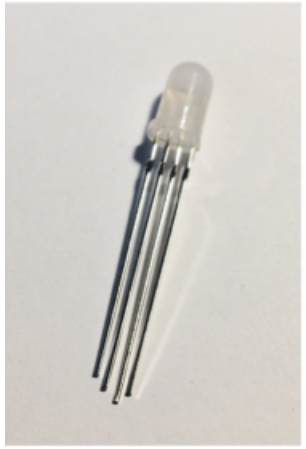
Hardware Datapath Components Lab

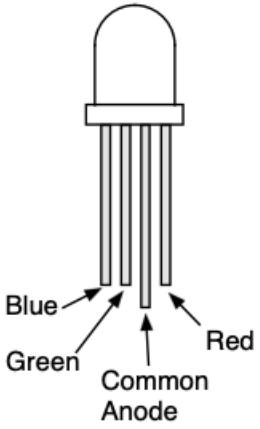
Lab Overview

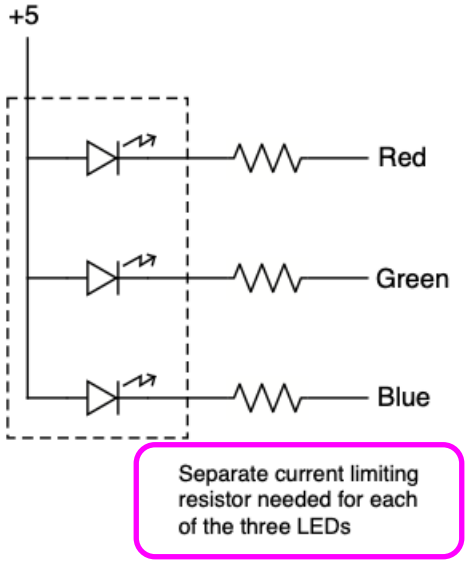
- This lab will use:
  - A new output: An RGB LED that can produce many different colors when combined with the hardware PWM of your Arduino
  - New inputs: The buttons on your LCD panel and a **potentiometer** (dial that creates a variable resistance) that generates an varying ANALOG voltage as you twist it (i.e. 0, 0.1, 0.2, …, 4.8, 4.9, 5V)
    - You will learn how to use the Arduino's built-in **Analog-to-Digital Converter (ADC)** to convert these analog voltage to digital numbers in the range 0-255
  - Combinational and sequential logic chips to offload some processing to hardware (and not software)

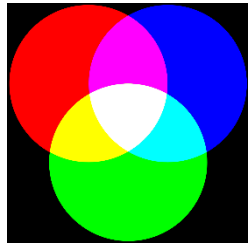
RGB LED

- You will build your own controllable PWM system to produce varying combinations of intensities of red, green, or blue light from an RGB LED
  - While normally we would control all 3 colors at the same time, our system will produce varying intensities on only 1 color at a time but allow you to turn the other LED's on or off to produce many combinations





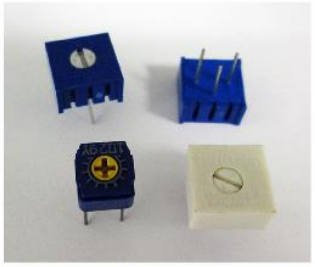




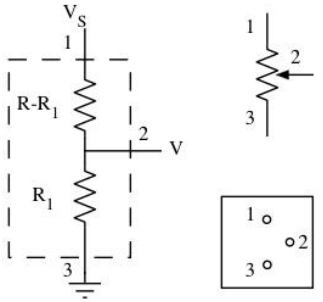
The RGB LEDs consist of three separate LEDs in one package. Each color has a separate cathode (–) lead, and all the the anode (+) leads are connected together.

Analog Inputs

- Potentiometer is a variable resistor that chances as you rotate it
- The LCD shield has 5 buttons
- However, they do not produce 5 individual signals like you are used to from previous labs
- They are configured in such a way such that they sum together to produce a single analog voltage which the shield connects to the A0 input of the Arduino

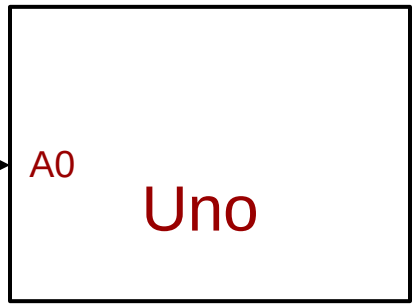


Potentiometers or "pots"



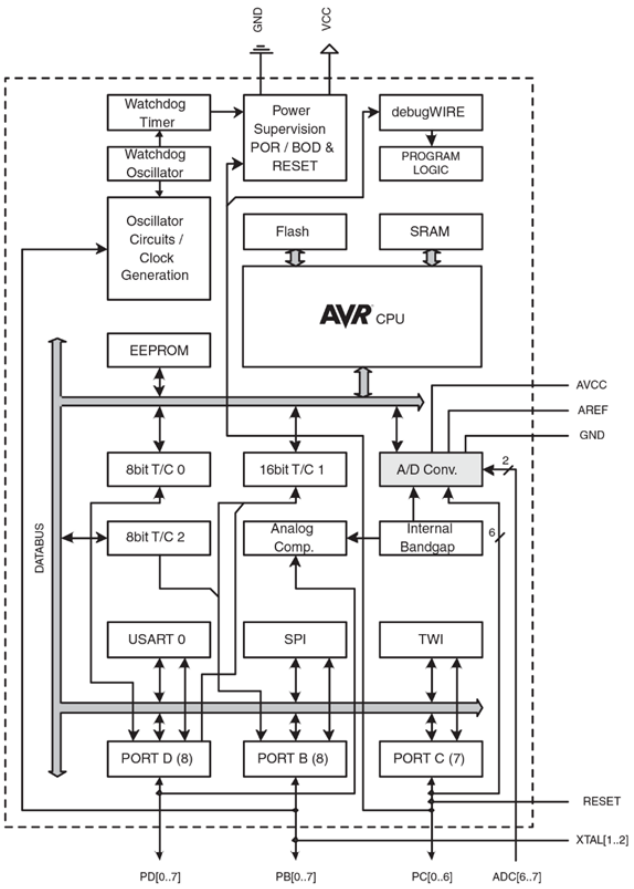
Functional diagram of a potentiometer, schematic symbol, and diagram of pin layout.

5 Button Inputs => 1 analog voltage



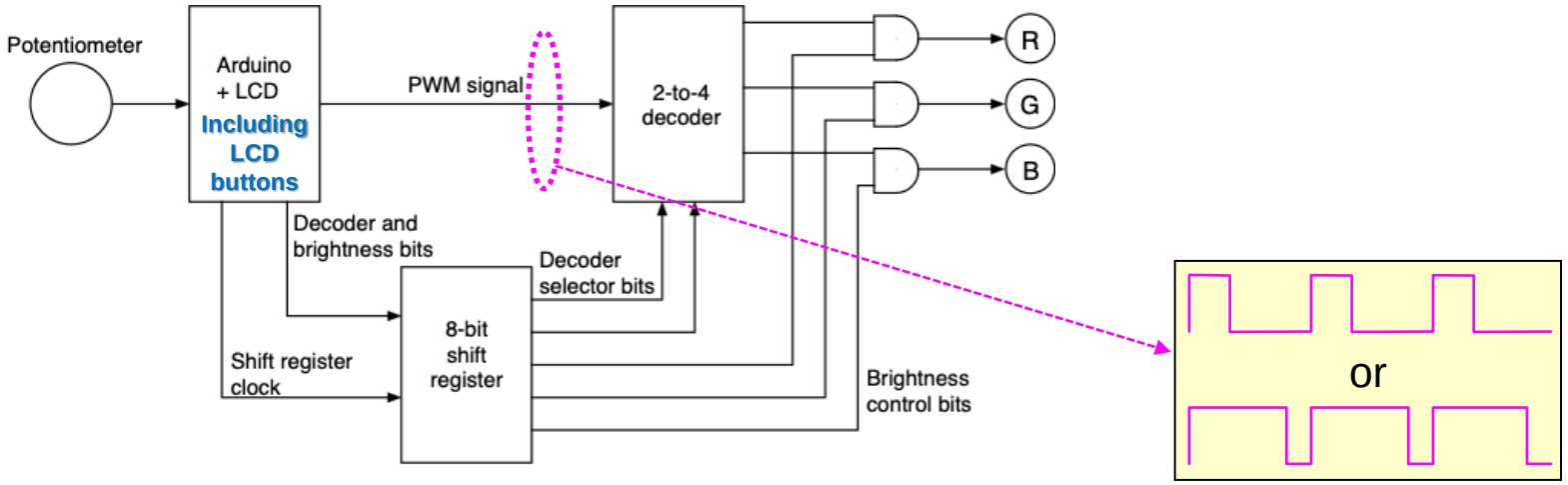
Hardware/Software Lab

- We will use combinational and sequential components to:
  - Offload software tasks from the Arduino.
    - In many embedded systems there will be too much processing and control for software to keep up with
  - Illustrate how to save I/O pins by using external hardware
  - Illustrate how the internal Arduino hardware operates



Overall System Description

- You will use a "potentiometer" dial to produce a continuous range of voltages that you will then digitize to the range 0-255.
- That digitized input will control the duty cycle (on-time) of a PWM signal that your Arduino will generate.
- Using buttons on the LCD and external hardware, you will then be able to route (demultiplex) that PWM signal to any of the 3 light segments (R, G, B).
- Using the buttons on the LCD you'll be able to also control whether the other segments are ON or OFF to produce a variety of colors.
- You'll save pins by using only 2 outputs to control the various selections of light segments and which color uses the PWM signal.

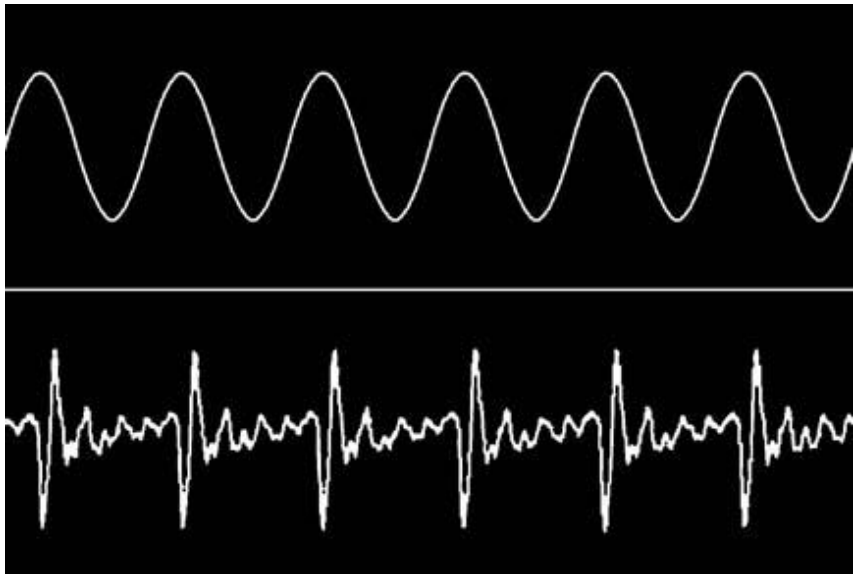


Block diagram of circuit to control 3 LEDs

ANALOG TO DIGITAL CONVERSION

Electric Signals

- Information is represented electronically as a time-varying voltage
  - Each voltage level may represent a unique value
  - Frequencies may represent unique values (e.g. sound)



Sound converted to electronic signal (voltage vs. time)

Electronic Information

- Digital Camera
  - CCD's (Charge-Coupled Devices) output a voltage proportional to the intensity of light hitting it
  - 3 CCD's filtered for measuring Red, Green, and Blue light produce 1 color pixel

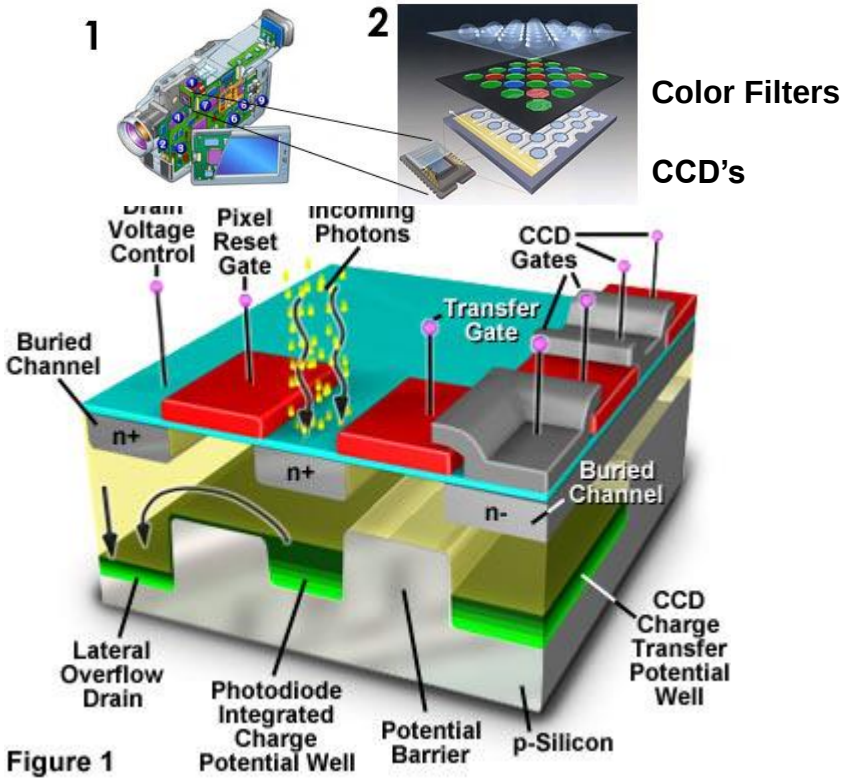
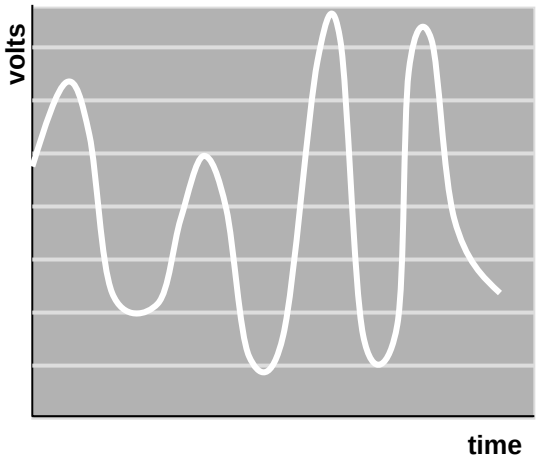


Figure 1

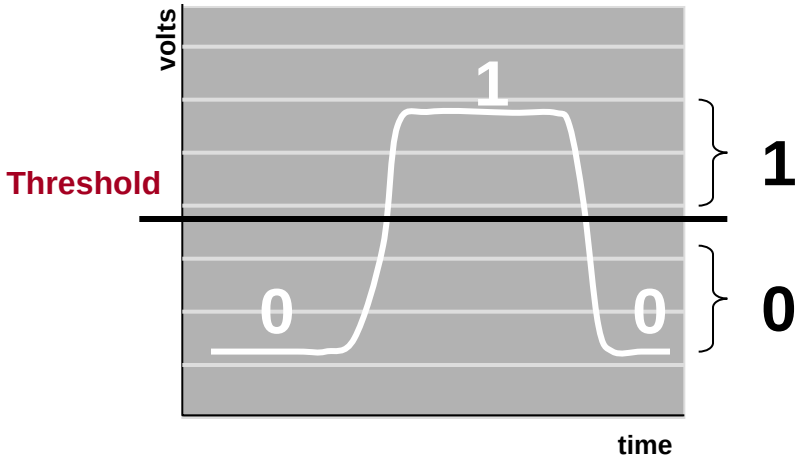
More info: http://www.science.ca/scientists/scientistprofile.php?pID=129
http://www.microscopy.fsu.edu/primer/digitalimaging/concepts/ccdanatomy.html

Signal Types

- Analog signal
  - Continuous time signal where each voltage level has a unique meaning
  - Most information types are inherently analog
- Digital signal
  - Continuous signal where voltage levels are mapped into 2 ranges meaning 0 or 1
  - Possible to convert a single analog signal to a set of digital signals



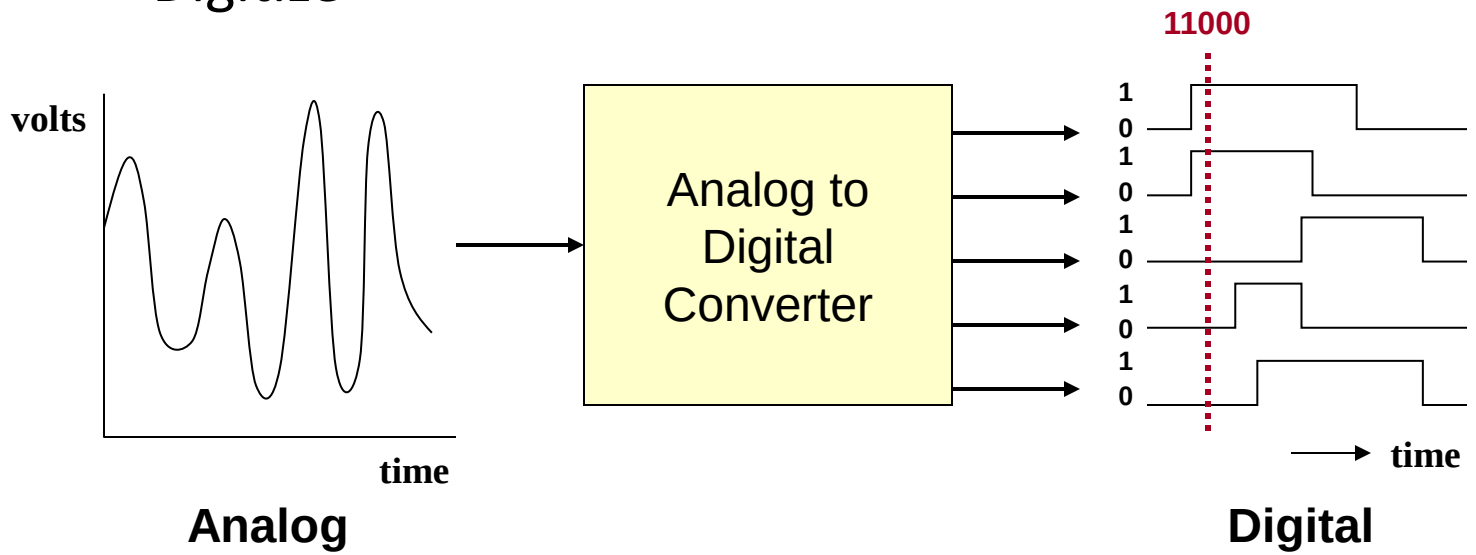
Analog



Digital

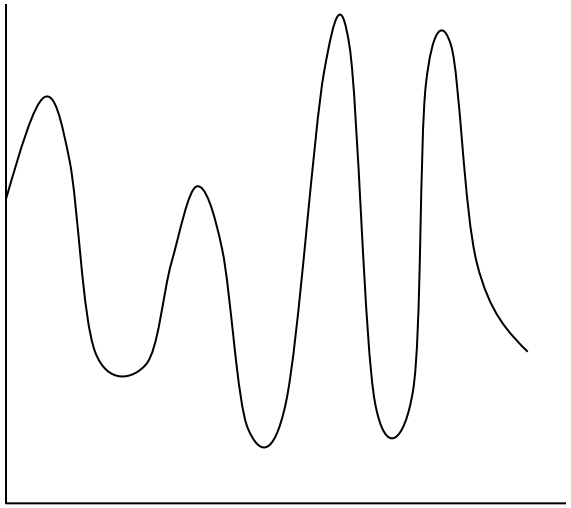
Analog to Digital Conversion

- 1 Analog signal can be converted to a *set* of digital signals (0's and 1's)
- 3 Step Process
  - Sample
  - Quantize (Measure)
  - Digitize

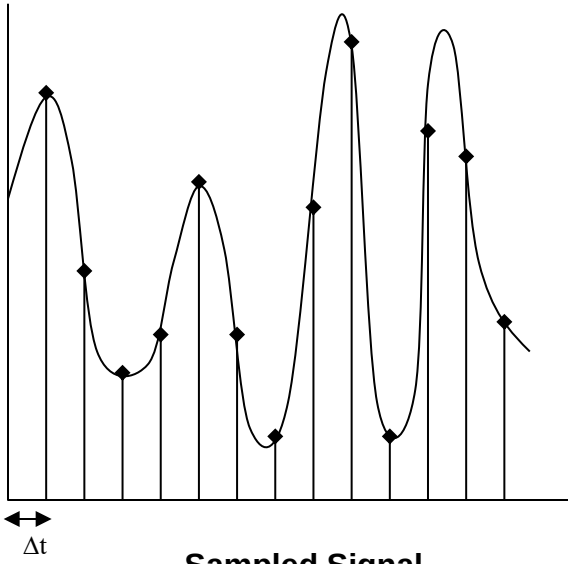


Sampling

- Measure (take samples) of the signals voltage at a regular time interval
- Sampling converts the continuous time scale into discrete time samples



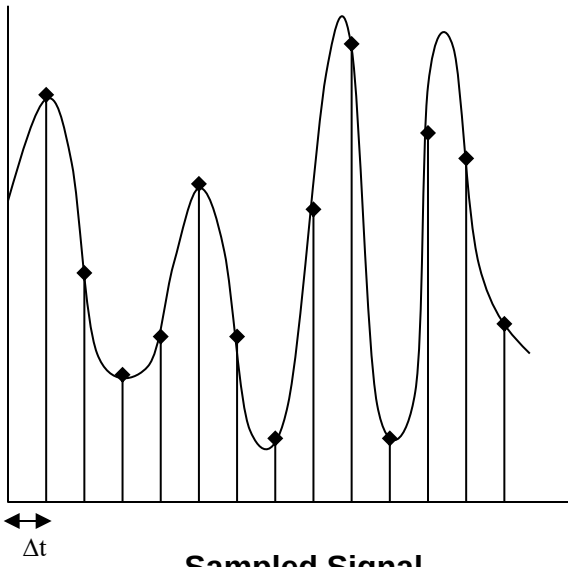
Original Analog Signal



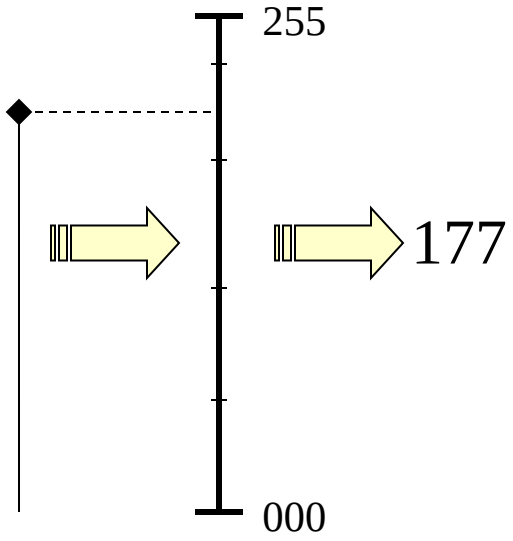
Sampled Signal

Quantization

- Voltage scale is divided into a set of finite numbers (e.g. 256 values: 0 – 255)
- Each sample is rounded to the nearest number on the scale
- Quantization converts continuous voltage scale to a discrete (finite) set of numbers



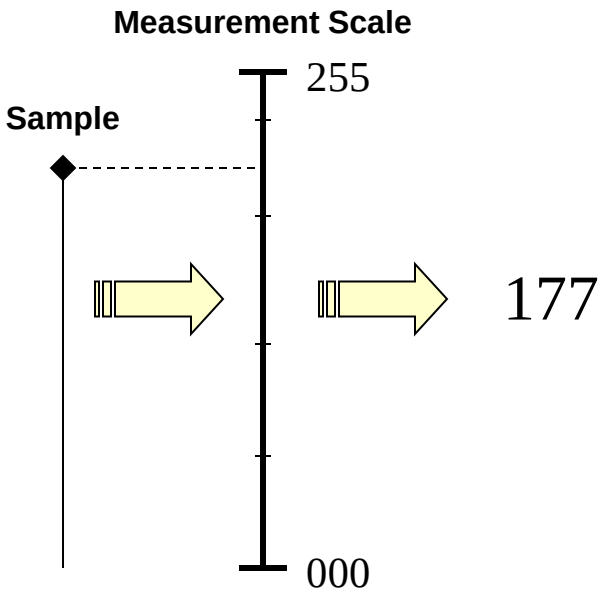
Sampled Signal



Each sample is quantized

Digitization

- The measured number from each sample is converted to a set of 1's and 0's



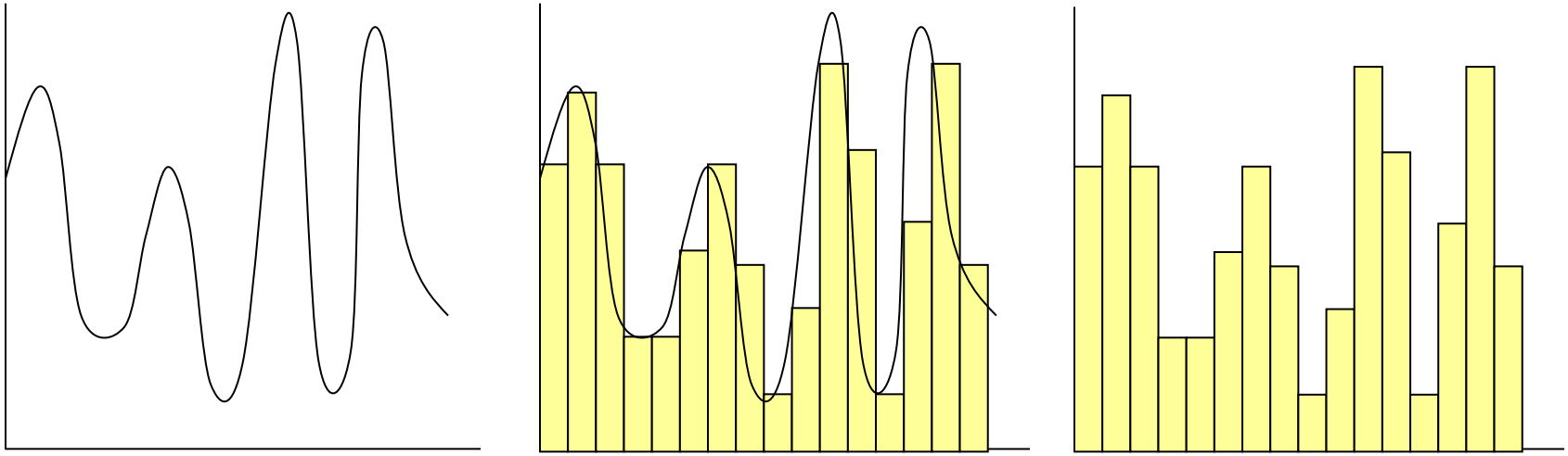
Each sample is quantized

177 = 10110001

Quantized value is converted to bits

Error

- Error is introduced because the discrete time and quantized samples only approximate the original analog signal

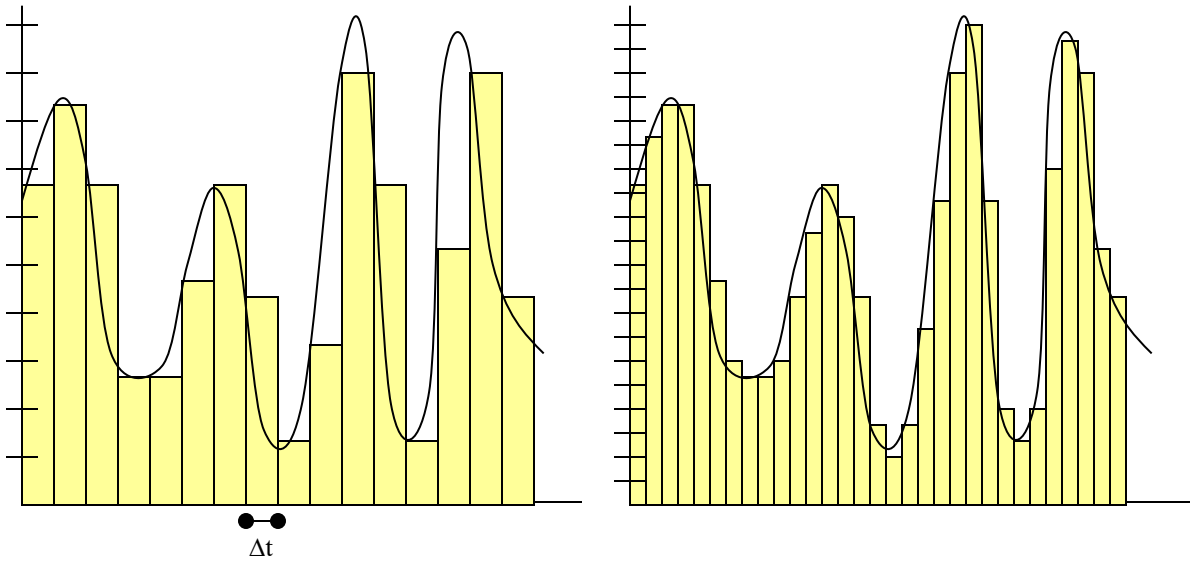


Original Analog Signal

Sampled Signal

Sampling Rates and Quantization Levels

- Higher sampling rates and quantization levels produce more accurate digital representations

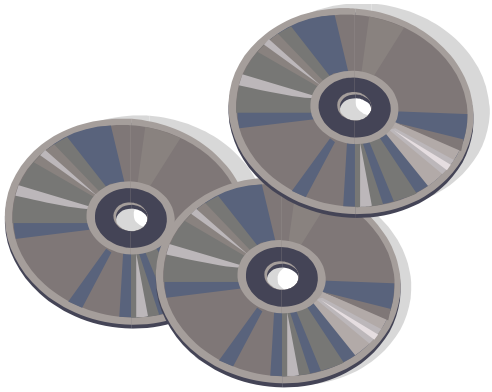


Lower sampling rate and quantization levels

Higher sampling rate and more quantization levels

Digital Sound

- Lossless / High Quality (aka CD Quality) Sound
  - 44.1 Kilo-samples per second
  - 65,536 quantization levels (16-bits per sample)
  - 44.1KSamples * 16-bits/sample = 705 Kbps
- MP3 files compress that information to 128Kbps – 320 Kbps



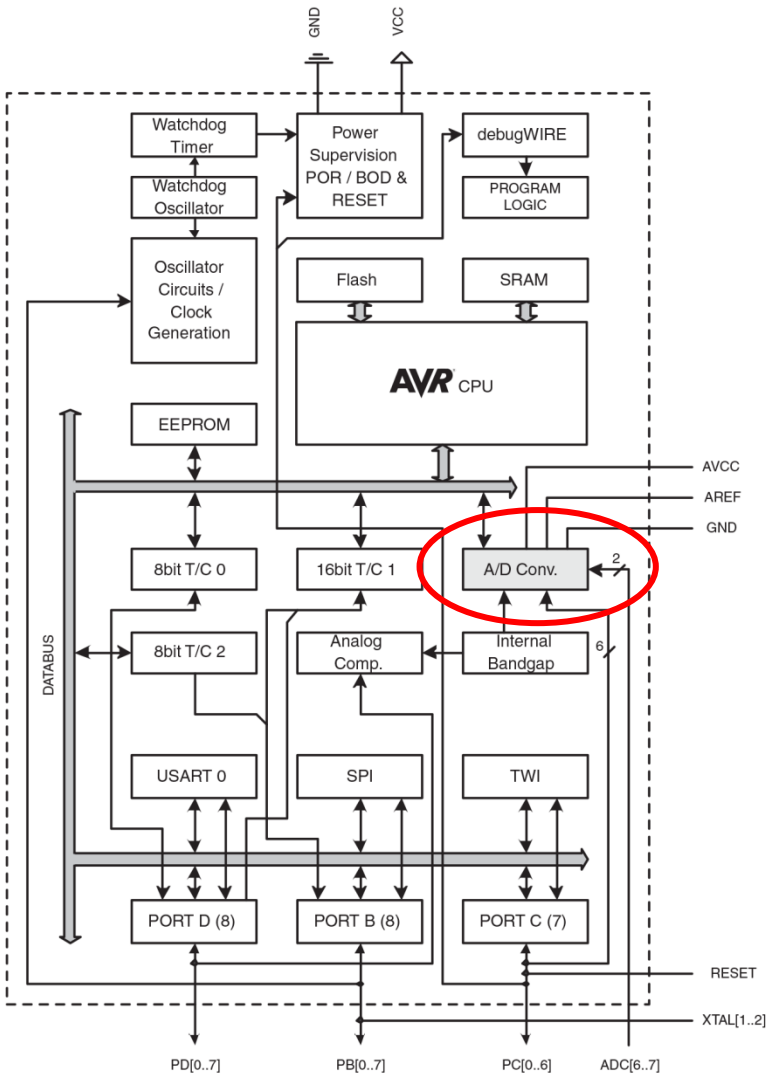
Your parents know what these are!

Converting voltages to digital numbers

ADC MODULE

ADC Module

- Your Atmel micro has an A-to-D Converter (ADC) built in
- The ADC module can be used to convert an analog voltage signal into 10 bit digital numbers.
- Not fast enough for video or audio.
- Controlled by a set of six registers which you must program appropriately



Note

- Microcontroller modules often come with many adjustable features and settings to make it useful to a wide variety of applications
- In EE 109 we may not want to use all that functionality, so we have to enable or disable those features or alter certain settings
- How do we do this? By setting bits in specific registers
  - The values we program into the registers control how the hardware works!

ADC Registers

- ADC is primarily controlled by two registers whose bits control various aspects of the ADC
  - ADMUX – ADC Multiplexor Selection Register
  - ADCSRA – ADC Control and Status Register A
- We will see what these bits means as we continue through our slides…

ADMUX

7	6	5	4	3	2	1	0
REFS1	REFS0	ADLAR		MUX3	MUX2	MUX1	MUX0

ADCSRA

7	6	5	4	3	2	1	0
ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

Only need to perform once before you start using the ADC

ADC INITIALIZATION PROCESS

ADC Code Organization

- Just like with our LCD, we will create separate files for our ADC software so we can easily reuse it in later labs
- We will walk through how to write each function

```
void adc_init();
uint8_t adc_sample(uint8_t channel);
```

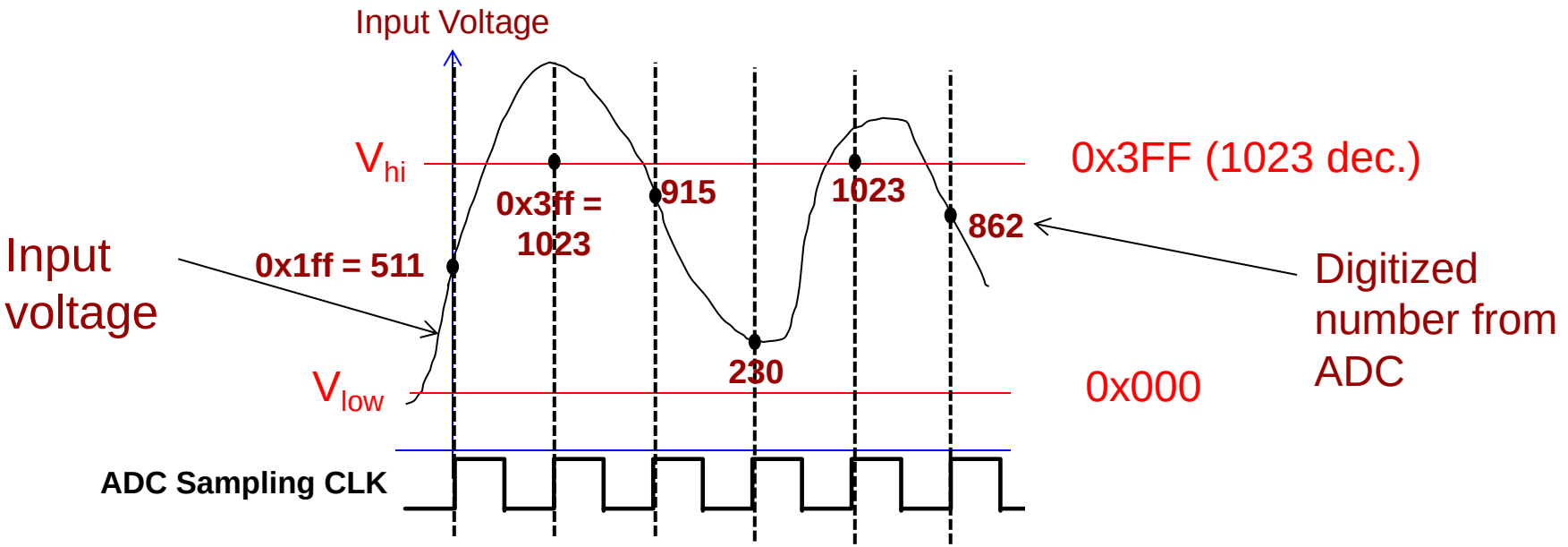
adc.h

```
void adc_init()
{
  // Initialization steps

}

uint8_t adc_sample(uint8_t channel)
{
   // Take a sample and

   // return the numeric result
}
```

adc.c

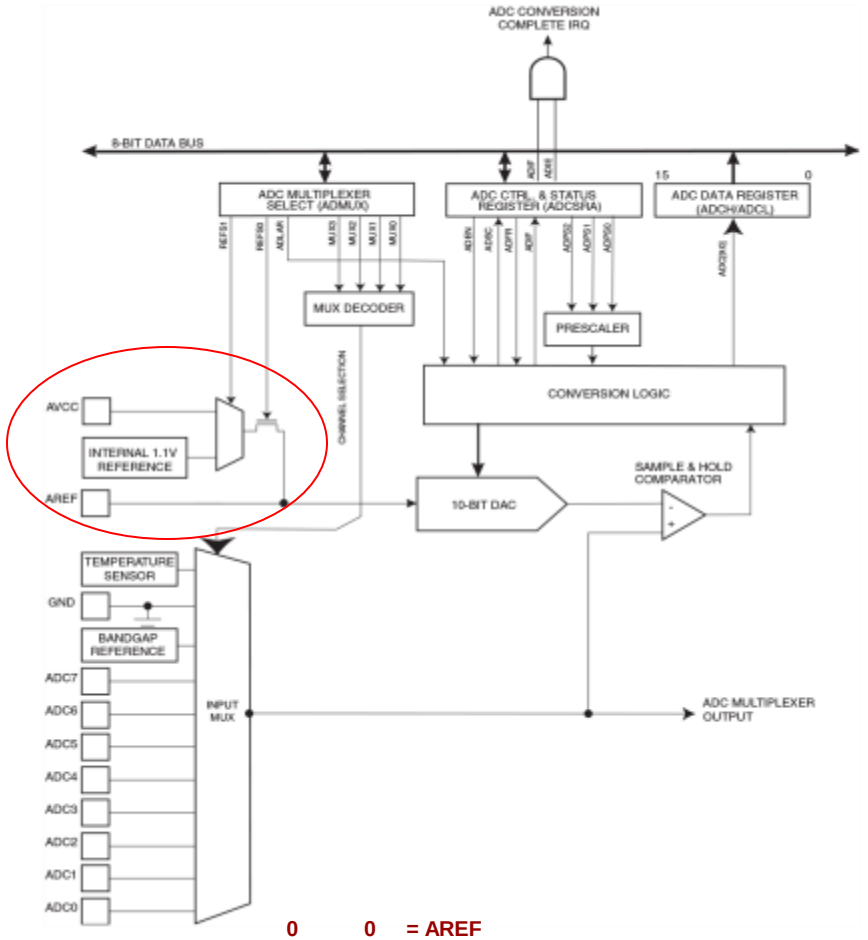
ADC Voltage Reference

- The ADC can only measure voltages in the range of V_{hi} to V_{low}
  - If the voltage is higher than Vhi it just converts to 1023=0x3ff
  - If the voltage is lower than Vlow it just converts to 0
  - Voltages between the limits are converted linearly to digital values.
- Samples will be taken either at regular intervals or just when you tell it to take a sample



ADC Voltage Reference

- The low reference is fixed at ground = 0V.
- High reference is selectable
  - AVCC (connected to VCC)
    - Usually the one we want!
  - AREF
  - Internal 1.1V reference
- Reference selection controlled by bits in a register
- **ADC Init Step 1**: Set REF bits to choose AVCC to give analog range of 0-5V
  - Set ADMUX register bit
    - REFS1 to a 0
    - REFS0 to a 1



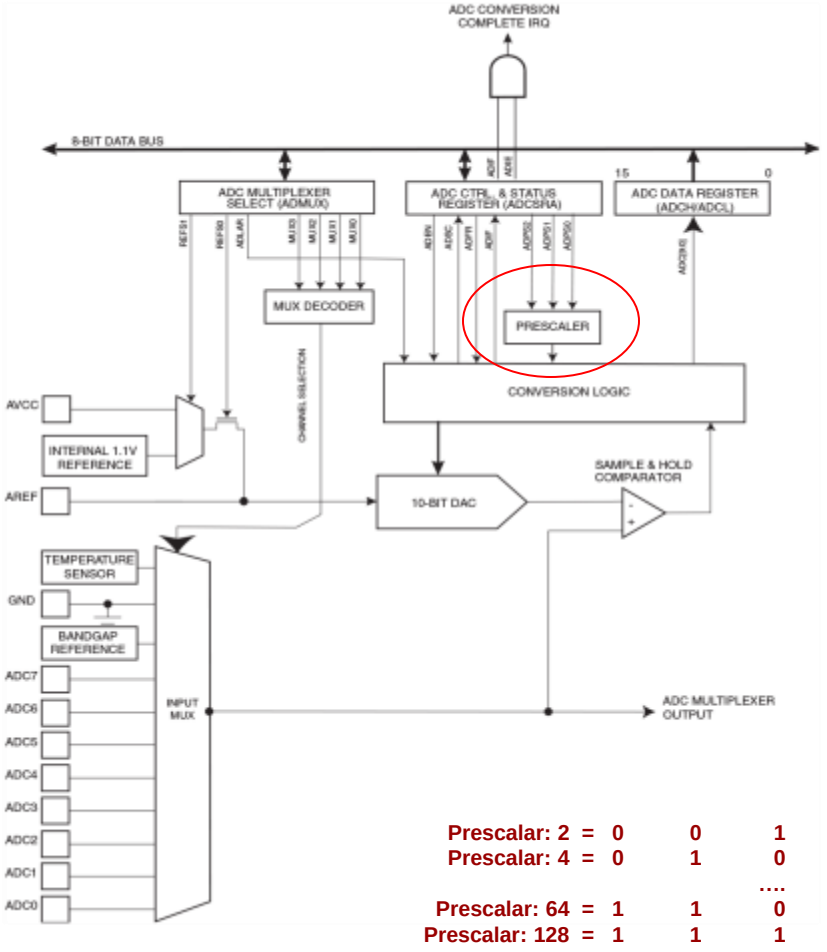
0 0 = AREF
0 1 = AVCC
1 1 = Int 1.1V

REFS1	REFS0	ADLAR		MUX3	MUX2	MUX1	MUX0

ADMUX Register

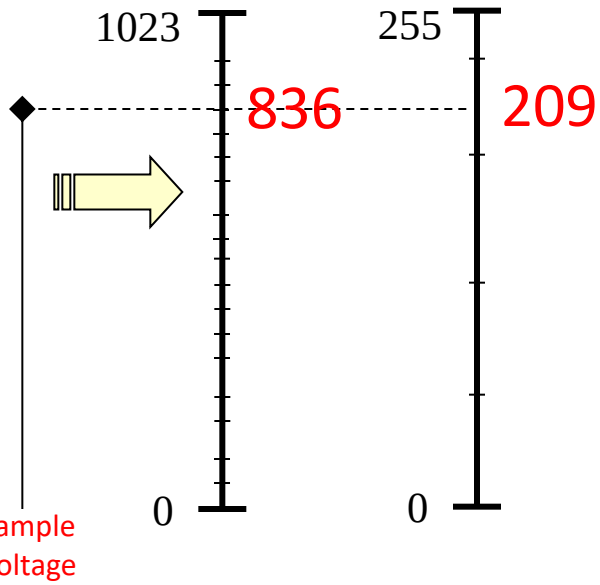
ADC Clock Generation

- **Documentation requirement**: The ADC needs a clock in the range 50kHz to 200kHz in order to operate.
- Clock generated for the Arduino's processor is 16Mhz
- Prescalar (a.k.a. divider) reduces the clock to a lower frequency by dividing its frequency
- Divide by 2, 4, 8, 16, 32, 64, or 128
  - $ADC\ Freq = \frac{CPU\ Clock\ Freq}{Prescalar}$
  - If Precalar=64 then ADC Freq = 16MHz / 64 = 250KHz (still too fast)
- **ADC Init Step 3**: Set prescalar to 128 by turning on (setting) ADPS2, ADPS1, ADPS0 bits in ADCSRA register



Scale

- Analogy: Some scales give your weight to the nearest pound (137) while others are accurate to the tenth of pound (137.6)
  - It's nice to have accuracy but for most of us we are content with the accuracy just at the nearest pound
- Our ADC can provide readings up to 10-bits accuracy (on a scale from 1023)…
- …but it can also drop the lower 2 bits to provide readings of 8-bit accuracy (on a scale from 256)
- The question is simply do we need 10-bit accuracy or is 8-bit accuracy sufficient
- **In EE109 we'll always use 8-bit readings**
- **ADC Init Step 4:** Set ADLAR bit to 1 in the ADMUX register (1 = 8-bit results, 0 = 10-bit results)

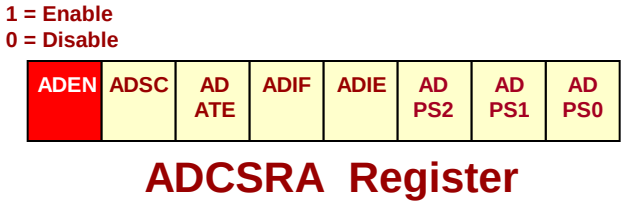


REFS1	REFS0	ADLAR		MUX3	MUX2	MUX1	MUX0

ADMUX Register

Enable the ADC

- The ADC module has an 'enable' bit which effectively acts as an on/off switch (turn off to save power)
- **ADC Init Step 5:** Set ADEN bit to 1



ADC Register Review

- ADMUX – ADC Multiplexor Selection Register
  - REFS - Voltage reference selection (bits 7-6)
    - 01 to select AVCC, connected to VCC (+5V) on µC
  - ADLAR - Left adjust results (bit 5)
    - 0 = "right adjust" for 10-bit result
    - 1 = "left adjust" for 8-bit result
  - MUX - Input channel selection (bits 3-0)
    - Use values 0000 to 0101 to select pins A0 to A5

ADMUX

7	6	5	4	3	2	1	0
REFS1	REFS0	ADLAR		MUX3	MUX2	MUX1	MUX0

ADC Register Review

- ADCSRA – ADC Control and Status Register A
  - ADPS - Prescalar selection (bits 2-0)
    - Selects the clock divisor used in the prescaler
  - ADEN – ADC Enable (bit 7)
    - Set to 1 to turn on the ADC (must do)
  - ADSC – ADC Start Conversion (bit 6) **[More on this in a few slides]**
    - Set to 1 to start a conversion
    - When goes to a zero, conversion is complete
  - Other bits for generating interrupts (to be discussed in future labs)

ADCSRA

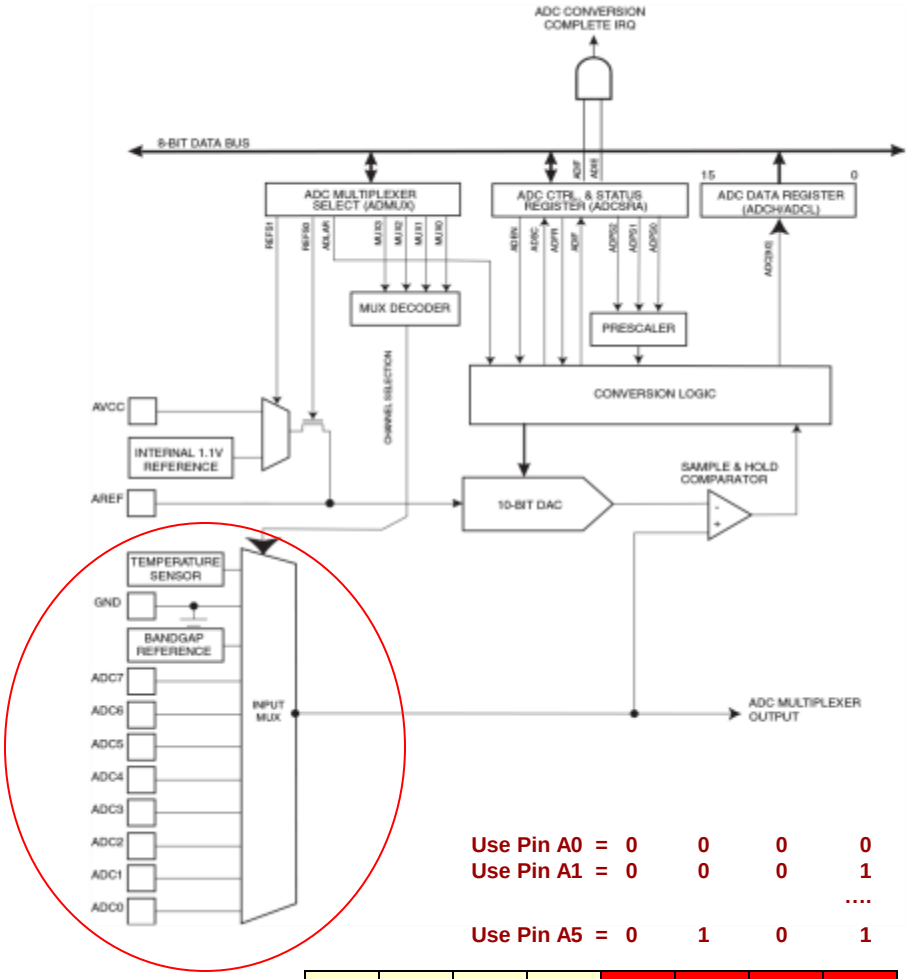
7	6	5	4	3	2	1	0
ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

Perform each time you want to take a new sample

ADC SAMPLING PROCESS

ADC Input Selection

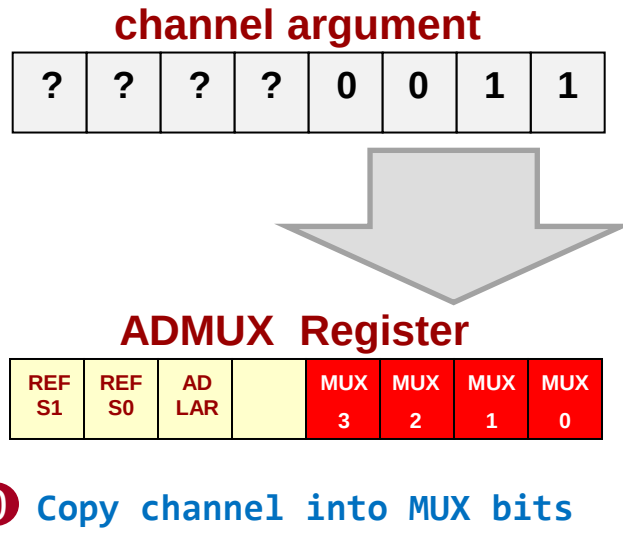
- The ADC has six input channels/pins that can be connected to the one built-in converter
- Only one channel can be converted at any one time (i.e. is internally muxed)
- Channel selection controlled by bits in a register
- **ADC Sample Step 0:** Set MUX bits in ADMUX register to desired channel number
  - If we want channel A3, set mux bits to 0011



Selecting a Channel

- **ADC Sampling Step 0**: Copy the 4-bit channel argument to the ADMUX register

```
unsigned char adc_sample(char channel)
{
  // Step 0: copy channel bits into ADMUX

  // Step 1: Start a sample

  // Step 2: Wait for ADC to indicate
  //         the sample is ready

  // Step 3: Retrieve and return the sample
}
```



❶ Copy channel into MUX bits

Starting a Sample

- The ADC does not continuously sample
- We must tell it when to take a sample by setting the 'start' bit (ADSC)
- **ADC Sampling Step 1**: Set the ADSC bit in the ADCSRA register
- Some time will elapse while the ADC takes the sample. During this time the ADSC bit will remain at 1
- When the ADC is done it will AUTOMATICALLY clear the ADSC bit to 0
- **ADC Sampling Step 2**
  - Need to continuously check whether the ADSC bit has turned back to 0 (i.e. loop *while* the ADSC is still a 1)

ADMUX Register

REFS1	REFS0	ADLAR		MUX3	MUX2	MUX1	MUX0

0 `Copy channel into MUX bits`

1 = Start/(ed)
0 = Done

ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

ADCSRA Register

1 `ADCSRA |= _____;`

ADEN	ADSC = 1	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

2

3 `while((ADCSRA & ___) != 0 )`

… `{}`

ADEN	ADSC = 1	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

t

ADEN	ADSC = 0	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

Retrieving a Sample

- [**From last slide**] Need to continuously check whether the ADSC bit has turned back to 0 (i.e. loop *while* the ADSC is still a 1)
  - Once the loop finishes we know the sample is ready!
- **ADC Sampling Step 3:** Read (retrieve) the 8-bit sample result from the **ADCH** register
  - Just read the value from ADCH (i.e. `unsigned char result = ADCH;`) and then use that value in your application
- You can repeat the process as many times as you like
  - Set the start (ADSC) bit
  - Loop until the start (ADSC) bit goes to 0
  - Retrieve the sample from ADCH

2
3
…

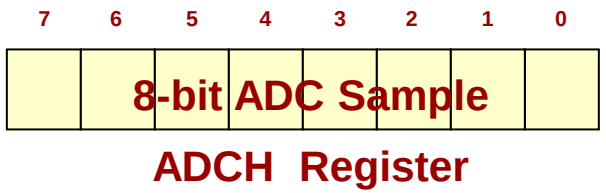
```
while((ADCSRA & ___) != 0 )
{}
```

ADEN	ADSC	AD ATE	ADIF	ADIE	AD PS2	AD PS1	AD PS0
	1						

t

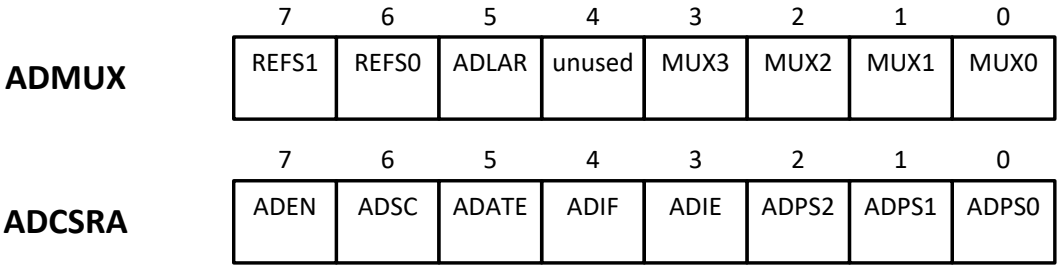
ADEN	ADSC	AD ATE	ADIF	ADIE	AD PS2	AD PS1	AD PS0
	0						

```
unsigned char result = ADCH;
```



Named Bit Constants

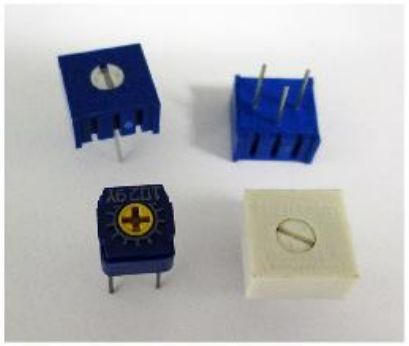
- In `<avr/io.h>` there are constants defined for each bit name and position
  - `REFS1 = 7, REFS0 = 6, ADLAR = 5, …`
  - `ADEN = 7, ADSC = 6, …`
- Using these we can write shift expressions with more clarity
  - `ADCSRA |= (1 << ADSC);`
  - `ADMUX &= ~(1 << ADLAR)`



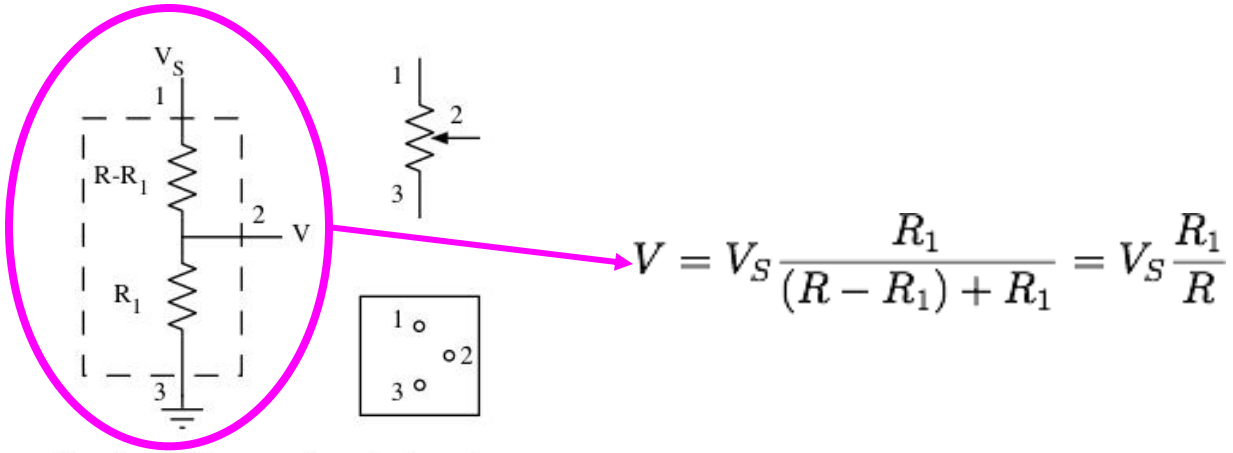
ADC SOURCES

Potentiometers: Generating Analog Signals

- A potentiometer acts as a slider or knob that can be set to the desired level or position
  - Use your screwdriver to twist the potentiometer
- A potentiometer is like a variable series resistor (i.e. voltage divider)



Potentiomers or "pots"

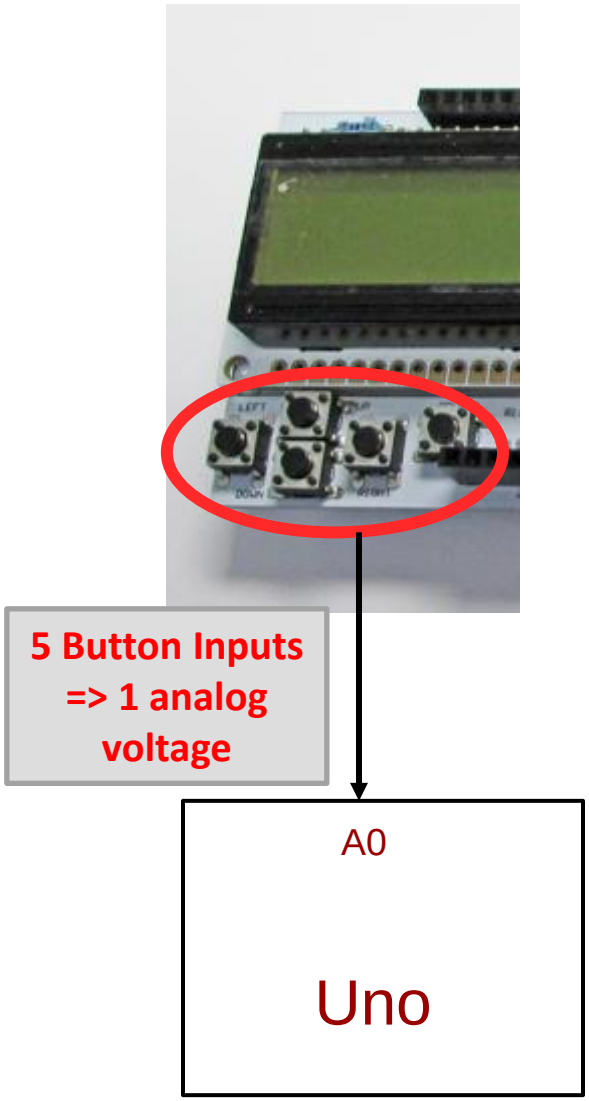


$$V = V_S \frac{R_1}{(R - R_1) + R_1} = V_S \frac{R_1}{R}$$

Functional diagram of a potentiometer, schematic symbol, and diagram of pin layout.

LCD Shield Buttons

- The LCD shield has 5 buttons
- However, they do not produce 5 individual signals like you are used to from previous labs
- They are configured in such a way such that they sum together to produce a single analog voltage which the shield connects to the A0 input of the Arduino
- If the voltage is in certain range we can infer that a particular button is being pressed



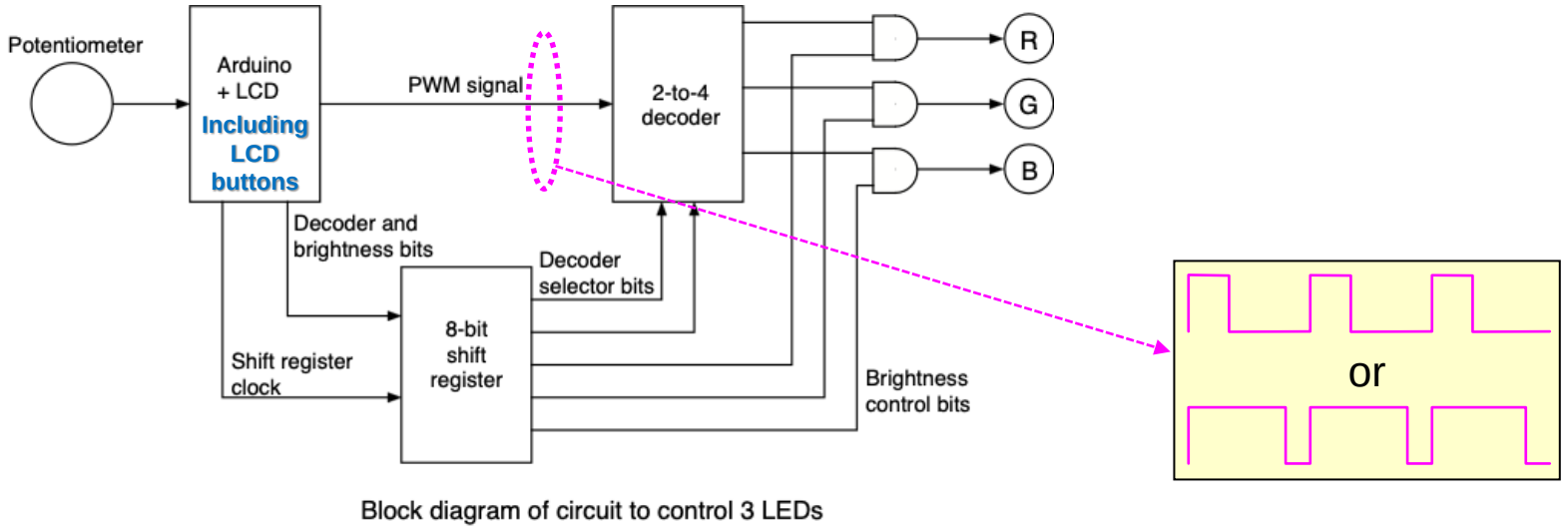
LCD Shield Buttons

- You can use the Arduino's A-to-D converter to sense when a button is pressed
- Each button produces a certain voltage when pressed and the default value of 5V when no button is pressed
- The table to the right shows the nominal voltages and 8-bit ADC result
  - Note these are nominal and could be different so it would be best to just split the range evenly (e.g. to know the 'Up' button is pressed check if the 8-bit ADC results is between 26 and 77)

Button	Volts (V)	Avg. 8-bit Value
Right	0 V	0
Up	1.0 V	52
Down	2.0 V	104
Left		
Select		
None		

DEMULTIPLEXERS AND DECODERS

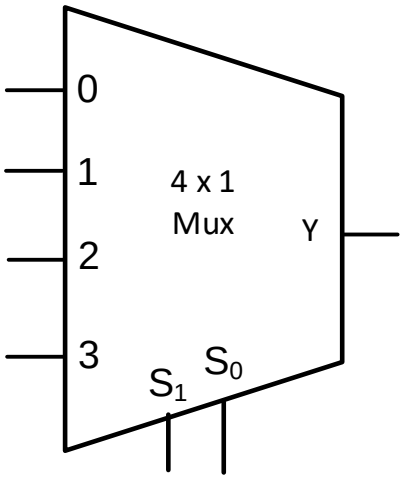
Recalling Our Circuit

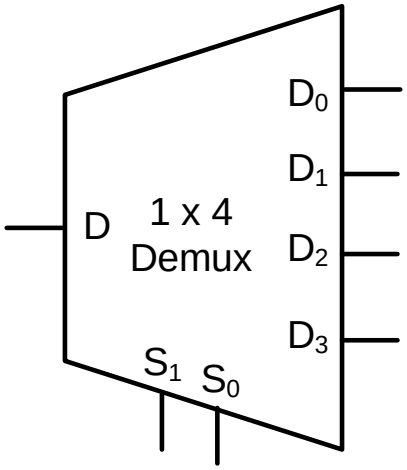


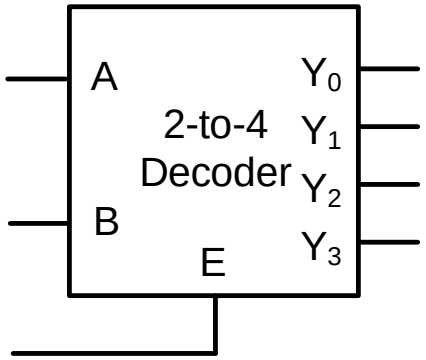
Block diagram of circuit to control 3 LEDs

Demuxes = Decoders

- A demultiplexer does the opposite job as a mux: passes the 1 input to the selected output
- It turns out a demux is EQUIVALENT to a decoder



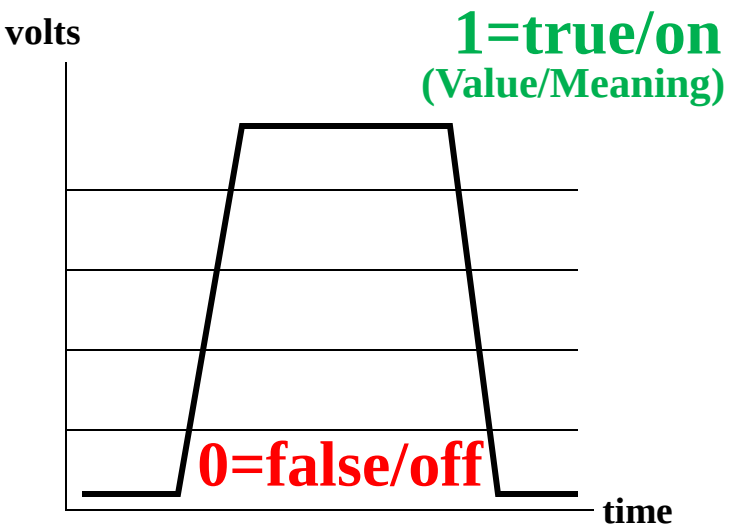




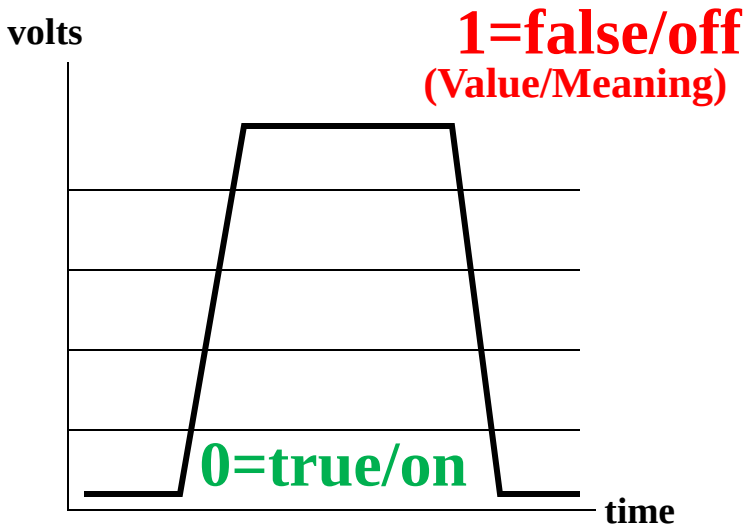
NEGATIVE (ACTIVE-LO) LOGIC

Negative (Active-Lo) Logic

- Recall it is up to us humans to assign **MEANING** to the **TWO** voltage levels our digital circuits produce and process
  - Thus, far we've (unknowingly) used the positive logic convention where: 1 means **true** and 0 means **false**
  - In negative logic, 0 means **true** and 1 means **false**



Positive Logic (Active-Hi) Convention

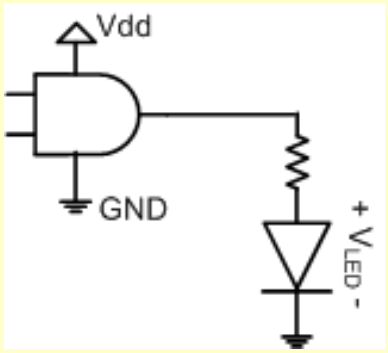


Negative Logic (Active-Lo) Convention

Why Active-low

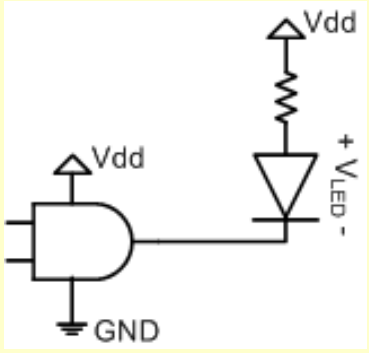
- Some digital circuits are better at “sinking” (draining/sucking) electric current than “sourcing” (producing) current

Active-hi output



LED is on when gate outputs '1'

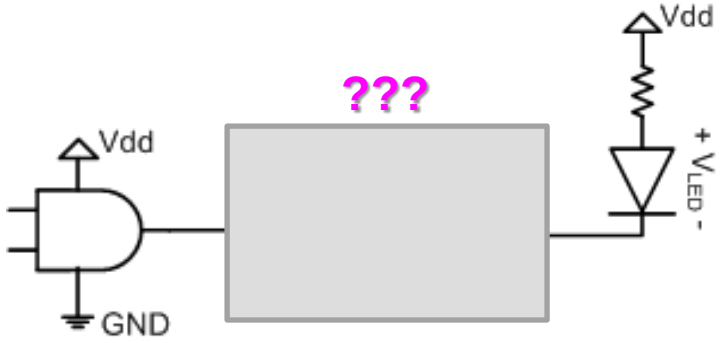
Active-low output



LED is on when gate outputs '0'

Converting Between Active-hi and low

- Active-hi convention
  - 1 = on/true/active
  - 0 = off/false/inactive
- Active-low convention
  - 0 = on/true/active
  - 1 = off/false/inactive



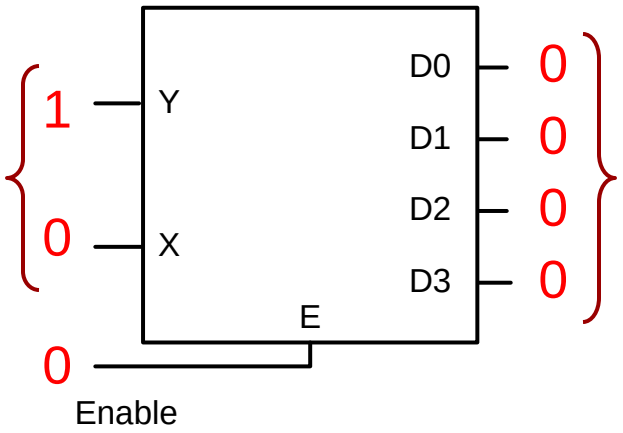
Active-high (Produces '1' when we want to turn the LED on)

Active-low (Needs '0' to turn the LED on)

- As shown above, what if I had an active-high output and wanted to connect it to an active-low input?
- To convert between conventions
  - _____

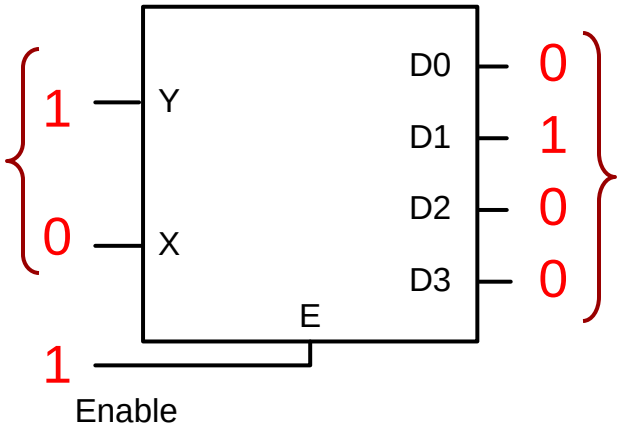
Enables

When E=0, inputs is ignored



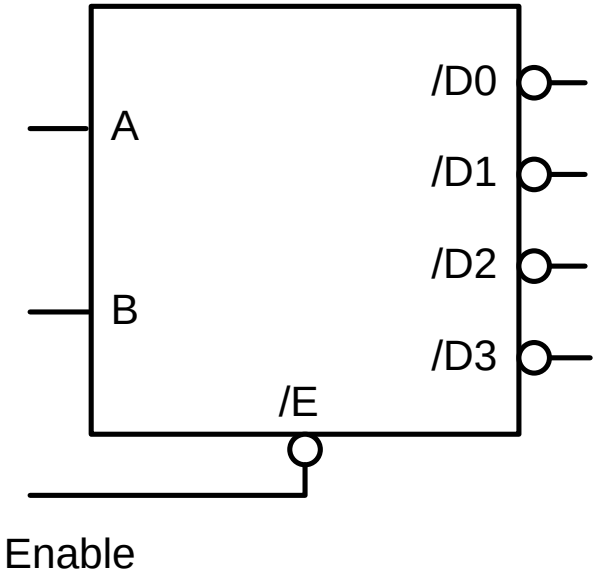
Since E=0, all outputs = 0

When E=1, inputs will cause the appropriate output to go active



Since E=1, outputs will function normally

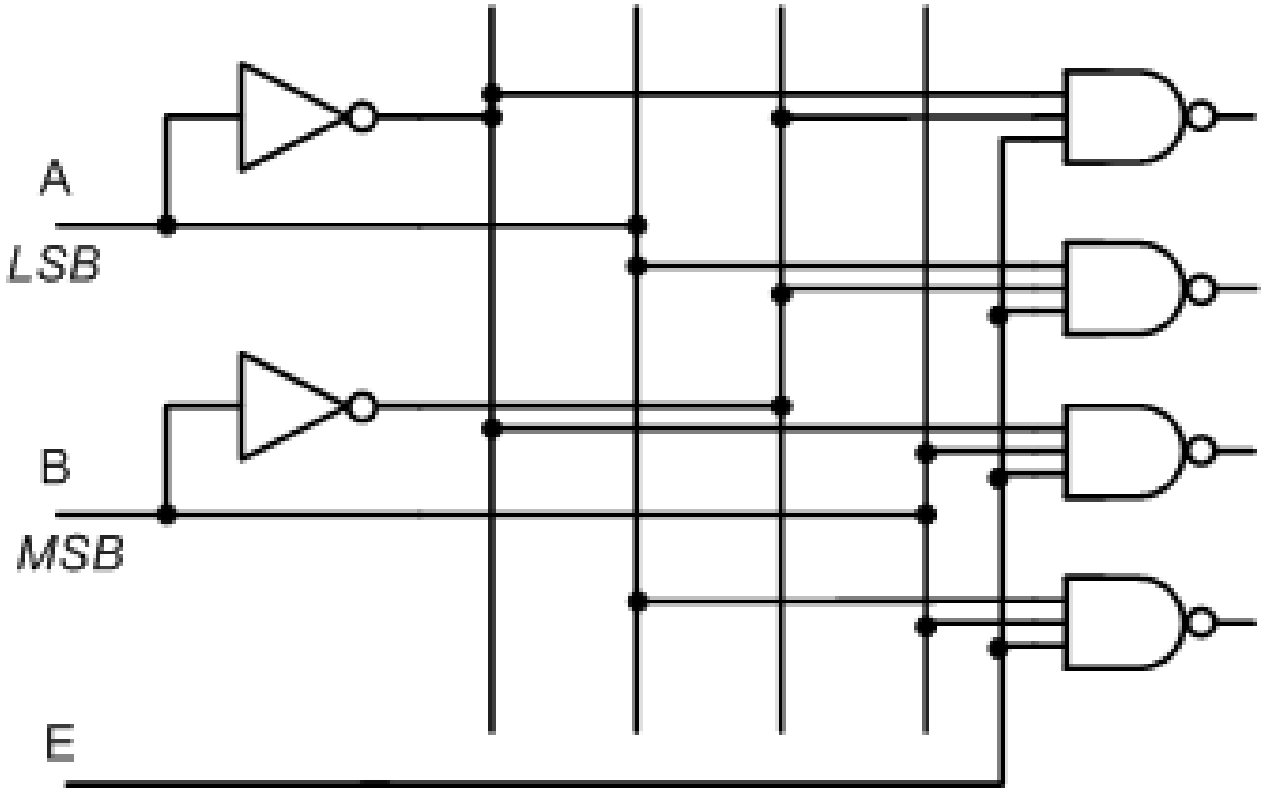
Decoder w/ Active Low Enable and Outputs



Inputs and outputs that have a "true/false" or "yes/no" meaning (e.g. enable or decoder outputs) are often candidates to be active-low.

Bubbles and signals starting with a slash '/' indicate an active-low input or output…not an inverter…the inverters are actually in the logic diagram on the next pages…

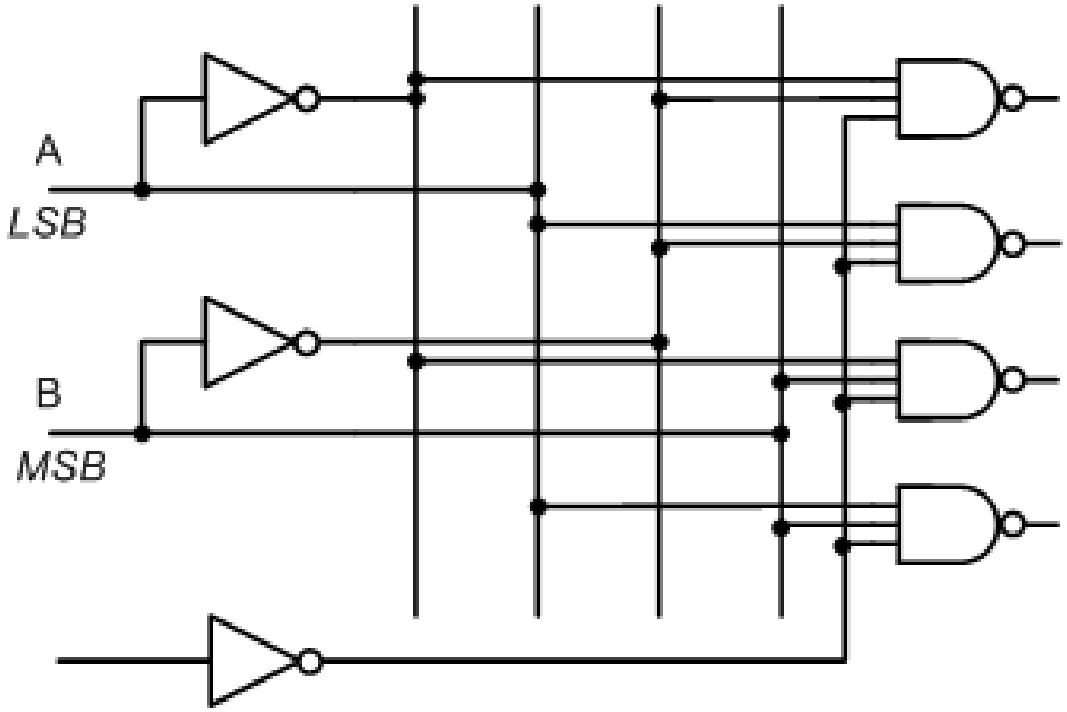
Active-Lo Outputs



When E=inactive (inactive means 0), Outputs turn off (off means 1)

When E=active (active means 1), Selected outputs turn on (on means 0)

Active-Lo Enable



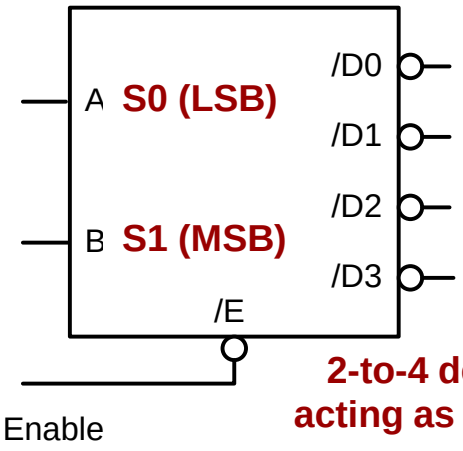
When E=inactive (inactive means 1), Outputs turn off (off means 1)

When E=active (active means 0), Selected outputs turn on (on means 0)

COMPONENTS USED

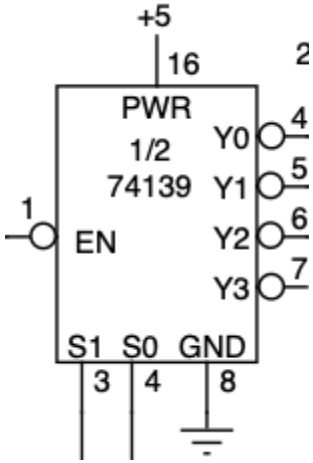
Decoder (Demux) Component

Components As Presented in Lecture

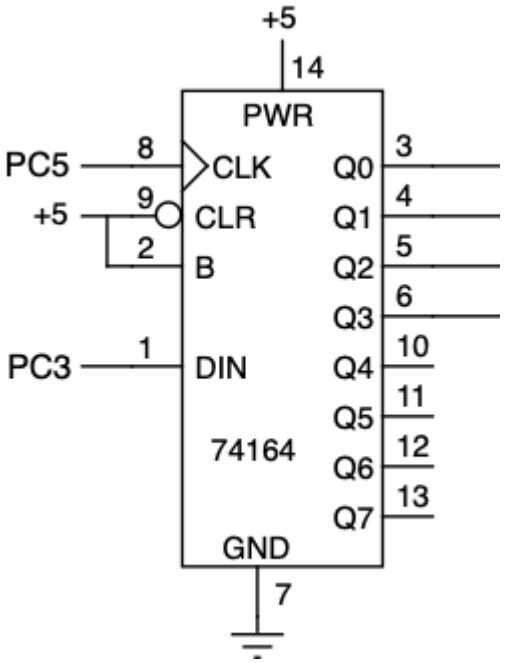


2-to-4 decoder acting as a demux

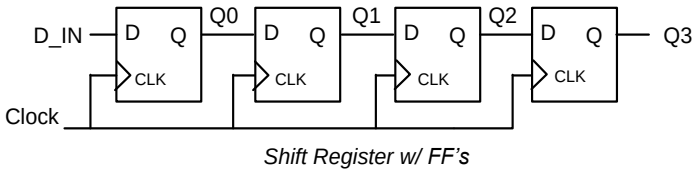
74LS139 Decoder/DeMux Component



Counter and Shift Register Components



74LS164 Shift Register Component



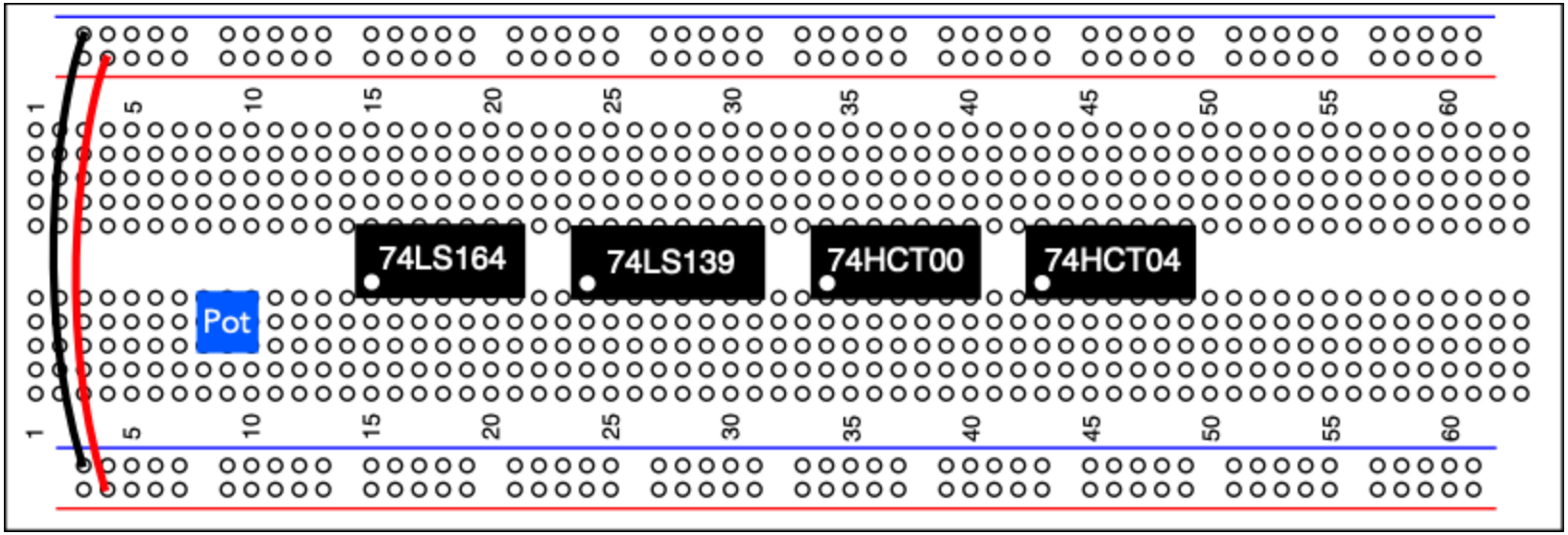
Shift Register w/ FF's

Component As Presented in Lecture

TASKS

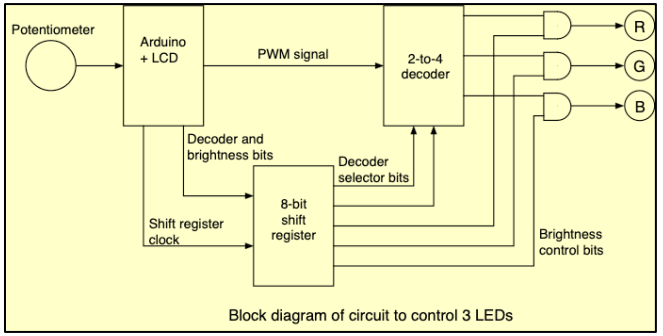
Laying Out your Circuit Board

- You have the 74HCT00 (NAND gates) and 74HCT04 (inverters) in your kit. All others can be collected when you come to lab.
- Layout your chips as we show below to make your wiring task easier and so our staff can help you more quickly via common placement.

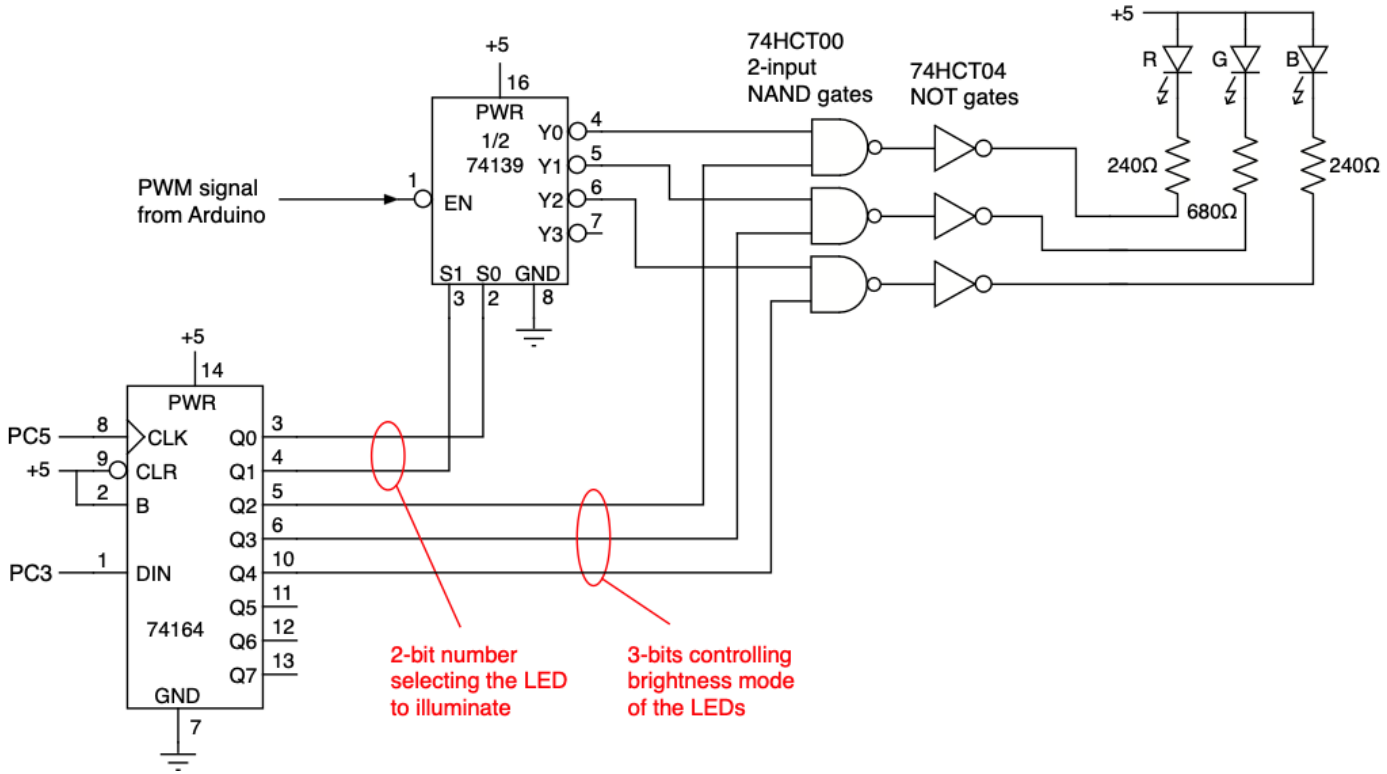


LED Control Circuit

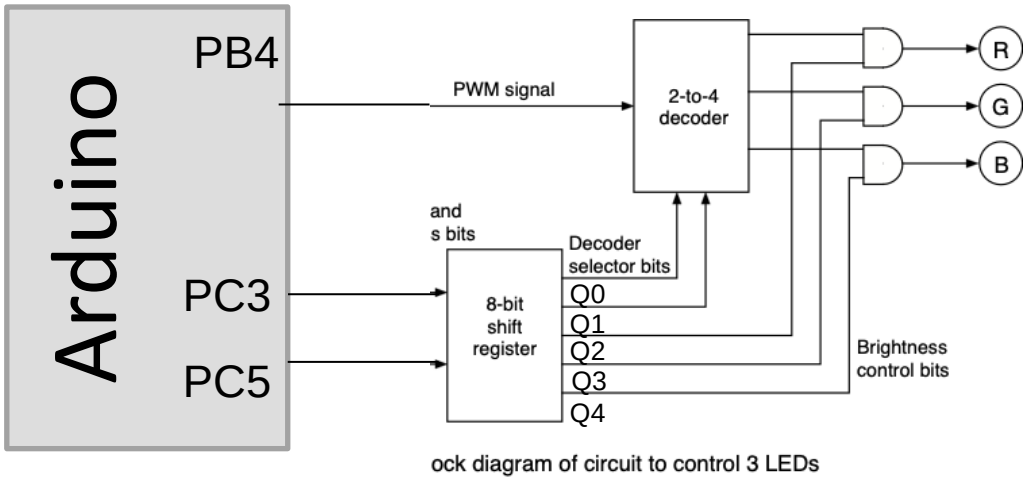
- Wire the remaining components



Block diagram of circuit to control 3 LEDs

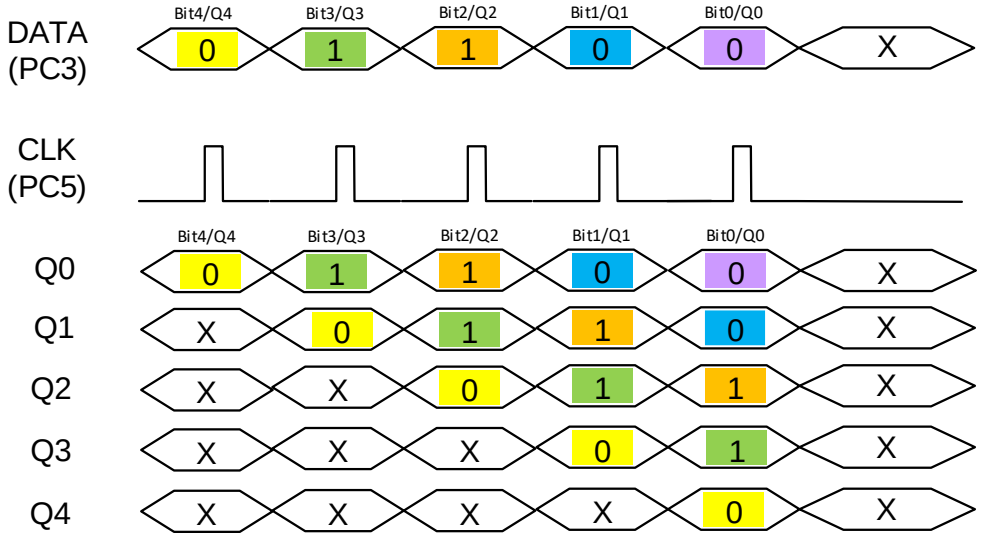


Software Task 1a



ock diagram of circuit to control 3 LEDs

- Sending bits to the shift register is similar to your LCD interface
- Output 1 data bit at a time on PC3 (in the correct order) and then generate your own "clock" pulse on PC5 which will cause the shift register to capture the data bit and shift all the other outputs over by 1 location.
- Notice we can't change just 1 or 2 bits without affecting others (since they all shift). Thus, we must always send 4 bits, repeating any bits we don't want to change.



Software Task 1b

- Actual button interface and display software are written
- You need only write the functions to serially send the 4 mux and demux (decoder) select bits to the shift register
- You will write
  - `shift1bit(uint8_t bit);`
    - Sends the LSB of **bit** variable (as data on PC3) and generates a clock pulse on PC5
  - `void shift_load(uint8_t demux, uint8_t r, uint8_t g, uint8_t b);`
    - Call shift1bit() multiple times to send all the 5-bits; The demux's select bits are assumed to be in the **lower 2 bits** of the argument, while each of r, g, and b have the desired value in the **LSB** of the byte.
    - Take care to decide the order to send the 5 bits (refer to the schematic and look at how the shift register outputs are wired)