CprE 288 – Introduction to Embedded Systems (Analog-to-Digital Converter)

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Overview of Today's Lecture

- Announcements
- ADC
  - Successive Approximation
- ADC on the ATmega128

Announcements

- This Thursday
  - Homework 5 due

ANALOG TO DIGITAL CONVERTERS

ADC and DAC

Analog-to-Digital Conversion (ADC) and
Digital-to-Analog Conversion (DAC)

Why do we need ADC and DAC?

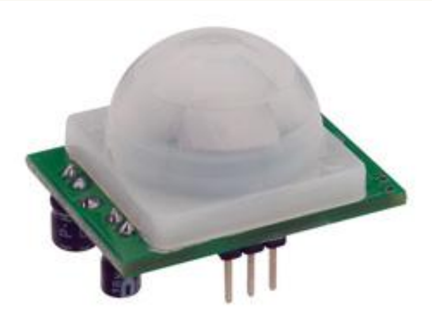
- Analog sensors: Temperature, pressure, light, humidity, compass, and so on
- Audio applications: Microphone and speakers
- Image and video applications: Digital cameras, camcorder

ADC and DAC

Analog sensor: Convert a physical signal into an ***analog*** electrical signal

Temperature Sensor $3.95

Photoresistor $1.95 (Light Sensor)



Passive IR sensor $9.95 for motion detection

Sensor pictures and prices from http://www.parallax.com

ADC and DAC

ADCs in microcontroller

- Most ***ADC***s also work as ***DAC***
- The ADC circuitry is located inside the microcontroller, with dozens of ADC pins going outside to support ***multiple input channels***
- Mostly 10-bit ***resolution*** (the higher the better, e.g. 14-bit in high-end digital cameras)
- Supports ***continuous mode*** and ***single conversion mode***
- ***Sampling rate*** in continuous mode ranges from tens of KHz to hundreds of KHz (the faster the better)

ADC Terminology

analog: continuously valued signal, such as temperature, speed, or voltage with infinite possible values in between

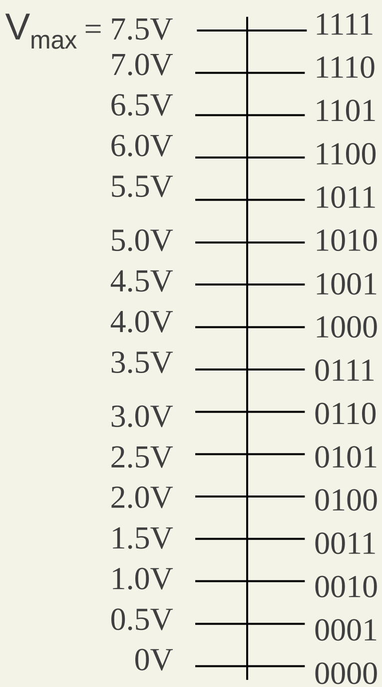
digital: discretely valued signal, such as integers, encoded in binary

analog-to-digital converter: ADC, A/D, A2D; converts an analog signal to a digital signal

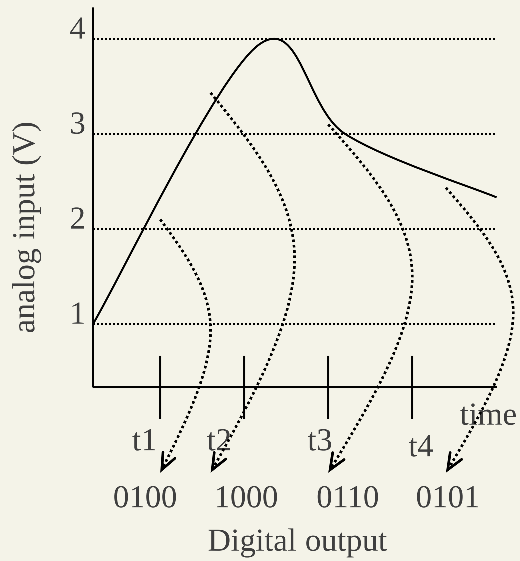
digital-to-analog converter: DAC, D/A, D2A; converts a digital number to an analog signal

An embedded system's surroundings typically involve many analog signals.

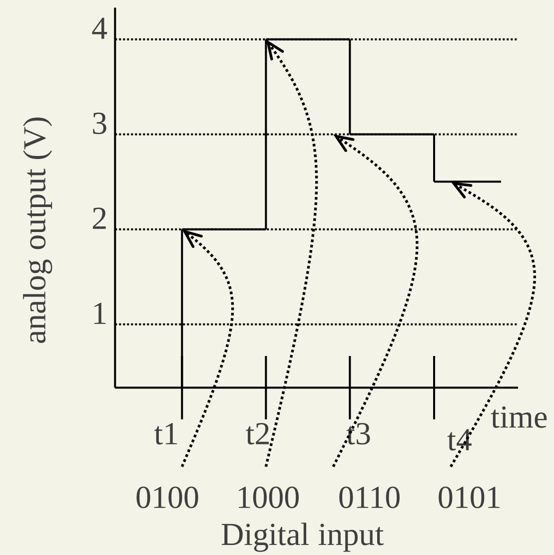
Analog-to-digital converters



proportionality



analog to digital



digital to analog

Proportional Signals

Simple Equation

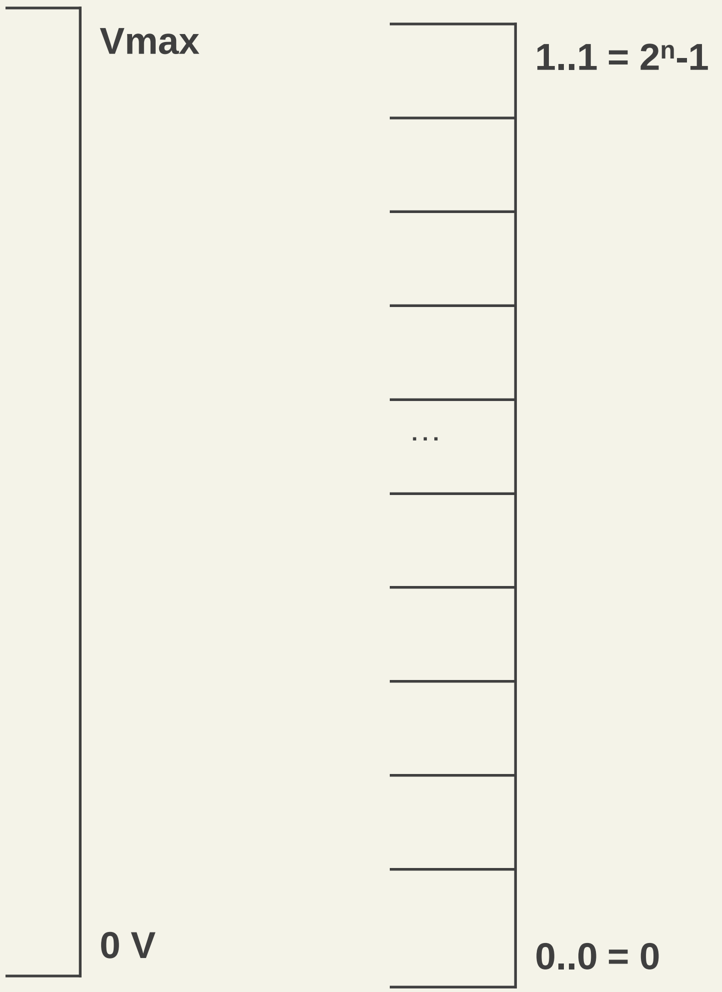
Assume minimum voltage of 0 V.
Vmax = maximum voltage of the analog signal
a = analog value
n = number of bits for digital encoding

2^n = number of digital codes

M = number of steps, either 2^n or $2^n - 1$

d = digital encoding

a / Vmax = d / M



Resolution

Let $n = 2$

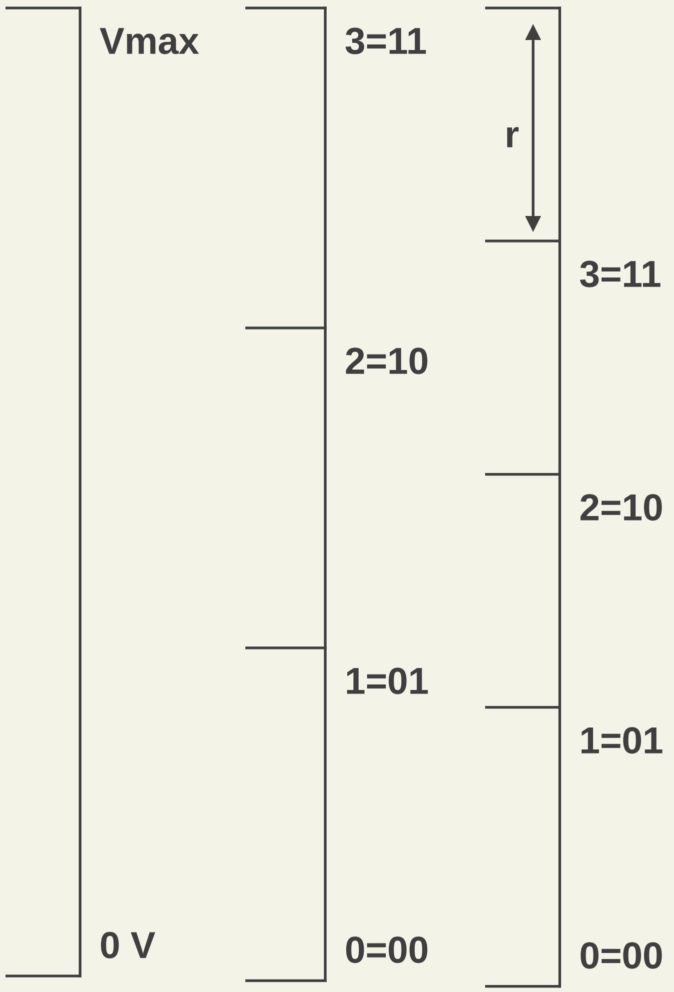
$\underline{M = 2^n - 1}$

3 steps on the digital scale
$d_0 = 0 = 0b00$
$d_{Vmax} = 3 = 0b11$

$\underline{M = 2^n}$

4 steps on the digital scale
$d_0 = 0 = 0b00$
$d_{Vmax - r} = 3 = 0b11$ (no d_{Vmax})

r, **resolution**: smallest analog change resulting from changing one bit



DAC vs. ADC

- DAC
  - n digital inputs for digital encoding **d**
  - analog input for **Vmax** and **Vmin**
  - analog output **a**

- ADC
  - n digital outputs for digital encoding **d**
  - analog input for **Vmax** and **Vmin**
  - analog input **a**

DAC vs. ADC

ADC:

Given a Vmax analog input and an analog input a, how does the converter know what binary value to assign to d in order to satisfy the ratio?

- may use DAC to generate analog values for comparison with a
- ADC “guesses” an encoding d, then checks its guess by inputting d into the DAC and comparing the generated analog output a’ with original analog input a
- How does the ADC guess the correct encoding?

ADC: Digital Encoding

Guessing the encoding is similar to finding an item in a list.

1. Sequential search – counting up: start with an encoding of 0, then 1, then 2, etc. until find a match.
    - 2^n comparisons: Slow!
2. Binary search – successive approximation: start with an encoding for half of maximum; then compare analog result with original analog input; if result is greater (less) than the original, set the new encoding to halfway between this one and the minimum (maximum); continue dividing encoding range in half until the compared voltages are equal
    - n comparisons: Faster, but more complex converter

→ Takes time to guess the encoding: start conversion input, conversion complete output

ADC Using Successive Approximation

- Given an analog input signal whose voltage should range from 0 to 15 volts, and an 8-bit digital encoding, calculate the correct encoding for 5 volts. Then trace the successive-approximation approach to find the correct encoding.
- Assume $M = 2^n - 1$

$$a / Vmax = d / M$$

$$5 / 15 = d / (256 - 1)$$

$$d = 85 \text{ or binary } 01010101$$

ADC Using Successive Approximation

Step 1-4: Determine bits 0-3

$\frac{1}{2}(V_{max} - V_{min}) = 7.5$ volts
$V_{max} = 7.5$ volts.

0	0	0	0	0	0	0	0

$\frac{1}{2}(7.5 + 0) = 3.75$ volts
$V_{min} = 3.75$ volts.

0	1	0	0	0	0	0	0

$\frac{1}{2}(7.5 + 3.75) = 5.63$ volts
$V_{max} = 5.63$ volts

0	1	0	0	0	0	0	0

$\frac{1}{2}(5.63 + 3.75) = 4.69$ volts
$V_{min} = 4.69$ volts.

0	1	0	1	0	0	0	0

ADC Using Successive Approximation

Step 5-8: Determine bits 4-7

½(5.63 + 4.69) = 5.16 volts
V_{max} = 5.16 volts.

0	1	0	1	0	0	0	0

½(5.16 + 4.69) = 4.93 volts
V_{min} = 4.93 volts.

0	1	0	1	0	1	0	0

½(5.16 + 4.93) = 5.05 volts
V_{max} = 5.05 volts.

0	1	0	1	0	1	0	0

½(5.05 + 4.93) =
4.99 volts

0	1	0	1	0	1	0	1

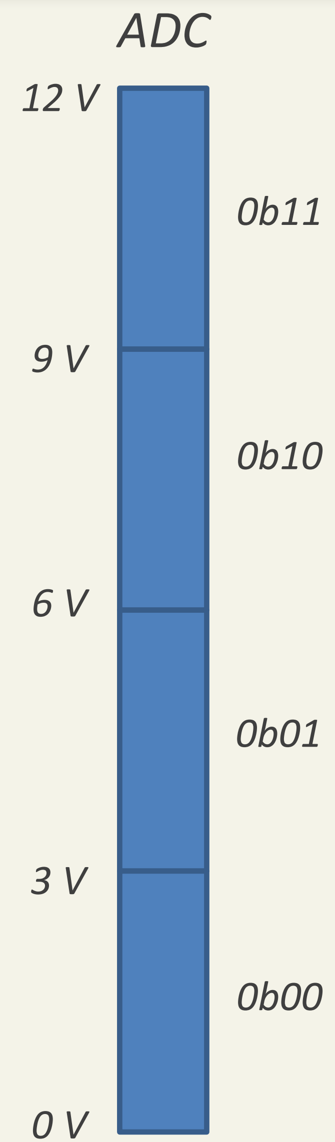
Resolution

- Example
  - 2-bits of resolution
  - Vmin = 0 Volts
  - Vmax = 12 Volts

$M = 2^n$

$2^2 = 4$ buckets (or ranges) for the analog signal to fall

r, resolution: smallest analog change resulting from changing one bit

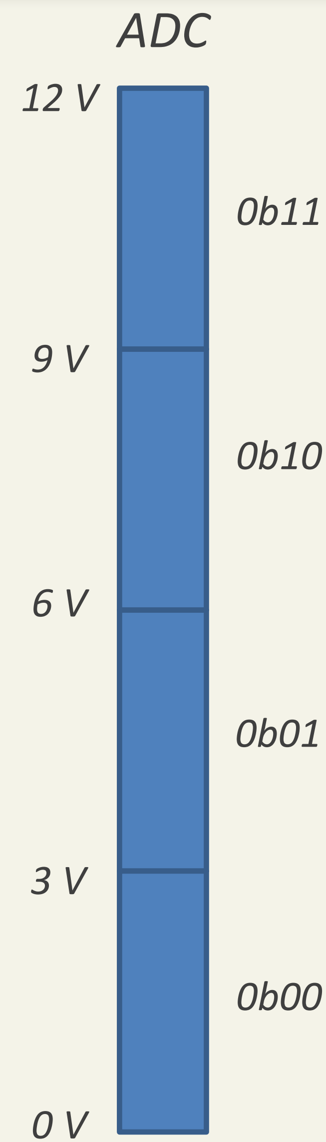


Practice Problem 1

- Question:
  - Given:
    - n = 2 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?

Practice Problem 1

- Question:
  - Given:
    - n = 2 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?



- Answer:
  - Analog and Digital signals are proportional

$$\frac{a\ - Vmin}{Vmax\ -\ Vmin} = \frac{d}{2^n}$$

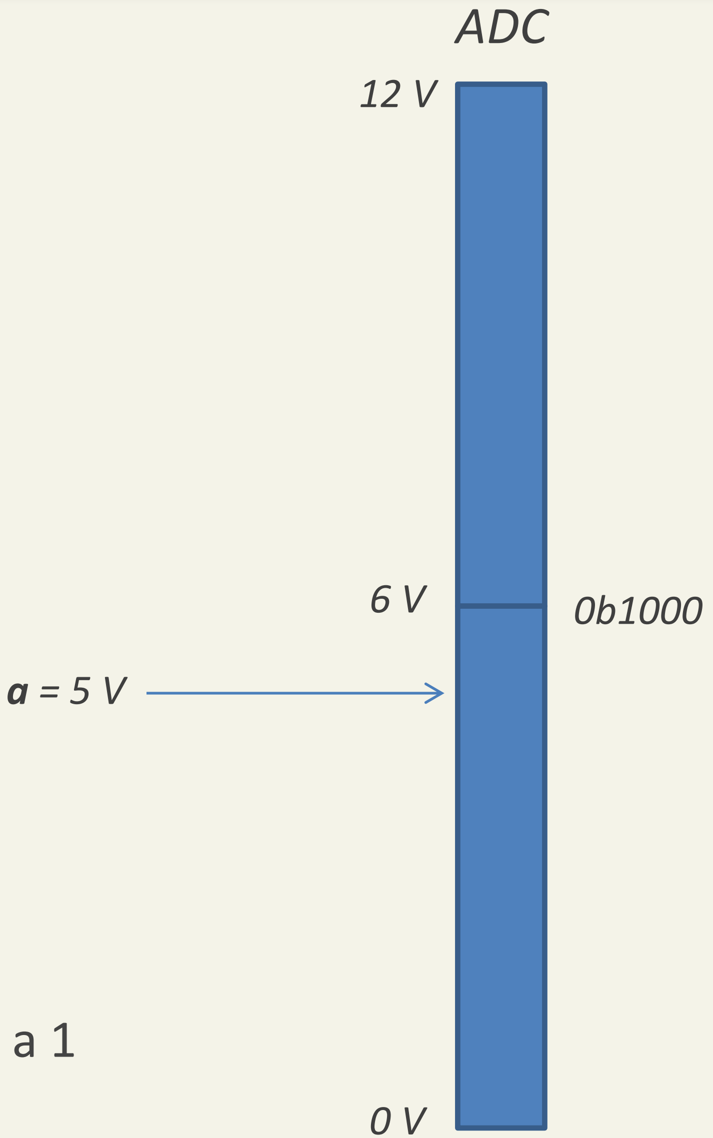
  - **d** is 0b01

Practice Problem 2

- Question:
  - Given:
    - n = 4 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?

Practice Problem 2

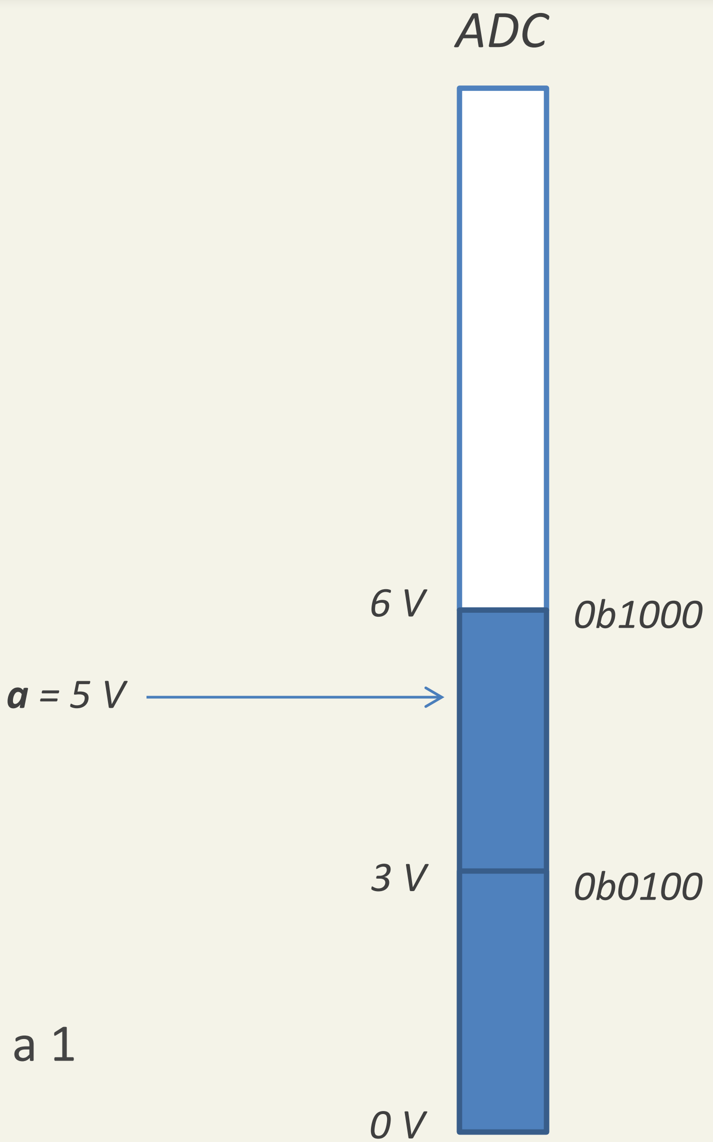
- Question:
  - Given:
    - n = 4 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?



- Answer:
  - Use successive approximation
  - **d** = 0b**?**???
    - Midpoint is 0b1000 at 6 volts
    - If **a** is greater than 6 volts, record a 1
    - If **a** is less than 6 volts, record a 0

Practice Problem 2

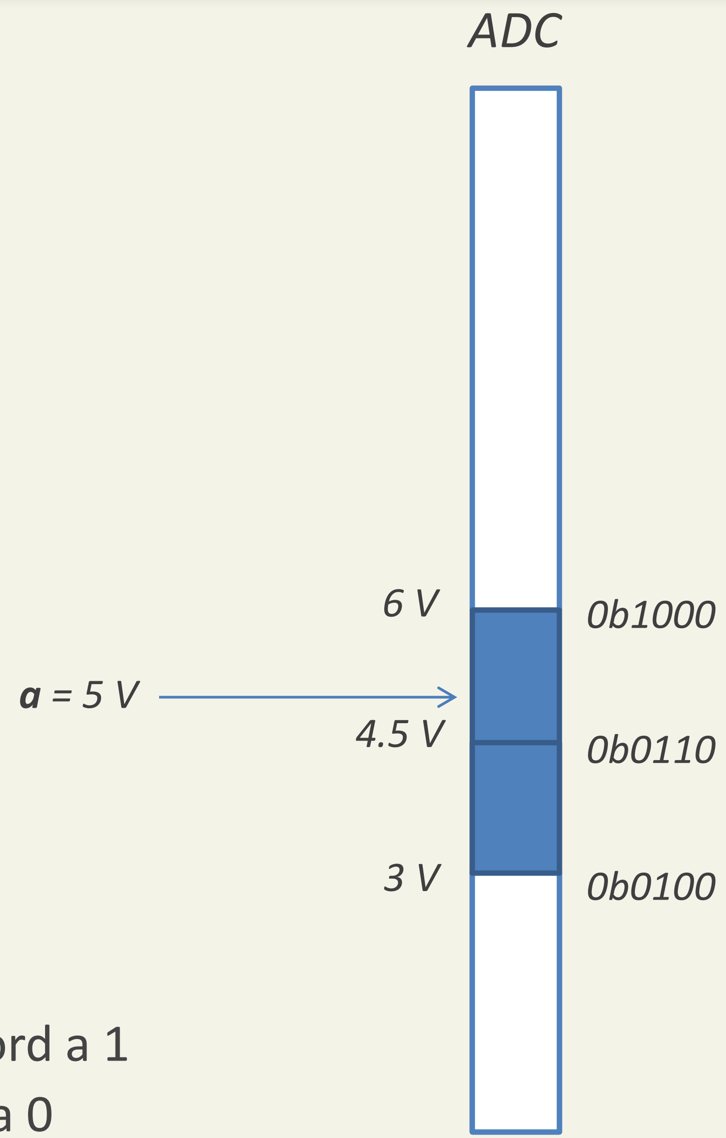
- Question:
  - Given:
    - n = 4 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?



- Answer:
  - Use successive approximation
  - **d** = 0b0**?**??
    - Midpoint is 0b0100 at 3 volts
    - If **a** is greater than 3 volts, record a 1
    - If **a** is less than 3 volts, record a 0

Practice Problem 2

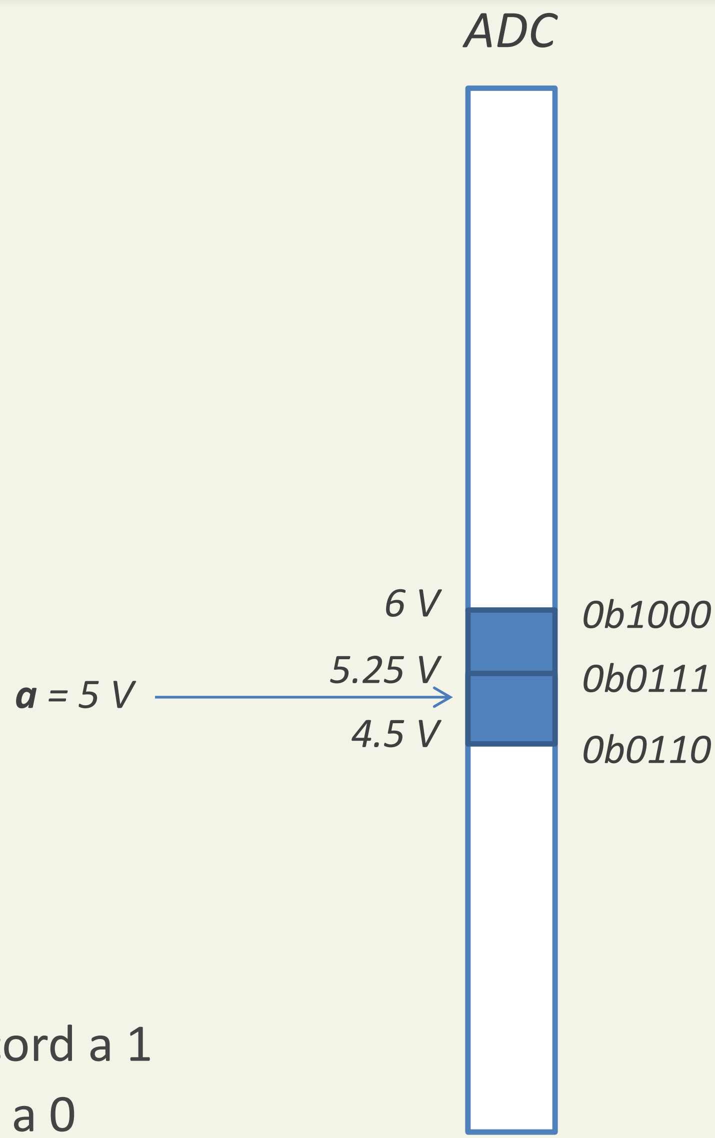
- Question:
  - Given:
    - n = 4 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?



- Answer:
  - Use successive approximation
  - **d** = 0b01**??**
    - Midpoint is 0b0110 at 4.5 volts
    - If **a** is greater than 4.5 volts, record a 1
    - If **a** is less than 4.5 volts, record a 0

Practice Problem 2

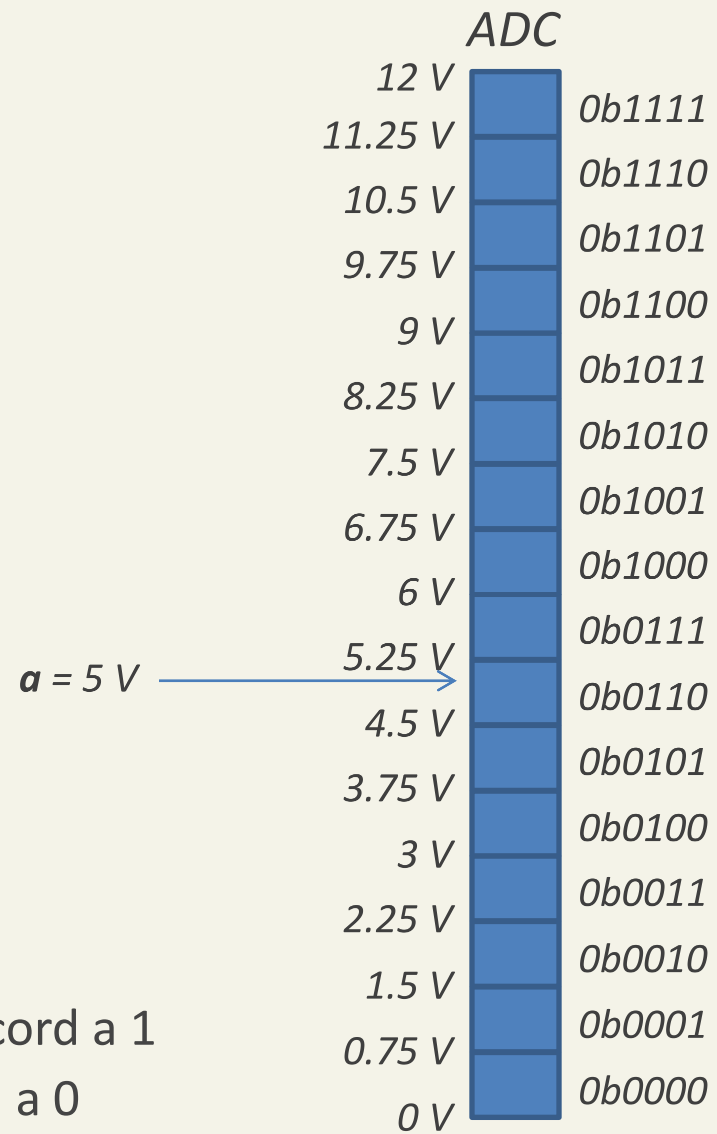
- Question:
  - Given:
    - n = 4 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?



- Answer:
  - Use successive approximation
  - **d** = 0b011**?**
    - Midpoint is 0b0111 at 5.25 volts
    - If **a** is greater than 5.25 volts, record a 1
    - If **a** is less than 5.25 volts, record a 0

Practice Problem 2

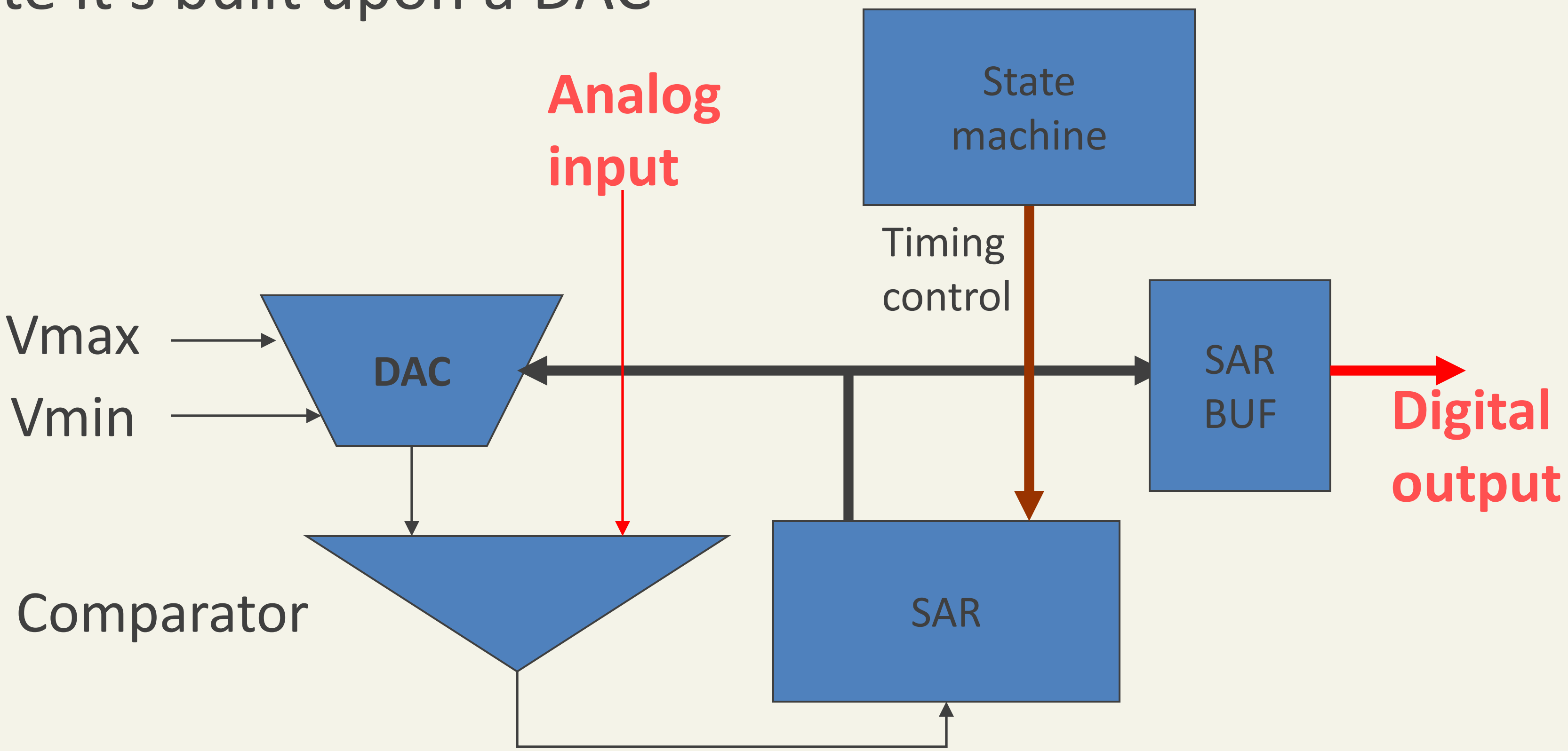
- Question:
  - Given:
    - n = 4 bit resolution
    - **Vmin** = 0 volts
    - **Vmax** = 12 volts
    - **a** = 5 volts
  - What is **d**?



- Answer:
  - Use successive approximation
  - **d** = 0b0110
    - Midpoint is 0b0111 at 5.25 volts
    - If **a** is greater than 5.25 volts, record a 1
    - If **a** is less than 5.25 volts, record a 0

Constructing the ADC

Note it's built upon a DAC



SAR: Successive
approximation register

ADC Using Successive Approximation

- Example: 0V-16V range, 9.5V input, 4-bit resolution.

- Essentially a form of binary search
- Each step works out the value of one bit.
- Instructor will fill in the table

Step	Range	Mid (digital)	Mid (voltage)	Is a > Mid (voltage)?
0	0bxxxx	0b1000	8 Volts	Yes
1	0b1xxx			
2				
3				
4				

ADC Using Successive Approximation

- Example: 0V-16V range, 9.5V input, 4-bit resolution.

- Essentially a form of binary search
- Each step works out the value of one bit.
- Instructor will fill in the table

Step	Range	Mid (digital)	Mid (voltage)	Is a > Mid (voltage)?
0	0bxxxx	0b1000	8 Volts	Yes
1	0b1xxx	0b1100	12 Volts	No
2	0b10xx	0b1010	10 Volts	No
3	0b100x	0b1001	9 Volts	Yes
4	0b1001	-	-	-

ADC Using Successive Approximation

- Example: 0V-16V range, 9.5V input, 4-bit resolution.

$$\frac{a - Vmin}{Vmax - Vmin} = \frac{d}{2^n}$$

$$\frac{9.5}{16 - 0} = \frac{d}{16}$$

$$d = \frac{9.5 * 16}{16} = 9.5$$

d = 0b1001 = 9

ADC Bit Weight

Notice the concept of <u>bit weight</u> in the last example:
bit 7 = 7.5 V = 15/2
bit 6 = 3.75 V = 15/4

Each bit is weighted with an analog value, such that a 1 in that bit position adds its analog value to the total analog value represented by the digital encoding.

Example: -5 V to +5 V analog range, n=8

Digital Bit	Bit Weight (V)
7	10/2 = 5
6	10/4 = 2.5
5	10/8 = 1.25
4	10/16 = 0.625
3	10/32 = 0.313
2	10/64 = 0.157
1	10/128 = 0.078
0	10/256 = 0.039

ADC Bit Weight

Example (continued): -5 V to +5 V analog range, n=8

Digital numbers for a few analog values

- Values shown increment by 6 bits (weight for bit position 5 is 1.25 V)
- Maximum digital number only approximates the maximum analog value in the range
  - Try (-5) + sum of all bit weights

Analog (V)	Digital (hex)
-5	00
-3.75	20
-2.5	40
-1.25	60
0	80
1.25	A0
2.5	C0
3.75	E0
5-0.039 = 4.961	FF

ADC Terms & Equations

Offset: minimum analog value

Span (or **Range**): difference between maximum and minimum analog values

Max - Min

n: number of bits in digital code (sometimes referred to as n-bit resolution)

Bit Weight: analog value corresponding to a bit in the digital number

Step Size (or **Resolution**): smallest analog change resulting from changing one bit in the digital number, or the analog difference between two consecutive digital numbers; also the bit weight of the

Span / 2^n (Assume $M = 2^n$)

ADC ON ATMEGA128

ATMega128 ADC

- 10-bit ADC conversion
- Eight input channels through a MUX
- Analog input on one of ADC0-ADC7 pins
- Up to 15K samples per second
- 0 – Vcc or 0 – 2.56V ADC input voltage range

Programming Interface: ADCSRA

Three registers

- **ADCSRA**: ADC control and status register A
- **ADMUX**: ADC input selection
- **ADCW**: ADC result register, 16-bit

ATMega128 I/O Ports

ATMega128 I/O Ports and **Alternative Functions**

Ports A-G, each pin can be configured as **General Purpose Digital I/O Pin**

- DDR*x* decides if a pin is for input or output *
- PORT*x* is for writing to output pins
- PIN*x* is for reading from input pins

(* There is a special tri-state configuration)

Alternatively, those pins can be used as I/O pins for internal I/O devices

- Activate a pin's alternative function by enabling the corresponding I/O devicce
- Then, the pin MAY NOT be used as GP I/O pin

ATMega128 I/O Pins

Most pins have Alternative Functions: USART, ADC, input capture, output compare, and others

USART0 uses port E

- PE2: External Clock (PE – Port E)
- PE1: Transmit Pin
- PE0: Receive Pin

USART1 uses port D

- PD5: External Clock
- PD3: Transmit Pin
- PD2: Receive Pin

ADC I/O Pins

The ADC uses Port F, all eight pins

- There are eight input channels
- PF0 – PF7 for channels 0-7

If ADC is enabled, then avoid using port F for external I/O device

- No need to configure Port F as input, just enable the ADC

Program Interface: ADCSRA

7	6	5	4	3	2	1	0	
ADEN	ADSC	ADFR	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCSRA
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

ADEN: ADC Enable

Write 1 to this bit to enable ADC

ADSC: ADC Start Conversion

Write 1 to this bit to start ADC conversion. It turns to 0 after conversion is done

Coding Examples

Enable ADC

```
ADCSRA |= 0x80;
```

Disable ADC

```
ADCSRA &= 0x7F;
```

Read an ADC word, assuming it’s ready

```
unsigned reading = ADCW;
```

Coding Examples

Using a different coding style

Enable ADC

```
ADCSRA |= (1 << ADEN);
```

Disable ADC

```
ADCSRA &= ~(1 << ADEN);
```

Notes

- <avr/io.h> declares ADEN and other names as macros
- ADEN is defined as 7: (1 << 7) == 0x80

Coding Example

Assume ADC has been configured appropriately and in one-shot mode with interrupts disabled.

Write code to (1) start ADC, (2) wait for the conversion to complete, and (3) read the output.

```
ADCSRA |= (1<<ADSC);
while (ADCSRA & (1<<ADSC))
    {}
unsigned ADC_reading = ADCW;
```

Program Interface: ADCSRA

7	6	5	4	3	2	1	0	
ADEN	ADSC	ADFR	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCSRA
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

ADFR: ADC Free Running Select

- 1: continues sampling, 0: one shot

ADIF: ADC Interrupt Flag

- 1: interrupt raised, 0: otherwise

ADIE: ADC Interrupt Enable

Coding Examples

Enable ADC interrupt

```
ADCSRA |= (1 << ADIE);
```

Disable ADC interrupt

```
ADCSRA &= ~(1 << ADIE);
```

Check ADC interrupt flag manually

```
if (ADCSRA & (1 << ADIF))
    … // do something
```

Coding Examples

Use a different coding style

Enable ADC interrupt

```
ADCSRA |= _BV(ADIE);
```

Disable ADC interrupt

```
ADCSRA &= ~_BV(ADIE);
```

_BV (**Bit Vector**) is declared in <arv/io.h> like follows:

```
#define _BV(x)    (1<<(x))
```

Program Interface: ADCSRA

7	6	5	4	3	2	1	0	
ADEN	ADSC	ADFR	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCSRA
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

ADPS2:0: ADC Prescaler Select Bits

Select one of seven division factors

000: 2, 001: 2, 010: 4, 011: 8,

100: 16, 101: 32, 110: 64, 111: 128

Typical conversion times:

- 25 ADC clock cycles for the first conversion
- Faster time (13 or 14 ADC cycles) for second conversion and thereafter in continuous sampling mode

Required ADC clock frequency: 50KHz – 200KHz

- Higher frequency possible with less than 10-bit accuracy

Coding Example

System clock is 16MHZ. What prescalar value is valid?

Pres. Bits	000	001	010	011	100	101	110	111
Div. Factor	2	2	4	8	16	32	64	128
Freq. (Hz)	8M	8M	4M	2M	1M	500K	250K	125K

What happens with higher frequency?

To set the frequency:

```
ADCSRA |= (7 << ADSP0);
```

Or

```
ADCSRA |= _BF(ADSP2) | _BF(ADSP1) | _BF(ADSP0);
```

Programming Interface: ADMUX

7	6	5	4	3	2	1	0	
REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0	ADMUX
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

REFS1:0: Reference Selection Bits

- Use code 01 to select Vcc as the reference voltage
- Can a 2.56V or external reference voltage; Use code 11 for 2.56V

ADLAR: ADC Left Adjust Result

- 1: 10-bit data is left adjusted in 16-bit reg
- 0: right adjusted

Coding Example

Set the reference voltage to 2.56V:

```
ADMUX |= _BV(REFS1) | _BV(REFS0);
```

Make the result left adjusted:

```
ADMUX |= _BV(ADLAR);
```

Programming Interface: ADMUX

7	6	5	4	3	2	1	0	
REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0	ADMUX
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

MUX4:0: Analog Channel and Gain Selection Bits

There are eight pins connected to ADC through a MUX

Code 00000 for ADC pin 0, 00001 for pin 1, …, and 00111 for pin 7.

01xxx, 10xxx, 11xxx are reserved for **differential inputs** (not to be discussed) with gain

Coding Example

Get a reading from a given ADC channel

```
unsigned ADC_read(char channel)
{
  ADMUX |= (channel & 0x1F);
  ADCSRA |= _BV(ADSC);
  while (ADCSRA & _BV(ADCS))
    {}
  return ADCW;
}
```

Code Example

Configure ADC as single shot, interrupt disabled, result right adjusted, precalar 128 and use 2.56 as the reference voltage

First, decide bits in ADCSR and ADMUX

7	6	5	4	3	2	1	0	
ADEN	ADSC	ADFR	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCSRA
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

7	6	5	4	3	2	1	0	
REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0	ADMUX
R/W	R/W	R/W	R/W	R/W	R/W	R/W	R/W	

Programming Example

```
ADC_init()
{
  // REFS=11, ADLAR=0, MUX don't care
  ADMUX = _BV(REFS1) | _BV(REFS0);

  // ADEN=1, ADFR=0, ADIE=0, ADSP=111
  //   others don't care
  // See page 246 of user guide
  ADCSRA = _BV(ADEN) | (7<<ADPS0);
}
```

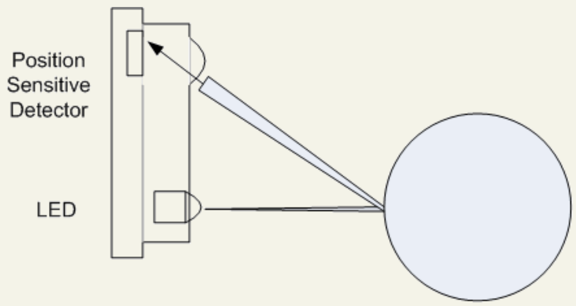
Note: It's a good idea to enable the device as the last step, so make change to ADCSRA as the last step

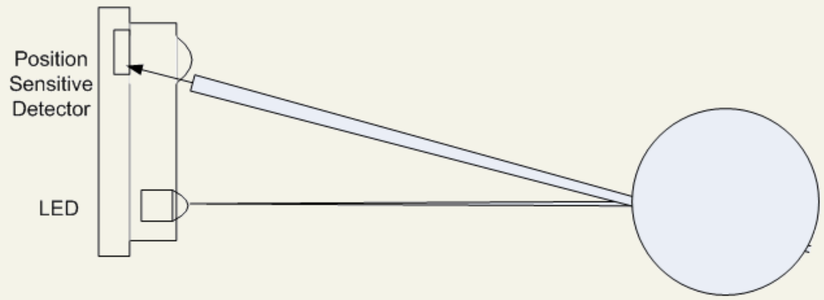
Typical Conversion Times

Condition	Sample & Hold	Conversion Time
First Conversion	13.5	25
Normal conversion, single ended	1.5	13
Normal conversion, differential	1.5/2.5	13/14

Measuring Distance with the IR Sensor

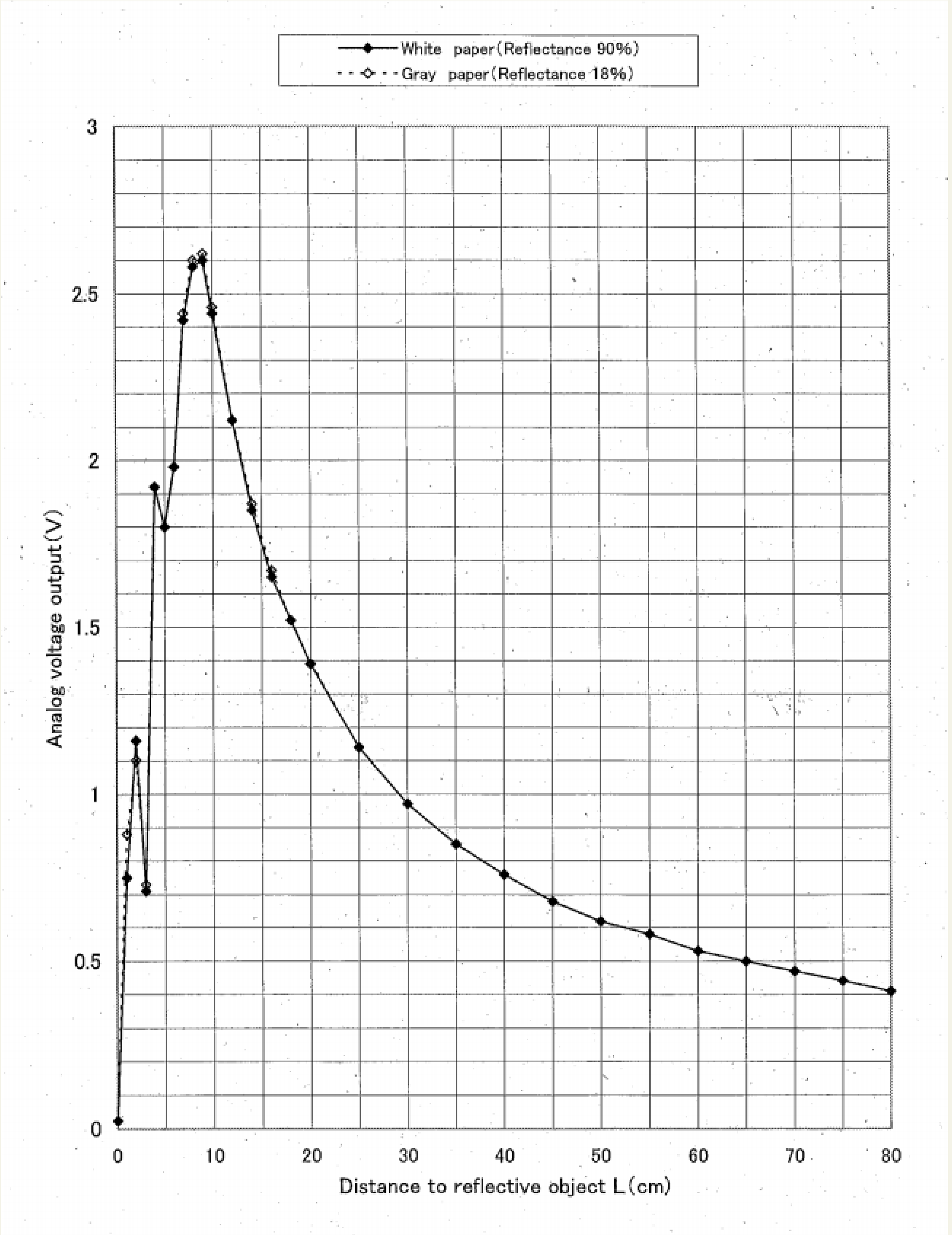
- The IR sensor emits an IR beam, and sets a voltage based on the distance of an object





From the IR Sensor Datasheet

- The voltage from the IR sensor depends on the distance
- As the distance increases, the voltage decreases (see graph)



How To Measure Distance with the IR Sensor

Getting a distance from the IR sensor involves the following process:

1. The IR sensor measures a distance and sets the voltage on the wire leading to **ADC2** (**channel 2**)
2. The ADC converts this voltage into a digital value between 0 and 1023 and stores it in the registers ADCL and ADCH (ADCW)
3. Your program reads ADCW and converts the value into a distance… but how?!?

How To Measure Distance with the IR Sensor

- Two methods to calibrate your distance
- Measure 50 points, create a table for comparing
  - Create a table that has the value of ADCW when an object is x centimeters away
  - Use this table to lookup the distance when a similar ADCW result is returned

- Measure 5 points, use Excel to get a trend line