystems *and conversion efficiencies*

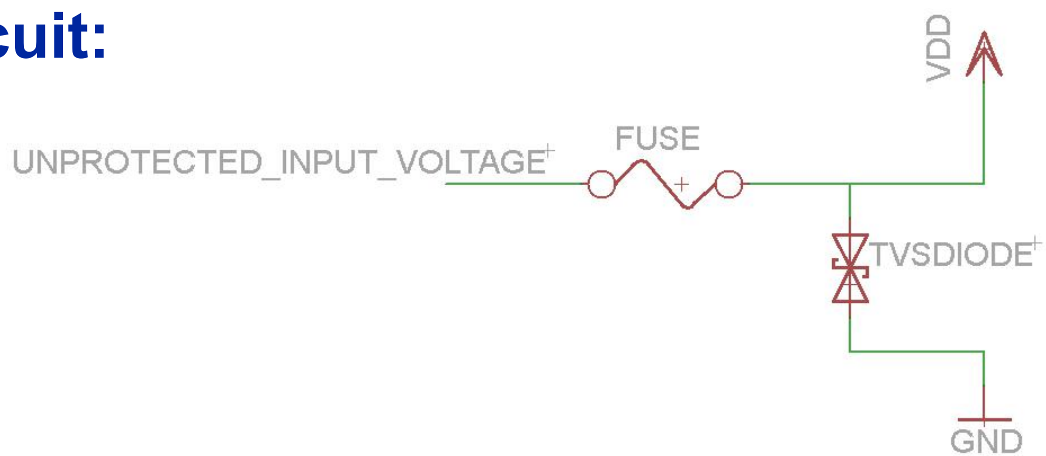
- **Determine voltages and current limits of regulated voltages**
  - Primary power systems frequently run *unregulated*
  - May need several logic voltages or other supplies

- **Other useful power system features**
  - Switches (e.g. ON/OFF) are helpful
  - Fuses / breakers may be needed
  - Voltage and current monitoring
  - *Battery charge management*

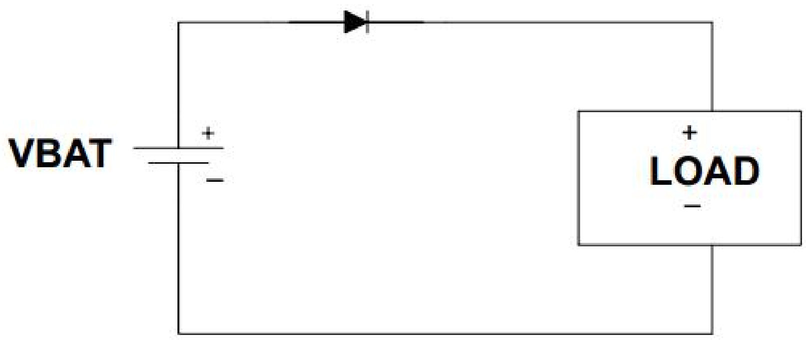
Overvoltage and Reverse-voltage Protection

- **It's 3 AM, and you just plugged your robot in backwards. Would you like to:**
  - A: Change a fuse?
  - B: Put out a small fire, go through the stages of grief, and then solder together new PCBs, order new parts, and explain to your professor why your project is going to be a week late because nobody from your group remembered this slide

- **Here's a circuit:**



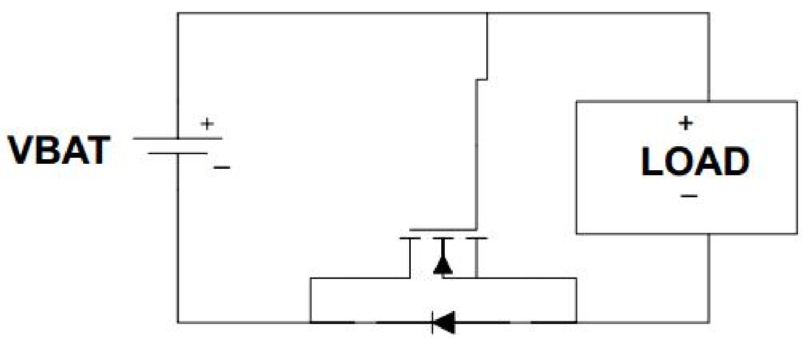
Reverse-Voltage Protection



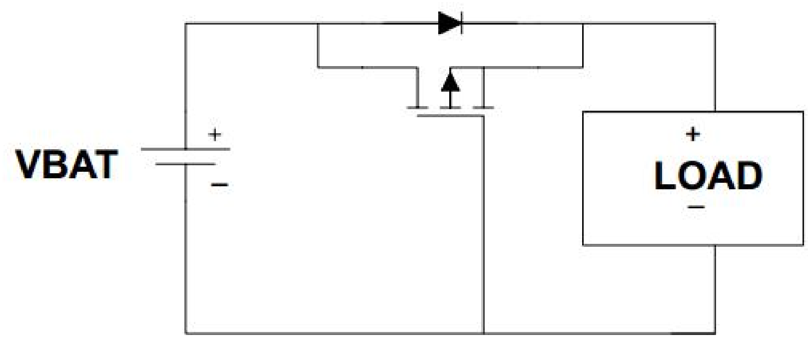
Diode in series with load

- Voltage drop
  - Batteries
  - Efficiency

- Use Schottky diode
  - Cost



NMOS FET in the ground return path



PMOS FET in the power path

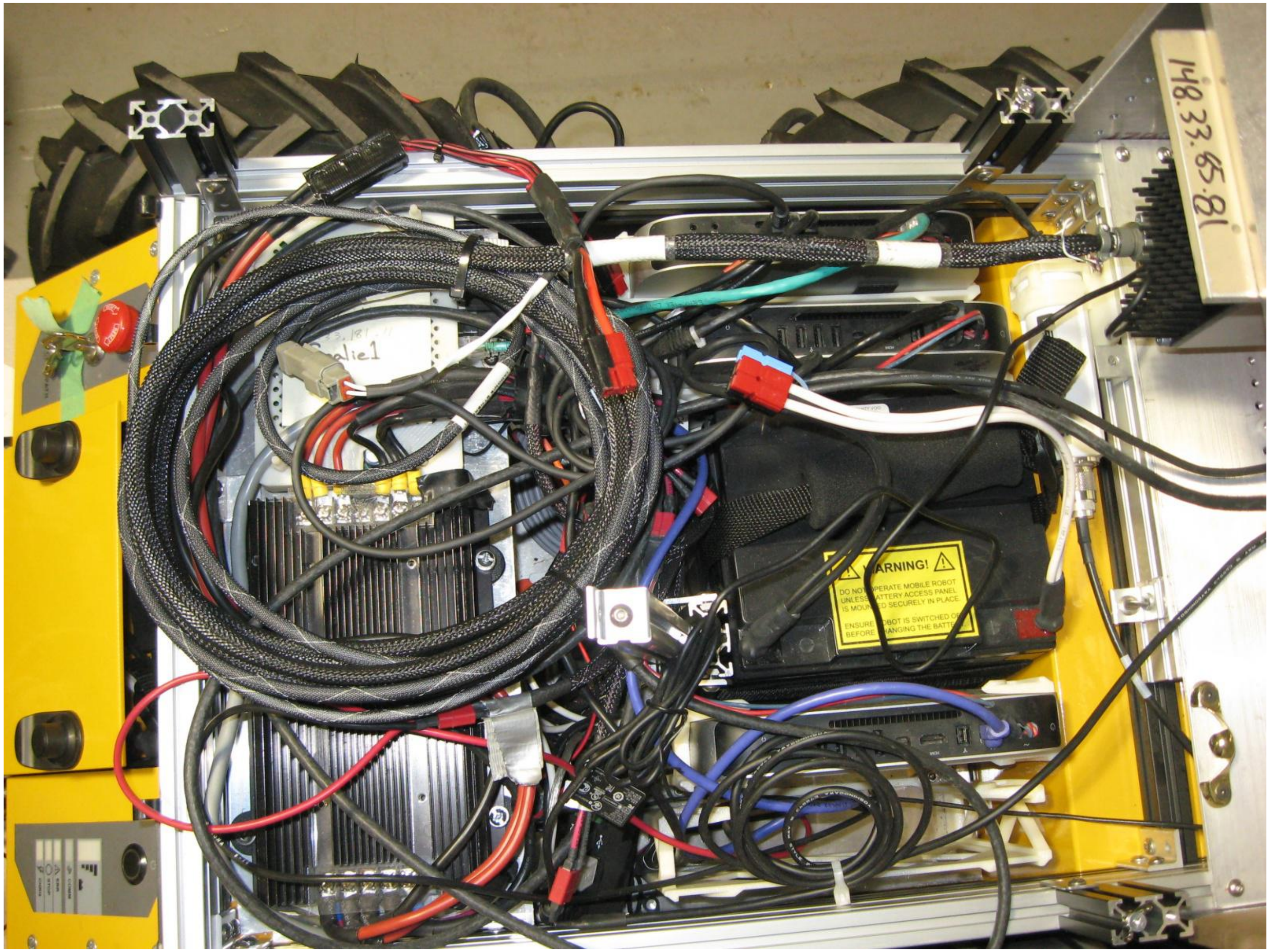
Finally, Using *Interconnect* Appropriately

- **Wire (and PCB traces) should be sized appropriately for current loads**
  - Trace Width Calculator is an invaluable tool
  - Many wiring tables for various gauges show current capacity
  - Use stranded wire for connections!

- **Avoid analog effects on your digital designs**
  - Use short, thick traces for analog signals
  - Keep analog away from fast switching digital signals
  - Use ground planes or guard bands when appropriate

- **Use appropriate connectors**
  - Every connector is a potential point of failure
  - Observe current and connection cycle ratings
  - Use board-to-board when possible instead of board-wire-board

System Integration: Never Underestimate!



Teamwork and PCBs – Divvying efficiently

- **Schematic accumulation**
  - Everyone can contribute subcircuits
  - One person in charge of overall schematic / collating contributions
- **Part hunter**
  - At least one person should be searching for parts
  - Parts should be **available** and **captured into Eagle**
- **Verifier**
  - Dedicated to finding logical errors in schematics or layout
  - Goes through internet/team created libraries and checks parts
- **Layout and physical space planner**
  - Determine board size and shape
  - Board mounting hole placement
  - Determine where all connectors should be located
  - Ensures parts sticking off board won't interfere with chassis

Assignment Overview: Individual Assignment

- **Due: Tuesday Nov. 7th**
- **Capture a hand-drawn schematic into Eagle, and make two layouts for it:**
  - One all through hole
  - One all surface mount
- **Create Eagle library versions of two parts from their datasheets**
- **Make sure to check out the two tutorials posted on Canvas, and send questions to us**
- **Please, make sure that you**
  - Follow the file naming guidelines
  - Address any issues reported by ERC, DRC
    - *Unaddressed issues will reduce your grade*

Thank you!