Smart Home Technologies
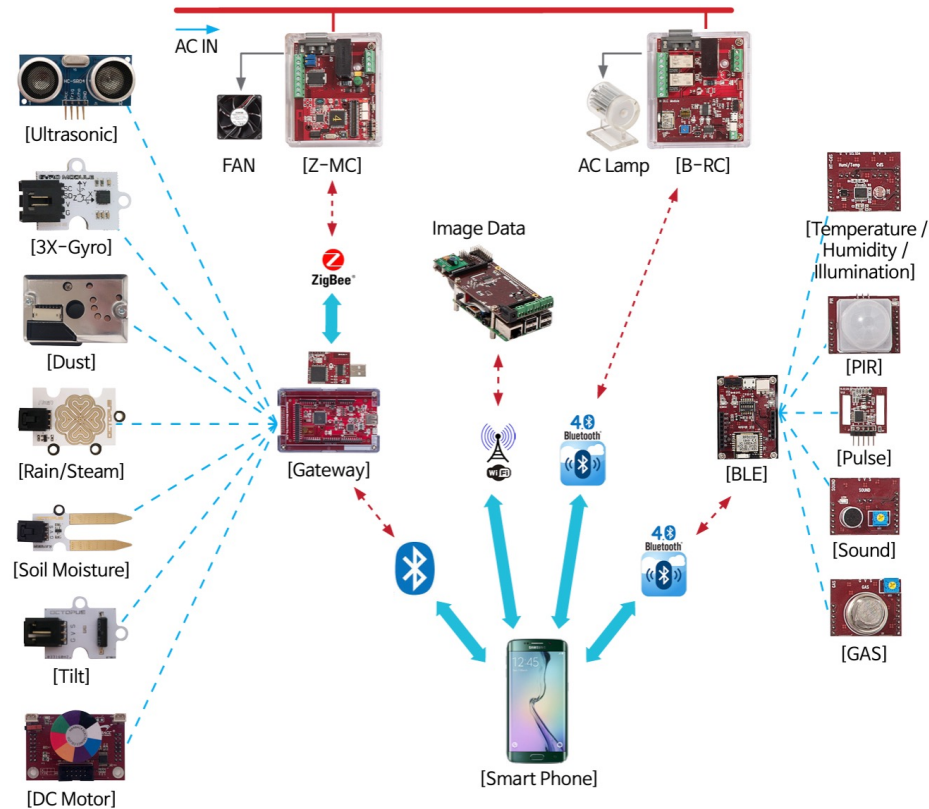
Building Smart Sensors

Smart Sensors and Actuators

- Sensor and Actuator Hardware

- Conditioning Circuitry

- Microcontroller
    - Signal Filtering
    - Data Fusion
    - Task-Specific Processing

- Networking Hardware

Sensor and Actuator Hardware

- To build sensors we have to understand the basic principles of electronic circuits
  - Voltage, Current, Resistance, Capacitance
  - Electronic components, ICs

Definition: Current

- How is current (I) defined?
  - Pick any point in an electrical circuit
  - Define a unit of charge (Q)
    - The charge of one electron = -1.6×10^{-19} coulombs
  - Measure the change in charge with respect to time at this point
    - $dQ/dt \equiv I$
- What is the unit for I?
  - 1 ampere = 1 coulomb / 1 second
  - Most of the time this is just referred to as an amp

Definition: Voltage

- At any point in a circuit, a positive charge (Q) has some level of potential energy (W)
  - Caused by its attraction to any build-up of negative charges in the circuit
  - Voltage (V) is defined as the normalized value of this PE
    - I.e., $V \equiv W/Q$
- Units
  - 1 volt = 1 joule / 1 coulomb
- So a voltage drop between two points in a circuit is really a relative measurement of the change in PE for a given charge

Definition: Resistance

- Static resistance is something that blocks the flow of Direct Current (DC)
- A resistance between point A and point B will cause a difference in the PE between the points, and thus a voltage difference
- This difference is also dependent on how much current is flowing from A to B
    - I.e., $R = (V_2 - V_1)/I$
- Units
    - 1 ohm = 1 volt /1 amp

Definition: Power

- Now that we have a definition for current and voltage, we can get a definition for power
  - $P \equiv dW/dt$ or more simply, $P = V \times I$
- Power is the amount of work that can result from the circuit
  - For example: lighting a light bulb
- If no useful work can be done, the power is lost as heat

Ohm's Law

- The voltage drop across a resistance is equal to the current times the resistance
  - $V = IR$

- Using what we have already defined, this can be expressed as
  - $V = IR = P/I = (PR)^{-1/2}$
  - $R = V/I = V^2/P = P/I^2$
  - $I = V/R = P/V \ (P/R)^{-1/2}$
  - $P = VI = I^2R = V^2/R$

Useful Info from Ohm's Law

- Resistance in series
  - $R_t = R_1 + R_2$
- Resistance in parallel
  - $R_t = 1/(1/R_1 + 1/R_2) = R_1 R_2 / (R_1 + R_2)$

Definition: Capacitance

- How is capacitance (C) defined?
  - $C \equiv Q/V$
- OK, what does that mean?
  - Capacitance occurs when two conducting surfaces are separated by a dielectric
- OK, what's a dielectric?
  - a substance that
    - is a poor conductor
    - but a good medium for an electromagnetic field
- What is the units for C?
  - 1 farad = 1 coulomb / 1 volt

Combining Capacitance

- The exact opposite of resistance
- Capacitance in parallel
    - $C_t = C_1 + C_2$
- Capacitance in series
    - $C_t = 1/(1/C_1 + 1/C_2) = C_1C_2/(C_1 + C_2)$

What Is a Semiconductor?

- A substance that has a natural property that
    - allows it to act like either a conductor or an insulator
- By adjusting this natural property by adding impurities to the substance
    - we can use two or more of these substances to control the way current flows through a circuit in very interesting ways
- To understand why this is important to the study of sensor and actuators
    - we need to introduce something called Band Theory

To get Started – A Simple Definition of a Circuit
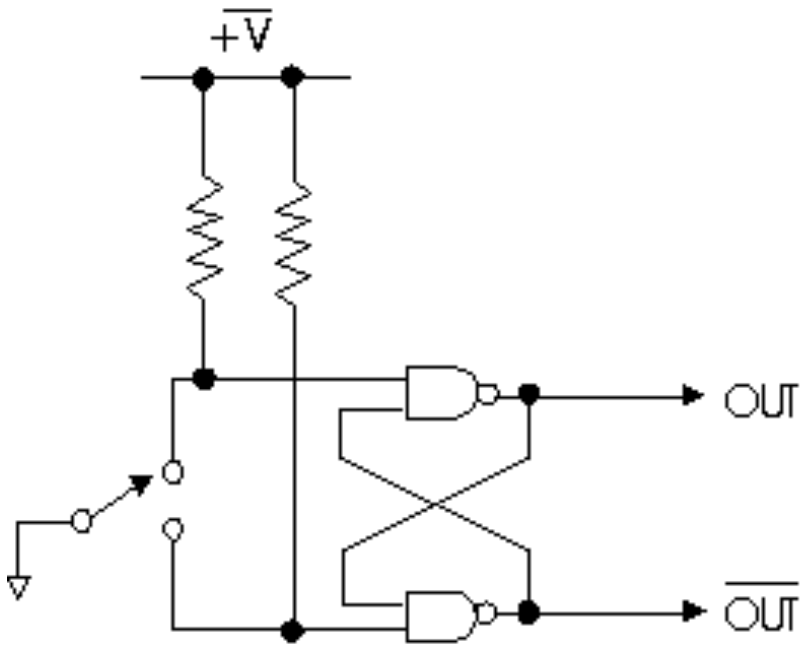
- A electronic circuit is simply a set of electronic components (resistors, capacitors, ICs, etc.) connected together via wires
- The example on the left is a circuit that debounces a switch sensor

Sensor Components for the Lab

- Now that we have the necessary foundation
  - we can briefly address the use of the electronic components you will be seeing in the lab
  - then, start designing some simple sensors and actuators
  - and finally, use this knowledge to talk about some sensors and actuators that are a little too complex to play with in this class

The Resistor

- A resistor provides a known resistance
- It has three values:
    - Resistance, measured in ohms
    - Tolerance, measured in +/- percent error
    - Power dissipation, measured in watts
- Using Ohm's law (V=IR), it can be used to create a desired voltage or current
    - but a voltage drop across a resistor is converted to waste heat, so this is not always the best way to do that

A Light Bulb

- It is a resistor encased in a vacuum in a clear or translucent container
- It has two values
    - Rated voltage (either AC or DC)
    - Lumen (how much light it puts out at its rated voltage)
- It obeys Ohm's law (V=IR)
    - but a voltage drop across a resistor is converted to both to light and to waste heat
- Even small light bulbs use a lot of current
    - so never try to drive them directly off an I/O line !

The Capacitor – A bit more complex

- First, some relative definitions
  - Let us assume that a capacitor already has some positive charge on one plate and some negative charge on the other, then
    - a positive voltage difference (between the plates) is one that supports (i.e, is in the same direction) as this existing charge
    - a negative voltage difference is one that counters (i.e, is in the opposite direction) as this existing charge
- OK, now we can start to talk about what it does
  - When there is a positive voltage increase between the two plates, more charge will build up on both plates
  - When there is an negative voltage increase, there will be a reduction in the charge built up on the plates

So What Does this Change in Charge Do?

- First, the effect of a change in the voltage difference between the plates only lasts until enough charge has been added or subtracted to match the change
  - I.e., assuming that you do not apply more voltage than the capacitor can handle, a capacitor's plate charge will always attempt to reach an equilibrium with new voltage difference
- During the change in charge,
  - current will appear to pass between the plates
- When a charge-voltage equilibrium is reached,
  - no current will pass between the plates

Capacitors in a DC Circuit

- When DC is first applied to a capacitor
  - current will 'pass' through the capacitor for a very short time while its plates charge to match the voltage difference seen by the capacitor
  - then, no DC will pass
- So, a capacitor will
  - once charged, look like an infinite resistance to any DC trying to pass through it
  - act like a very short term battery when the DC current in the circuit is turned off or reduced

Capacitors in a AC circuit

- Alternating Current (AC) can pass through a capacitor
  - How 'well' it passes depends on
    - the frequency of the AC
    - the relative charge capacity of the capacitor for the given AC voltage (measured in farads)
    - the way the capacitor is wired to the circuit
- So, the impedance (or AC resistance) of a capacitor can be used to filter out AC at frequencies you do not want

Capacitors - A Useful Unit

- Unless you are building a large AM radio station,
    - a farad is an absurdly large unit of capacitance
    - so, we need to find something smaller
- In enters our standard powers-of-ten prefixes
    - $0.000,001F$ ($1\text{x }10^{-6}$) = $1\mu F$ (microfarad)
    - $0.000,000,001F$ ($1\text{x }10^{-9}$) = $1nF$ (nanofarad)
    - $0.000,000,000,001F$ ($1\text{x }10^{-12}$) = $1pF$ (picofarad)
    - so, $1\mu F$ = $1000nF$ = $1,000,000$ pF
    - capacitors are normally labeled using μF or pF

The Diode

- It is a P-N junction device that come in many varieties
- Diodes normally have two leads called the anode and cathode
- Uses
  - DC power supplies use four *power* diodes in something called a full-wave bridge to convert AC to DC
  - We will be using a *Light Emitting Diode* (LED) as an actuator
    - Just as with other diodes, it works like a one way street for current, but converts almost all of its waste energy to light
  - The reverse photo process from a LED can be used to create one type of photo-detector called a photo-diode
  - We may discuss some other types later

The Bipolar Transistor

- It is made up of a NP-PN or PN-NP junction (called a NPN and PNP transistor)
- It normally has three leads called the base, collector and emitter
- It is most commonly used as
  - a current amplifier by allowing a small current flowing through the base to modulate a larger current flowing through to the collect-emitter
  - A solid-state switch by using the base current to turn on and off the collector-emitter current
- In actuator circuits, it is normally used as a switch to allow a processor to safely drive a high current device

The Field Effect Transistor

- It is made up of a P surrounded by two Ns or a N surrounded by two Ps

- It can have three leads called the gate, source, and drain, but often has only a source and drain

- A FETs is basically a solid-state resistor with most of its resistance being controlled by the amount of reverse bias applied to the gate

- FETs are useful for building certain types of sensors since the gate can be designed to allow its overall source-drain resistance to be controlled by a number of different types of energy

Other Semiconductor Types

- Semiconductors can be doped with a number compounds that have quite unique properties to start with
  - So, some sensors can be built from a single semiconductor type
    - for example, we will be using a Cadmium Sulfide (CdS) photoresistor
- There is also many more ways to create junctions than the three main ones described here
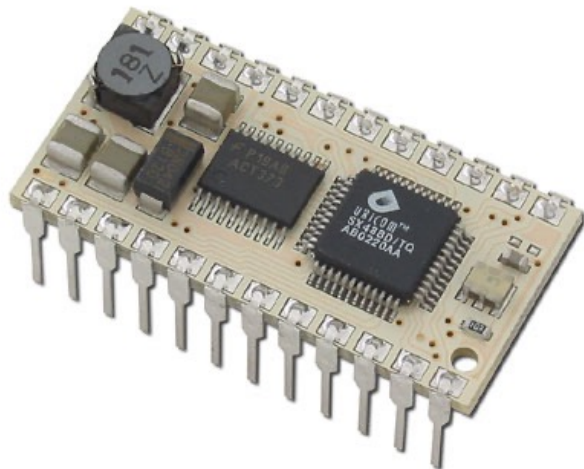
Integrated Circuits (ICs)

- ICs are basically just a bunch of semiconductors built on the same main substrate
- Far too many ICs could be used in sensor/actuator designs to allow any kind of comprehensive list
- For the lab, we will use
  - A Javelin stamp (containing an SX48BD microcontroller)
  - a LM34 temperature sensor
- For general information will will discuss
  - A LMD18200 motor controller
  - A UNC5804B stepper controller
  - PCF8591 analog-to-digital converter
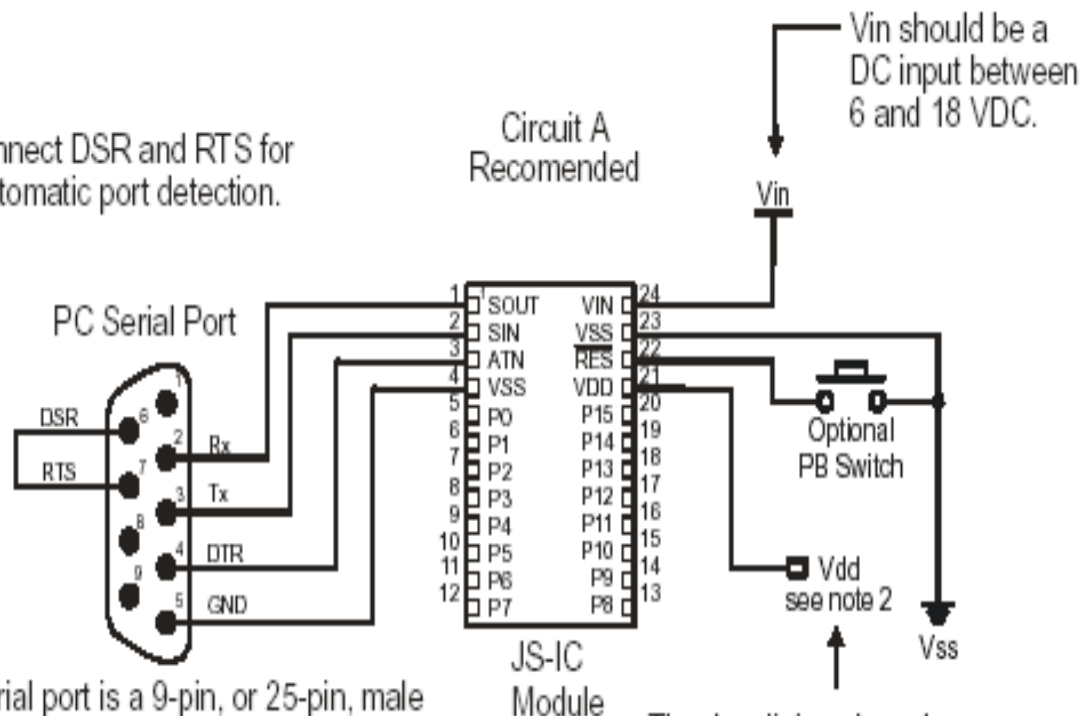 - And some general buffer and conditioner IC's

Example Processing Unit

- For the Lab the Javelin Stamp will be used as a Microcontroller to locally process the sensor data (http://www.parallax.com/javelin)

  - Fast prototyping microcontroller with built-in Java interpreter

  - Allows for interactive execution of commands

  - Provides digital and analog inputs

  - Connection to the host computer using an RS232 serial line

The Javelin Stamp – Basic Interface

Connect DSR and RTS for automatic port detection.

Circuit A Recomended

Vin should be a DC input between 6 and 18 VDC.

PC Serial Port

DSR
RTS
Rx
Tx
DTR
GND

JS-IC Module

	SOUT	VIN	24
1	SIN	VSS	23
2	ATN	RES	22
3	VSS	VDD	21
4	P0	P15	20
5	P1	P14	19
6	P2	P13	18
7	P3	P12	17
8	P4	P11	16
9	P5	P10	15
10	P6	P9	14
11	P7	P8	13

Optional PB Switch

Vdd
see note 2

Vss

The Javelin's onboard switching regulator can be used to supply low power circuits with regulated 5VDC.
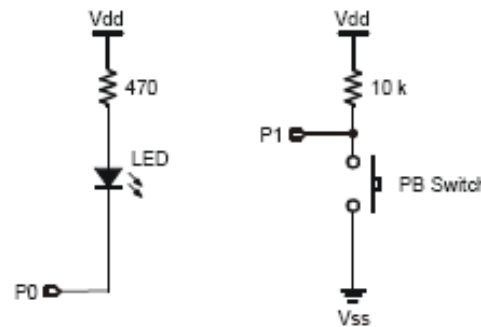
Note: The serial port is a 9-pin, or 25-pin, male connector, usually on the back of the computer. Use a 25-pin to 9-pin adapter when trying to interface to a 9-pin cable.

Javelin Stamp Programming

- Simple program and circuit to use a switch to flash an LED:
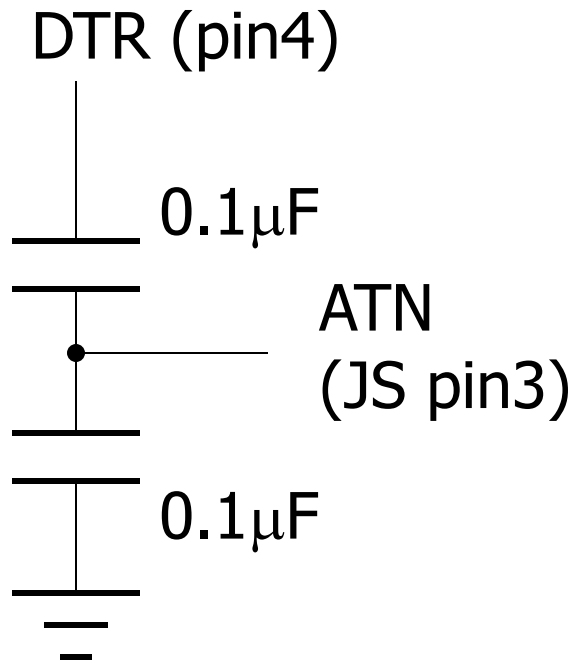
  - Circuit:

  - Program:

```
import stamp.core.*;
public class ButtonLED {
  static boolean P0 = true;
  public static void main() {
    while(true) {
      if (CPU.readPin(CPU.pins[1]) == false) {          // If button p
        P0 = !P0;                                        // Negate P0
        CPU.writePin(CPU.pins[0],P0);                    // LED [On]
        CPU.delay(1000);
      }                                                  // end if
      else {
        CPU.writePin(CPU.pins[0],true);                  // LED [Off]
      }                                                  // end else
    }                                                    // end while
  }                                                      // end main
}                                                        // end class
```

Javelin- Some App Notes

DTR (pin4)

0.1μF

ATN
(JS pin3)

0.1μF

- The circuit on the left should be used to condition the DTR/ATN connection
- Connect the +5V side of your power supply to pin 21 and the GND to pin 23. DO NOT use pin 24
- There is nothing optional about connecting a reset button between GND and pin 22. It is absolutely necessary!
- Be careful, the Javelin is expensive

The Temperature Sensor

+5v

P9 (pin 14)

P8 (pin 13)

LM34

1MΩ   1MΩ

1μF

Note: make sure you connect the voltages correctly to LM34 or you are going to have a short-lived room heater.

- This circuit supports a poor man's approach to ADC called delta sigma using the ADC VP object (page159)
- You may need to play with the resistor and capacitor values to get useful output, but be careful not to over drive P8

How The Circuits Works (1)

- The output of the LM34
  - changes +10mV/°F
  - should be very close to 0mV at 0°F
- Now the trick for doing ADC without an ADC chip
  - the SX controller of the Javelin is a CMOS device so its logic threshold voltage for a high value (i.e., when a zero becomes a one) is 2.5 volts
  - This means that if you apply a value less than 2.5 volts to an input line, the Javelin will assume it is a zero

How The Circuits Works (2)

- ## Assume that the LM34 is putting out zero volts
  - applying a high voltage (5V) to P8 would generate a 2.5V drop across both resistors and the capacitor would be held at 2.5 volts above ground
  - applying a low to P8 would cause the charge on the capacitor to begin bleeding off and the voltage would drop below 2.5 volts
  - every 2.1 ms the ACD object reads the truth value of pin P9 (equal to the voltage across the capacitor)
  - since the duty cycle of the pulse is timed to allow some bleed off before the measurement is taken, if the LM34 is putting out zero volts, and all 255 samples would be zero
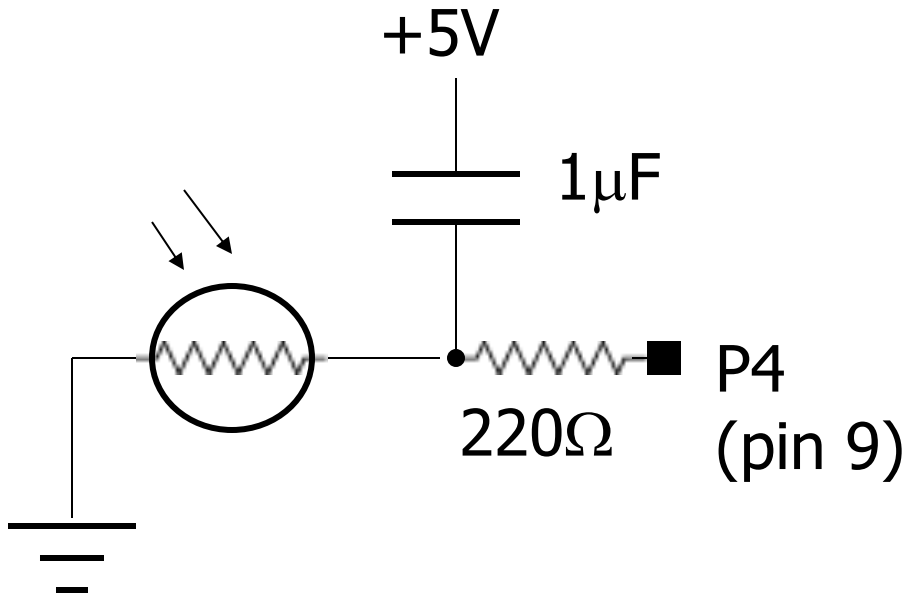
How The Circuits Works (3)

- Now, assume that the LM34 is putting out 5 volts
    - applying a high voltage (5V) to P8 would generate no voltage drop across the resistors and the capacitor would be held at 5 volts above ground
    - applying a low to P8 would cause the charge on the capacitor to begin bleeding off but the voltage would never drop below 2.5 volts
    - thus, all 255 samples would be ones
- At this point, it should be obvious that LM34 voltage outputs between 0 and 5 volts would generate values between 0-255

Issues With the Circuit

- From the discussion, it should be fairly clear that a delta sigma ADC is both slow and fairly inaccurate

- Further, the ADC has a resolution which is about ½ that of the temperature sensor so we are losing a great deal of information

- Last, it does not help that the LM34D only generates a voltage range of 320-2120 mV losing more than half of the ADC's range

- Is there a way to fix any of these problems?

The Light Sensor

+5V

$1\mu F$

220Ω

P4
(pin 9)

- The good news is that this circuit supports a very common approach to measuring resistance called rcTime (page 55)
- The bad news is that
  - CdS photoresistors are notoriously inaccurate
 - They have a memory which can last up for days

How The Circuits Works (1)

- The resistance of a typical CdS is inversely proportional to the amount of light falling on its surface

- Built into the Javelin CPU object are all of the methods needed to support this circuit
  - First you call a CPU.writePen method to set the pin high, and thus, charge the capacitor
  - Then you call a CPU.delay method to ensure that it is fully charged
  - Finally, you call a CPU.rcTime method which track how long it takes for the capacitor to bleed below 2.5 volt

How The Circuits Works (2)

- The time it takes for the capacitor to bleed down is directly proportional to the resistance of the photoresistor, and thus, to the amount of light falling on its surface

- Once you characterize your photoresistor's performance, the rcTime output can be used to keep track of how much light your sensor is seeing at any given time

- This light can be from an ambient source or from one of your own actuators
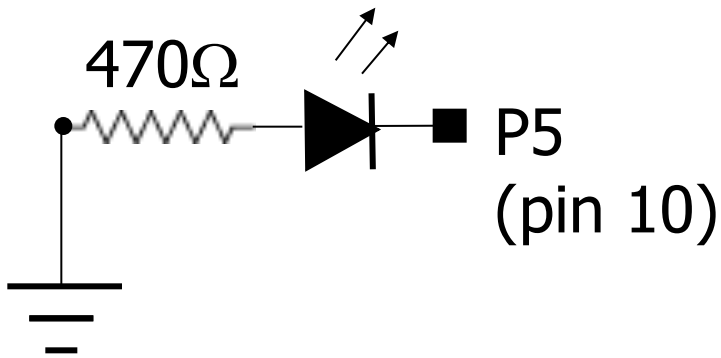
The Light Bulb

+5v

c

1kΩ

P3
(pin 8)

b

e

TIP120

Note: *make sure you connect The TIP120 correctly.*
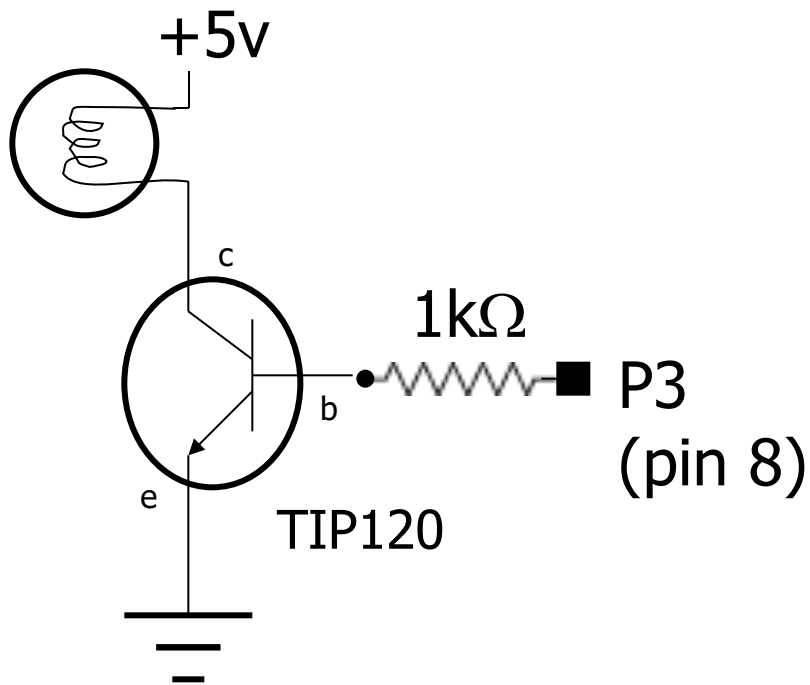
- This circuit allows a standard light bulb to be driven by a output pin
- Set the pin high to turn in the light and low to turn it off

The LED
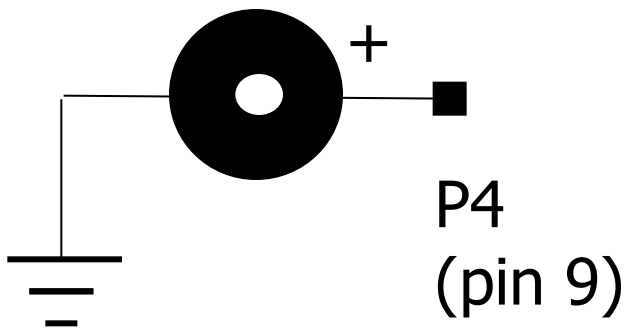
470Ω

P5
(pin 10)

- This circuit drives an LED off an output pin

- Set the pin high to turn on the LED and low to turn it off

- Since LEDs take so little current, no amplifier/buffer stage is needed

The Piezo Speaker/Buzzer

+

P4
(pin 9)

- This circuit drives an piezo device off an output pin
- You will need to use the Freqout object to control this device
- If your device can generate different tones based on a square wave input, the Freqout object can be used to play musical alerts

PCF8591 Analog-to-Digital Converter

- One of the many combined A/D–D/A converters
- Multiplexes up to four inputs and has a I^{2}C bus
- But, we want to make two points here
  - First, a SPD can always out-perform a GPD, especially if the general purpose device's solution is software based
    - The PCF8591 samples about 1000 times faster than our lab approach
  - Second, all the sophistication in the world cannot overcome a basic physical limit
    - The PCF8591 is still an 8-bit device, and thus is limited to 256 different output values

Buffer and Conditioner

- μcontrollers and μcontroller modules (like the Javelin) expect to be talking to discrete components so they are designed to handle it

- PCs are not

- Never connect a sensor like the ones we are building to a PC without adding a buffer or conditioner to protect the PC from stray signals which might damage it

- A number of ICs exist to support such buffering

The LMD18200 Motor Controller

- A standard DC motor develops its maximum torque when it is running its fastest

- This means if we want to run it slower (by reducing its the input voltage) it will generate less torque

- One way to get around this is to reduce speed by reducing the duty cycle of the signal, not the amplitude

- It's a great idea, but hard to execute

- The LMD18200 is an IC designed to control the direction and speed of a DC motor using a PWM signal

- Now the only problem is getting your processor/ controller to generate enough PWM signals

The UNC5804B Stepper Controller

- A stepper motor develops its maximum torque when it is not turning at all (the reverse of a standard DC motor)
- It does this by breaking its coil windings down into a set of phased windings
- Therefore, getting it to turn in the right direction for the right number of turns is not as simple as sending in a voltage, in fact it is a lot like coding in binary with the number of digits being related to the number of phases
- The UNC5804B is an IC designed to allow you to simply send the number of steps you want the motor to take and it handles the rest of the problems for you