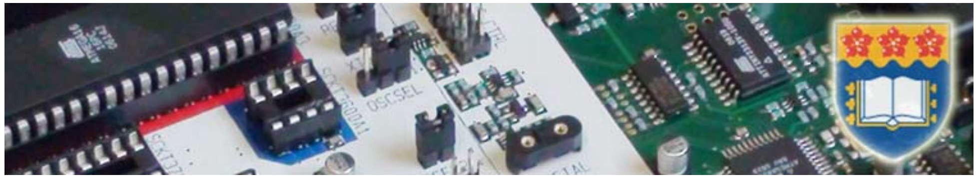


ECTE333
Lecture 11 - Analogue-to-Digital Converter

School of Electrical, Computer and Telecommunications Engineering
University of Wollongong
Australia

ECTE333 Spring 2011 — Schedule

Week	Lecture (2h)	Tutorial (1h)	Lab (2h)
1	L7: C programming for the ATMEL AVR		
2		Tutorial 7	Lab 7
3	L8: Serial communications		
4		Tutorial 8	Lab 8
5	L9: Timers		
6		Tutorial 9	Lab 9
7	L10: Pulse width modulator		
8		Tutorial 10	Lab 10
9	L11: Analogue-to-digital converter		
10		Tutorial 11	Lab 11
11	L12: Case studies		
12			Lab 12
13	L13: Revision lecture		
	Final exam (25%), Practical exam (20%), Labs (5%)		

Lecture 11's sequence

11.1 Introduction to analogue-to-digital conversion

↓

11.2 Analogue-to-digital converter in ATmega16

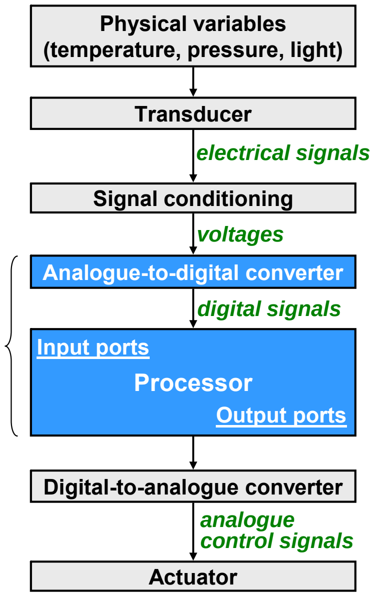
↓

11.3 Example application of ADC

11.1 Introduction to A-to-D conversion

- An ADC samples an analogue signal at discrete times, and converts the sampled signal to digital form.
- Used with transducers, ADCs allow us to monitor real-world inputs and perform control operations based on these inputs.
- Many dedicated ICs are made for ADC.
  - ADC0804: 8-bit, successive approximation.
  - Maxim104: 8-bit, flash type.

A-to-D conversion: Typical embedded application



Because of ADC is commonly needed, most modern microcontrollers has an in-built ADC unit.

A-to-D conversion: Example applications

- **Local positioning sensor for object tracking**
  [ECTE457 Project in 2007]
  - Measure the distance between FM transmitter/receiver.
  - The receiver has an RSSI output (Receiver Signal Strength Indicator).
  - The RSSI voltage is inversely proportional to the squared distance.

- **Temperature sensor for shower water**
  [ECTE350 Third-year Group Project in 2007, 3rd prize]
  - Measure the temperature of shower water and control hot/cold water valves.
  - Use a thermistor as sensor.

A-to-D conversion: Example applications

- **Obstacle sensor & audio cues in the cane for the blind**
  [ECTE250 Second-year Group Project in 2008, 1st prize]
  - Measure distance to nearest object with an ultrasonic sensor.
  - The sensor output is digitized using the ADC.

- **Electric fence monitoring**
  [ECTE350 Third-year Group Project in 2007]
  - Determine if a electric fence is being tampered.
  - Measure the voltage level of an electric fence.

A-to-D conversion: Example applications

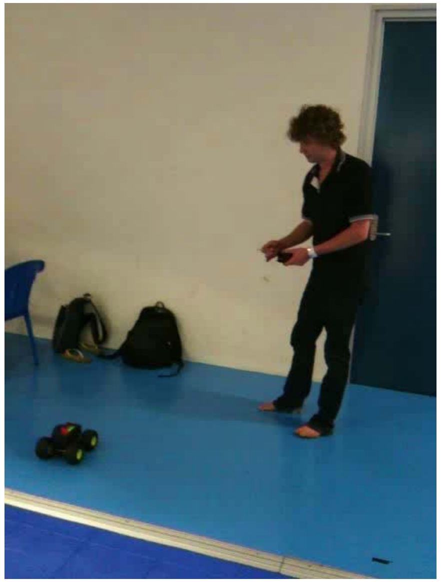
- **Wireless irrigation system**
  [ECTE250 Third-year Group Project in 2007, 1st prize]
  - Measure the moisture of the soil with resistor & ADC.
  - Transmit data wirelessly to base station & turn on/off sprinkler.

- **Intelligent clothesline**
  [ECTE350 Third-year Group Project in 2008]
  - Use a set of sensors to measure humidity, temperature, wind speed.
  - Open/close the cover of the clothesline to protect against rain.

A-to-D conversion: Example applications

- Car control using 3-D accelerometers

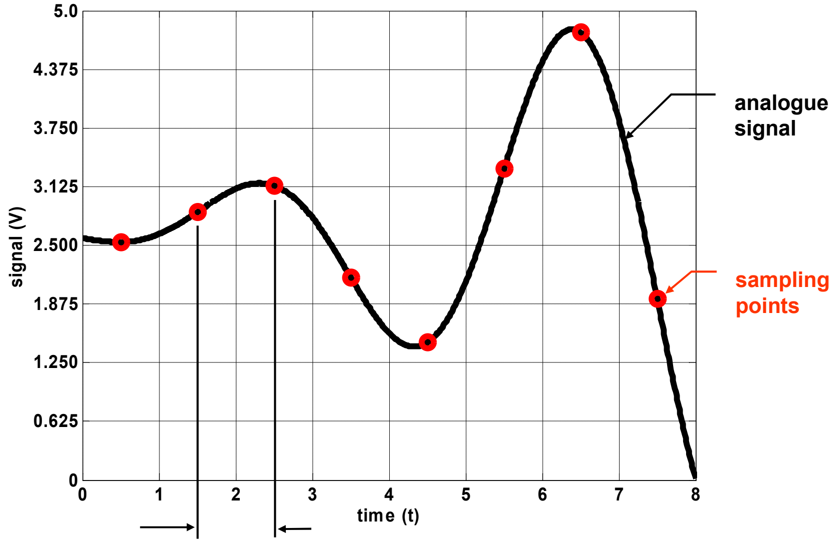
  [ECTE350 Third-year Group Project in 2010, 2nd prize]



A-to-D conversion: The process

- There are two related steps in A-to-D conversion:
  - Sampling
  - Quantization
- Sampling:
  - the analogue signal is extracted, usually at regularly spaced time instants.
  - the samples have real values.
- Quantization:
  - the samples are quantized to discrete levels.
  - each sample is represented as a digital value.

Sampling an analogue signal



What is a suitable sampling period for a signal?

The sampling theorem

An analogue signal $x(t)$ with frequencies of no more than F_{max} can be reconstructed exactly from its samples if the sampling rate satisfies:

$$F_s \geq 2F_{max}.$$

Significance

- If maximum frequency of the signal is known to be F_{max}, the sampling rate we use should be at least:

$$\text{Nyquist rate} = 2 \times F_{\max}$$

- If the sampling rate is known to be F_s, the maximum frequency in the signal must not exceed:

$$\text{Nyquist frequency} = \tfrac{1}{2} F_s$$

Quantizing the sampled signal

A-to-D converter

$$V_{\text{in}} \longrightarrow \boxed{V_{\text{ref}},\ n\ \text{bits}} \longrightarrow d = \overline{D_{n-1}D_{n-2}...D_0}$$

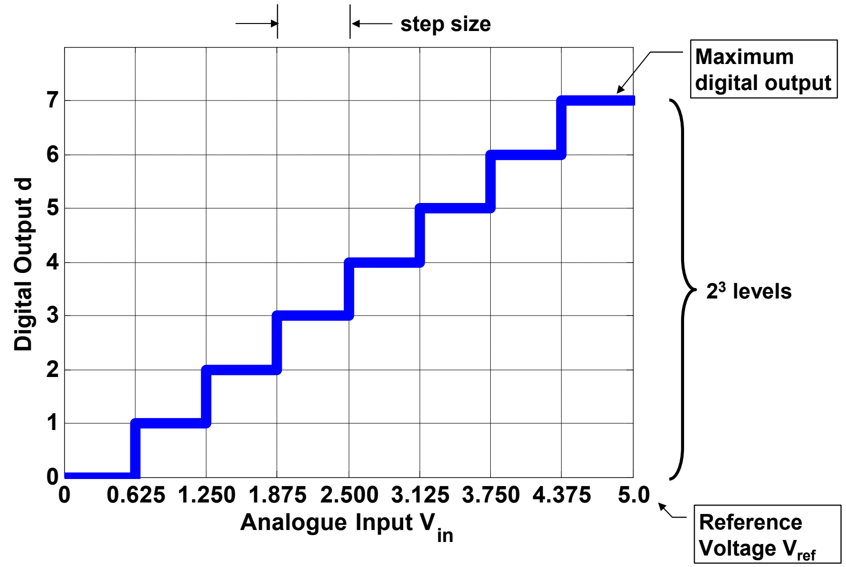
- Let's consider an n-bit ADC.
- Let V_{ref} be the reference voltage.
- Let V_{in} be the analogue input voltage.
- Let V_{min} be the minimum allowable input voltage, usually $V_{min} = 0$.
- The ADC's digital output, $d = D_{n-1}D_{n-2} \ldots D_0$, is given as

$$d = \text{round down}\left[\frac{V_{\text{in}} - V_{\text{min}}}{\text{step size}}\right]$$

- The step size (resolution) is the smallest change in input that can be discerned by the ADC:

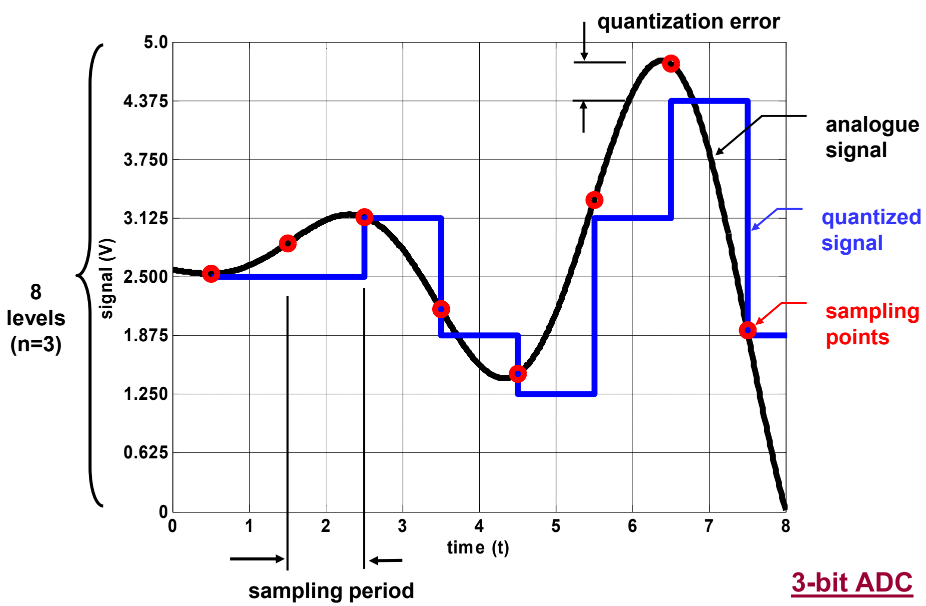
$$\text{step size} = \frac{V_{\text{ref}} - V_{\text{min}}}{2^n}$$

Quantizing the sampled signal



A 3-bit A-to-D converter

Quantizing the sampled signal



3-bit ADC

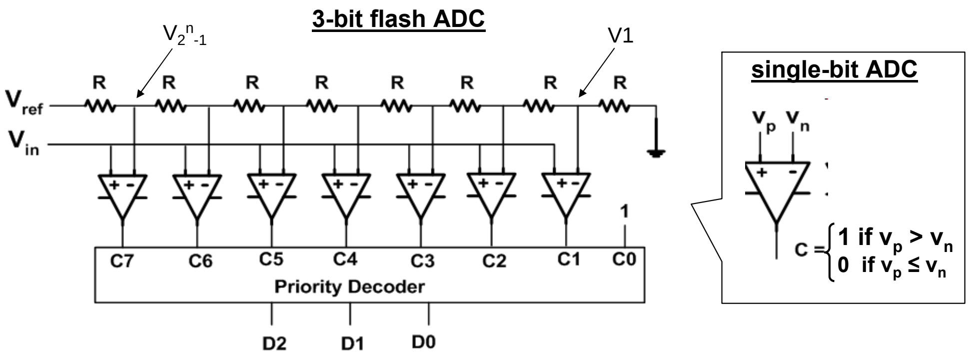
A-to-D converter: Parameters

- Number of bits n: The higher the number of bits, the more precise the digital output.
- Quantisation error E_q: the average difference between the analogue input and the quantized value. The quantization error of an ideal ADC is half of the step size.
- Sample time T_{sample}: a sampling capacitor must be charged for a duration of t_{ASM} before conversion taking place.
- Conversion time T_{conv}: time taken to convert the voltage on the sampling capacitor to a digital output.

A-to-D converter: Designs

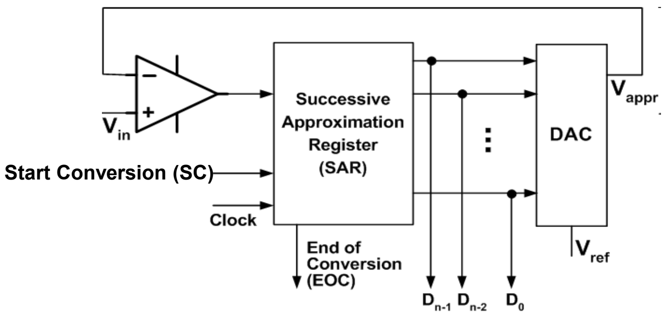
- There are many designs for analogue-to-digital converters.
- We'll consider two common designs.
  - Flash ADC.
  - Successive-approximation ADC.

Flash ADC



- A n-bit flash ADC uses 2^n-1 comparators and a priority decoder.
- **Advantage**: the fastest type of ADC.
- **Disadvantages**: limited resolution, expensive, and large power consumption.

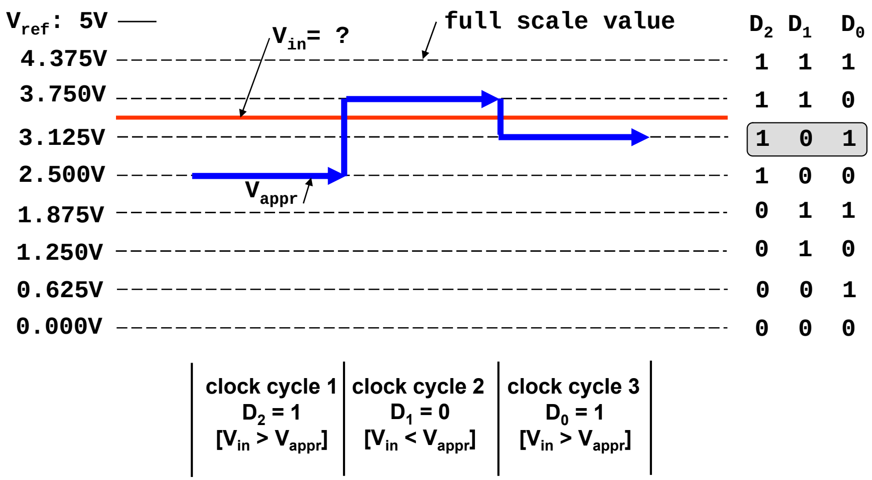
Successive-approximation ADC



- A DAC is used to generate approximations of the input voltage.
- A comparator is used to compare V_{in} and V_{appr}.
- In each cycle, SAR finds one output bit using comparator's output.
- To start conversion, set SC = 1. When conversion ends, EOC = 1.
- Quite fast, one of the most widely used design for ADCs.

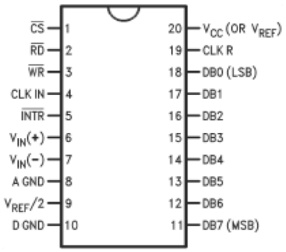
Successive-approximation ADC

Binary search for a 3-bit ADC



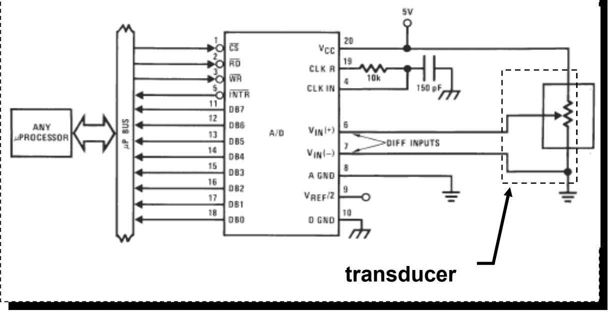
Example IC for ADC

ADC0804
(National Semiconductor)



- V_{CC}: reference voltage
- RD: to read digital output
- WR: to start a new conversion
- INTR: when conversion completes
- $V_{IN}(+)$, $V_{IN}(-)$: analogue input
- DB0-DB7: 8-bit output
- CLK IN, CLK R: clock signal

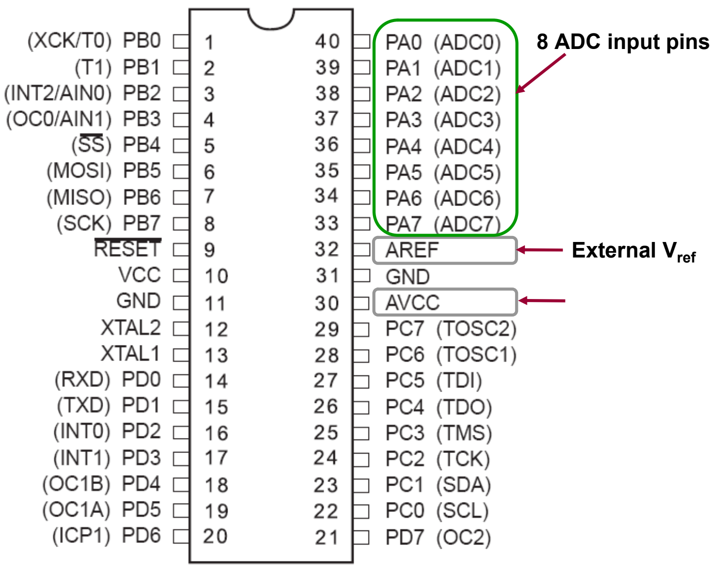
A typical application of ADC0804



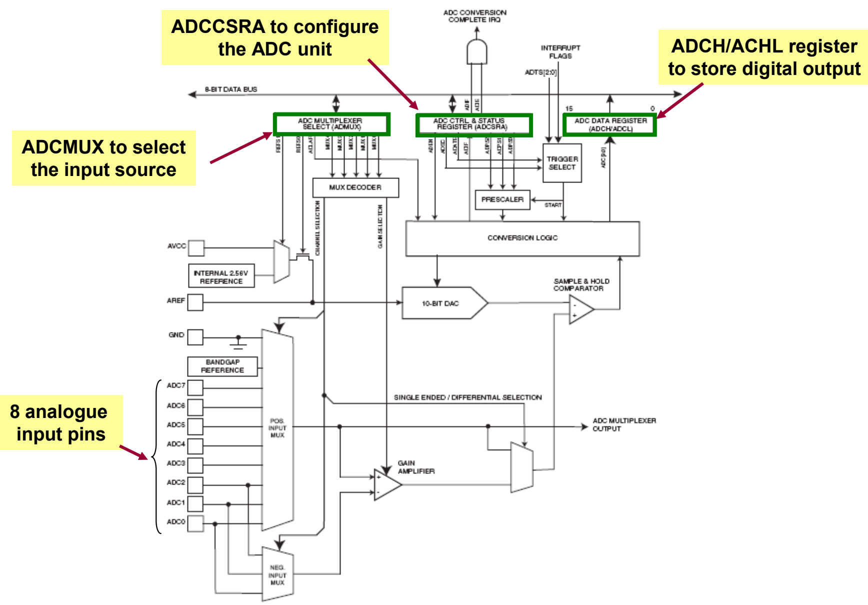
11.2 The ADC in ATmega16

- The ADC in ATmega16 has a 10-bit resolution.
  - The digital output has n = 10 bits.
- The ADC has 8 input channels.
  - Analogue input can come from 8 different sources.
  - However, it performs conversion on only one channel at a time.
- If default reference voltage V_{ref} = 5V is used.
  - step size: 5(V)/1024 (steps) = 4.88mV.
  - accuracy: ± 2 LSB = $\pm$9.76mV
- The clock rate of the ADC can be different from the CPU clock rate.
  - One ADC conversion takes 13 ADC cycles.
  - An ADC prescaler will decide the ADC clock rate.

ADC unit — Relevant pins



ADC unit — Block diagram



ADC unit — Main aspects

We focus on the major aspects of the ADC unit.

11.2.1 What are the relevant ADC registers?

- a) ADCMUX
- b) ADCH/ADCL
- c) ADCCSRA
- d) SFIOR

11.2.2 What are the steps to use the ADC?

11.2.3 How to use ADC interrupt?

© University of Wollongong, 2011.

11.2.1a ADC Multiplexer Selection Register (ADCMUX)

REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0

MUX4-0: Select analogue channel and gain selection

ADC Left Adjust Result: 1 left adjust the result stored in ADC

Reference Selection bits: To select reference voltage

- Reference voltage V_{ref} can be selected among 3 choices. [Slide 28]
- Analogue input voltage can be selected as among different pins. Differential input and custom gain factor can also be chosen [Slide 29].
- ADLAR flag will determine how the 10-bit digital output will be stored in output registers [Slide 30].

© University of Wollongong, 2011.

Selecting reference voltage V_{ref}

Table 11.1: ADC reference voltage selection

REFS1	REFS0	Voltage Reference Selection
0	0	AREF, Internal Vref turned off
0	1	AVCC with external capacitor at AREF pin
1	0	Reserved
1	1	Internal 2.56V Voltage Reference with external capacitor at AREF pin

- Usually, mode 01 is used: AVCC = 5V as reference voltage.
- However, if the input voltage has a different dynamic range, we can use mode 00 to select an external reference voltage.

© University of Wollongong, 2011.

Selecting input source and gain factor

Table 11.2: ADC input source

MUX4..0	Single Ended Input	Positive Differential Input	Negative Differential Input	Gain
00000	ADC0	N/A		
00001	ADC1			
00010	ADC2			
00011	ADC3			
00100	ADC4			
00101	ADC5			
00110	ADC6			
00111	ADC7			
01000	N/A	ADC0	ADC0	10x
01001		ADC1	ADC0	10x
01010[1]		ADC0	ADC0	200x
01011[1]		ADC1	ADC0	200x
01100		ADC2	ADC2	10x
01101		ADC3	ADC2	10x
01110[1]		ADC2	ADC2	200x
01111[1]		ADC3	ADC2	200x
10000		ADC0	ADC1	1x
10001		ADC1	ADC1	1x
10010		ADC2	ADC1	1x
10011		ADC3	ADC1	1x
10100		ADC4	ADC1	1x
10101		ADC5	ADC1	1x
10110		ADC6	ADC1	1x
10111		ADC7	ADC1	1x
11000		ADC0	ADC2	1x
11001		ADC1	ADC2	1x
11010		ADC2	ADC2	1x
11011		ADC3	ADC2	1x
11100		ADC4	ADC2	1x

- Analogue input voltage can be selected as
  - 8 ADC pins ADC7 to ADC0,
  - the differential input between two of ADC pins.
- A gain factor of 1, 10 or 200 can be selected for differential input.

© University of Wollongong, 2011.

11.2.1b) ADC Left Adjust flag and ADCH/L registers

When bit ADLAR = 0 (Right Aligned)

ADCH	#	#	#	#	#	#	ADC9	ADC8
ADCL	ADC7	ADC6	ADC5	ADC4	ADC3	ADC2	ADC1	ADC0

When bit ADLAR = 1 (Left Aligned)

ADCH	ADC9	ADC8	ADC7	ADC6	ADC5	ADC4	ADC3	ADC2
ADCL	ADC1	ADC0	#	#	#	#	#	#

- Digital output of A-to-D conversion is stored in two 8-bit registers ADCH and ADCL.
- The format of ADCH and ADCL are interpreted differently depending on bit ADLAR.
- Important: When retrieving digital output, register ADCL must be read first, before register ADCH.

11.2.1c ADC Control and Status Register (ADCCSRA)

ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0

ADC Prescaler Select bits: next slide

ADC Interrupt Enable: 1 to enable ADC interrupt

ADC Interrupt Flag: set to 1 when conversion is completed

ADC Auto Trigger Enable: 1 to enable auto-triggering of ADC by certain events

ADC Start Conversion: 1 to start conversion

ADC Enable: 1 to enable the ADC unit

- ADC unit can operation in two modes: manual or auto-trigger.
- In manual mode, set bit ADSC will start conversion.
- In auto-trigger mode, an predefined event will start conversion.

ADC clock

Table 11.3: ADC Prescaler Selection

ADPS2	ADPS1	ADPS0	Division Factor
0	0	0	2
0	0	1	2
0	1	0	4
0	1	1	8
1	0	0	16
1	0	1	32
1	1	0	64
1	1	1	128

- The clock of the ADC is obtained by dividing the CPU clock and a division factor.
- There are 8 possible division factors, decided by the three bits {ADPS2, ADPS1, ADPS0}
- Example: Using internal clock of 1Mz and a ADC prescaler bits of '010', the clock rate of ADC is: 1MHz/4 = 250Hz.

11.2.1d Special Function IO Register (SFIOR)

ADC Auto Trigger Source bits

ADTS2	ADTS1	ADTS0	-	ACME	PUD	PSR2	PSR10

Table 11.4: ADC Auto Trigger Source

ADTS2	ADTS1	ADTS0	Trigger Source
0	0	0	Free Running mode
0	0	1	Analog Comparator
0	1	0	External Interrupt Request 0
0	1	1	Timer/Counter0 Compare Match
1	0	0	Timer/Counter0 Overflow
1	0	1	Timer/Counter1 Compare Match B
1	1	0	Timer/Counter1 Overflow
1	1	1	Timer/Counter1 Capture Event

- Three bits in register SFIOR specify the event that will auto-trigger an A-to-D conversion.

11.2.2 Steps to use the ADC

- Step 1: Configure the ADC using registers ADMUX, ADCSRA, and SFIOR.
  - What is the ADC source?
  - What reference voltage to use?
  - Align left or right the result in ADCH, ADCL?
  - Enable or disable ADC auto-trigger?
  - Enable or disable ADC interrupt?
  - What is the prescaler?
- Step 2: Start ADC operation
  - Write 1 to flag ADSC of register ADCCSRA.
- Step 3: Extract ADC result
  - Wait until flag ADSC becomes 0.
  - Read result from registers ADCL and then ADCH.

Example 11.1: Performing ADC

Write C program that repeatedly performs ADC on a sinusoidal signal and displays the result on LEDs.

- Step 1: Configure the ADC
  - What is the ADC source? ADC0
  - What reference voltage to use? AVCC = 5V
  - Align left or right? Left, top 8-bit in ADCH
  - Enable or disable ADC auto-trigger? Disable
  - Enable or disable ADC interrupt? Disable
  - What is the prescaler? 2 (fastest conversion)

Example 11.1: Performing ADC

- Step 1: Configure the ADC
  - What is the ADC source? ADC1 (pin A.1)
  - What reference voltage to use? AVCC = 5V
  - Align left or right? Left, top 8-bit in ADCH
  - Enable or disable ADC auto-trigger? Disable
  - Enable or disable ADC interrupt? Disable
  - What is the prescaler? 4 (010)

0	1	0	0	0	0	0	1	
REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0	ADCMUX

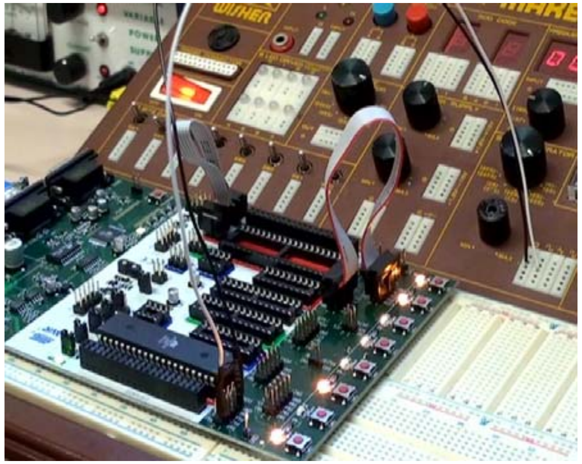
1	0	0	0	0	0	1	0	
ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCCSRA

- Steps 2 and 3: Show next in the C program.

Example 11.1: adc.c

```
#include<avr/io.h>
int main (void){
   unsigned char result;

   DDRB = 0xFF;  // set port B for output

   // Configure the ADC module of the ATmega16
   ADMUX = 0b01100000;  // REFS1:0 = 01    -> AVCC as reference,
                        // ADLAR   =  1    -> Left adjust
                        // MUX4:0  = 00000 -> ADC0 as input

   ADCSRA = 0b10000001; // ADEN = 1: enable ADC,
                        // ADSC = 0: don't start conversion yet
                        // ADATE = 0: disable auto trigger,
                        // ADIE  = 0: disable ADC interrupt
                        // ASPS2:0 = 001: prescaler = 2

   while(1){            // main loop
        // Start conversion by setting flag ADSC
        ADCSRA |= (1 << ADSC);

        // Wait until conversion is completed
        while (ADCSRA & (1 << ADSC)){;}

        // Read the top 8 bits, output to PORTB
        result = ADCH;

        PORTB = ~result;
   }
   return 0;
}
```

Example 11.1: Testing



Video demo link: [avr]/ecte333/adc.mp4

11.2.3 Using ADC interrupt

- In polling approach shown previously, we must check ADSC flag to know when result of an ADC operation is ready.
- The ADC unit can trigger an interrupt when ADC operation is completed.
- We need to enable ADC interrupt through ADIE flag in register ADCCSRA.
- In the ISR, we can write code to read the ADC result from ADCL and then ADCH register.
- ADC interrupt is usually combined with auto-trigger mode [Tutorial 11].

Example 11.2: ADC interrupt

Write interrupt-driven program to digitise a sinusoidal signal and display the result on LEDs.

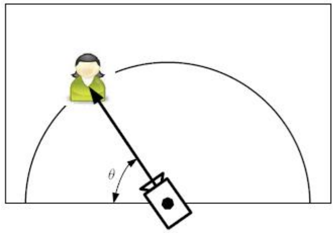
- Step 1: Configure the ADC
  - What is the ADC source? ADC0
  - What reference voltage to use? AVCC = 5V
  - Align left or right? Left, top 8-bit in ADCH
  - Enable or disable ADC auto-trigger? Disable
  - Enable or disable ADC interrupt? Enable
  - What is the prescaler? 2 (fastest conversion)
- Step 2: Start ADC operation
- Step 3: In ISR, read and store ADC result.

Example 11.2: adc_int.c

```
#include<avr/io.h>
#include<avr/interrupt.h>

volatile unsigned char result;

ISR(ADC_vect){
   result = ADCH; // Read the top 8 bits, and store in variable result
}

int main (void){
   DDRB = 0xFF;  // set port B for output

   // Configure the ADC module of the ATmega16
   ADMUX = 0b01100000;  // REFS1:0 = 01    -> AVCC as reference,
                        // ADLAR   =  1    -> Left adjust
                        // MUX4:0  = 00000 -> ADC0 as input

   ADCSRA = 0b10001111; // ADEN = 1: enable ADC,
                        // ADSC = 0: don't start conversion yet
                        // ADATE = 0: diable auto trigger,
                        // ADIE  = 1: enable ADC interrupt
                        // ASPS2:0 = 002: prescaler = 2

   sei();               // enable interrupt system globally
   while(1){            // main loop
        ADCSRA |= (1 << ADSC); // start a conversion

        PORTB = ~result;       // display on port B
   }
   return 0;
}
```

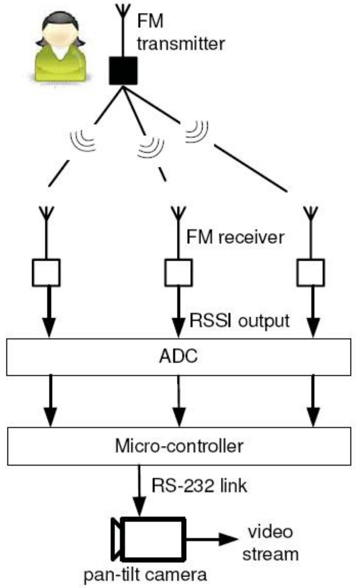
11.3 Example application of the ADC

- This section presents an application of the ADC in ATmega16 to track the movements of an object in an indoor environment.
- The motivation is to control a video camera to follow a speaker as he or she moves in a room.

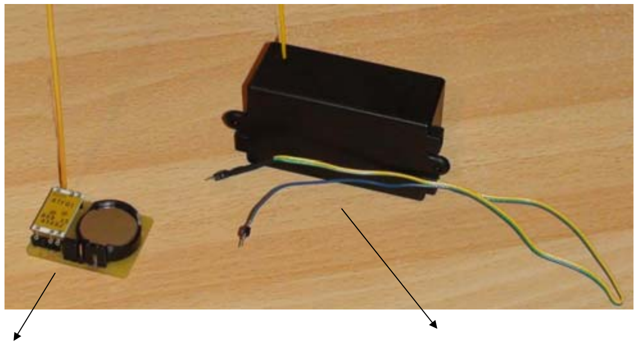


Example application of the ADC

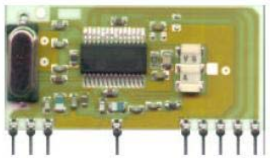
- The speaker will keep a small FM transmitter.
- 3 FM receivers at 3 different points are used to provide the received signal strengths.
- The received signal strength is inversely proportional to the distance.
- The Receiver Signal Strength Indicator (RSSI) is an analogue voltage.
- ATmega16 is used to digitise and process RSSI inputs.



Example application of the ADC



FM Transmitter @ 443MHz
RS part no: FM-RTFQ1



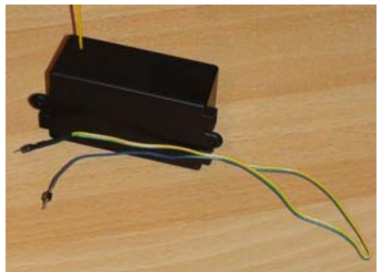
FM Receiver @ 433 MHz
RS part no: FM-RTFQ2

3 pins are used:
* GRD pin (green wire)
* 5V supply pin (yellow)
* RSSI pin (blue)

Example 11.3: Digitising RSSI output

Write ATmega16 program to digitise the RSSI output of an FM receiver.

- Hardware connection
  - GRD pin (green) of FM receiver → GRD of STK500 board.
  - 5V-supply pin (yellow) of FM receiver → VTG of STK500 board.
  - RSSI pin (blue) of FM receiver → ADC1 (A.1) of ATmega16.



Example 11.3: Digitising RSSI output

- **Step 1**: Configure the ADC
  - What is the ADC source? ADC1
  - What reference voltage to use? AVCC = 5V
  - Align left or right? Right, bottom 8-bit in ADCL
  - Enable or disable ADC auto-trigger? Disable
  - Enable or disable ADC interrupt? Disable
  - What is the prescaler? 128 (slowest conversion)

0	1	0	0	0	0	0	1	
REFS1	REFS0	ADLAR	MUX4	MUX3	MUX2	MUX1	MUX0	ADCMUX

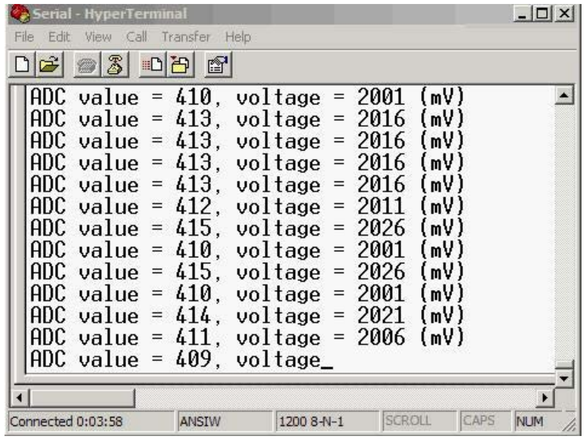
1	0	0	0	0	1	1	1	
ADEN	ADSC	ADATE	ADIF	ADIE	ADPS2	ADPS1	ADPS0	ADCCSRA

- **Steps 2 and 3**: Show next in C program.

Example 11.3: adc_rssi.c

```
#include<avr/io.h>
#include<avr/interrupt.h>
int main (void){
    unsigned int result_low, result_high, result;
    unsigned long voltage;
    // Serial port code ...
    DDRB = 0xFF;  // set port B for output

    // Configure the ADC module of the ATmega16
    ADMUX = 0b01000001;  // REFS1:0 = 01    -> AVCC as reference,
                         // ADLAR   =  0    -> Right adjust
                         // MUX4:0  = 00001 -> ADC1 as input
    ADCSRA = 0b10000111; // ADEN = 1: enable ADC,
                         // ADSC = 0: don't start conversion yet
                         // ADATE = 0: disable auto trigger,
                         // ADIE  = 0: disable ADC interrupt
                         // ASPS2:0 = 111: prescaler = 128
    while(1){
        ADCSRA |= (1 << ADSC);            // Start conversion by setting flag ADSC

        while (ADCSRA & (1 << ADSC)){;} // Wait until conversion is completed

        // Read digital output
        result_low  = ADCL;               // low 8 bits in ADCL
        result_high = ADCH & 0b00000011; // bit 8 and 9 in ADCH
        result = result_high * 256 + result_low;
        voltage = ((unsigned long) result * 5000ul)/ 1024ul;

        // Serial port code ...
        PORTB = ~result_low;
        delay();
    }
    return 0;
}
```


Example 11.3: Testing



Video demo link: [avr]/ecte333/adc_rssi.mp4
[An live demo will be shown in the lecture theatre]

Lecture 11's summary

- **What we learnt in this lecture**:
  - Analogue-to-digital conversion process.
  - Sampling and quantization steps.
  - Using the ADC in the ATmega16 microcontroller.
  - An example application of ADC.
- **What are the next activities?**
  - Tutorial 11: 'Analogue-to-Digital Converter'.
  - Lab 11: 'Analogue-to-Digital Converter'.
    - Complete the online Pre-lab Quiz for Lab 11.
    - Write programs for Tasks 1 and 2 of Lab 11.
    - See video demos of Lab 11: [avr]/ecte333/lab11_task1.mp4
      [avr]/ecte333/lab11_task2.mp4

Lecture 11 references

- Atmel Corp., 8-bit AVR microcontroller with 16K Bytes In-System Programmable Flash ATmega16/ATmega16L, 2007, [Analog to Digital Converter]. **Manual**

- S. F. Barrett and D. J. Pack, Atmel AVR Microcontroller Primer: Programming and Interfacing, 2008, Morgan & Claypool Publishers, [Chapter 3: Analog-to-Digital Conversion].

Lecture 11 references

- M. Mazidi, J. Mazidi, R. McKinlay, "The 8051 microcontroller and embedded systems using assembly and C," 2nd ed., Pearson Prentice Hall, 2006, [Chapters 13.1].

- P. Spasov, "Microcontroller technology the 68HC11," 3rd ed., Prentice Hall, 1999, [Chapters 12].

- H. Huang, "MC68HC12 an introduction: software and hardware interfacing," Thomson Delmar Learning, 2003, [Chapter 10].