Newbie's Guide to the AVR ADC

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What is an ADC?

An ADC, or Analog to Digital Converter, allows one to convert an analog voltage to a digital value that can be used by a microcontroller. There are many sources of analog signals that one might like to measure. There are analog sensors available that measure temperature, light intensity, distance, position, and force, just to name a few.

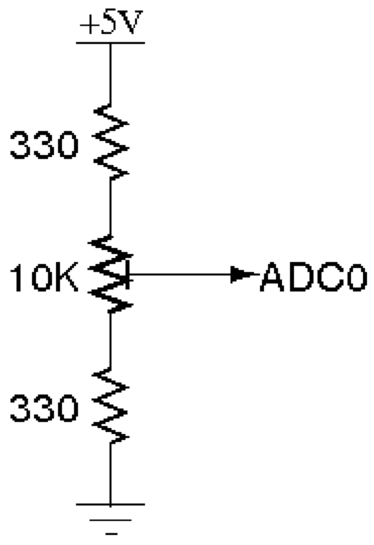
Introduction The AVR ADC

The AVR ADC allows the AVR microcontroller to convert analog voltages to digital values with few to no external parts. The author wrote this tutorial with the ATMega128 in mind, though other AVRs use similar hardware. The ADC built into the ATMega128 is capable of 10 bit resolution. The ATMega128 microcontroller has 8 ADC channels, allowing up to 8 analog sources to be attached to the microcontroller. The 8 ADC channels are connected to the internal DAC through a device called a multiplexer. The multiplexer connects the 8 ADC channels (the 8 pins of Port F on the ATMega128) to the internal ADC. One channel at a time is passed through the multiplexer to the ADC. The ADC has its own power supply, labeled AVCC, on the ATMega128. This pin needs to be connected to a power source within .3 volts of the chip's VCC supply. Most of the time, you would wire this to VCC. With the 10 bit DAC, this allows measuring voltages from 0 to 5 volts with a resolution of 5/1024 volts, or 4.88 mV.

The ADC channels in the ATMega128 can be configured in several different ways. In this tutorial, the channels are being used in single-ended mode. In this mode, the analog voltages presented on the ADC channels are compared to ground. There are several selectable voltage references, which determine the range of the ADC conversion. In this tutorial, AVCC is used as the voltage reference. The ADC can also be set to run continuously (the free-running mode) or to do only one conversion. The first example in this tutorial uses the free-running mode to continuously update the ADC reading.

Part 1 A Simple Free-Running ADC Example

This example uses the simplest variable voltage source I could think of a potentiometer. I wired up a 10k potentiometer on a breadboard as in the example below.



The two outside terminals were attached to 5 volts and ground, with the center terminal attached to the first ADC channel. The two 330 ohm resistors protect the microcontroller pin from being shorted to ground or to 5 volts at the edges of the potentiometer's travel. With this setup, turning the potentiometer will give you a range of .15 volts to 4.85 volts between ground and ADC0. In order to read the voltage of this circuit, its ground and the ground of the microcontroller need to be connected.

To give an indication of the value the ADC is reading, two LEDs are hooked to the microcontroller. We can toggle these to give us a high or low indication. Here is the pseudocode for this example:

Code:
```
Set up output LEDs
Configure ADC Hardware
Enable ADC
Start A2D Conversions

WHILE Forever
    IF ADC Value High, Turn on LED1
    ELSE Turn on LED2
END WHILE
```

To simplify this example, we will set up the ADC to continuously measure the voltage on ADC0. We will then poll the value in an endless loop and change the LEDs' statuses as we need to. The skeleton code for our example would then be:

Code:
```
#include <avr/io.h>

int main (void)
{
   DDRE |= (1 << 2); // Set LED1 as output
   DDRG |= (1 << 0); // Set LED2 as output

   // TODO:  Configure ADC Hardware
   // TODO: Enable ADC
   // TODO: Start A2D Conversions

for(;;)  // Loop Forever
   {
      // TODO: Test ADC Value and set LEDs
   }
}
```

Setting up the LEDs is outside the topic of this tutorial, so the code to set them up is shown above without explanation. You can use any unused i/o line for the LEDs. Check out the Programming 101 tutorial on the AVRFreaks forum for more information on this if you need it.

The next step is to configure the ADC hardware. This is done through setting bits in the control registers for the ADC. First, let's set the prescalar for the ADC. According to the datasheet, this prescalar needs to be set so that the ADC input frequency is between 50 KHz and 200 KHz. The ADC clock is derived from the system clock. With a system frequency of 16 MHz, a prescaler of 128 will result in an ADC frequency of 125 Khz. The prescaling is set by the ADPS bits in the ADCSRA register. According to the datasheet, all three ADPS bits must be set to get the 128 prescaler.

Code:

```
ADCSRA |= (1 << ADPS2) | (1 << ADPS1) | (1 << ADPS0);
```

Next, let's set the ADC reference voltage. This is controlled by the REFS bits in the ADMUX register. The following sets the reference voltage to AVCC.

Code:

```
ADMUX |= (1 << REFS0);
```

To set the channel passed through the multiplexer to the ADC, the MUX bits in the ADMUX register need to be set accordingly. Since we are using ADC0 here, which corresponds with all 5 MUX bits being zero, we don't need to set anything here.

In order to put the ADC into free-running mode, set the aptly-named ADFR bit in the ADCSRA register:

Code:

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

One last settings change will be made to make reading the ADC value simpler. Though the ADC has a resolution of 10 bits, this much information is often not necessary. This 10 bit value is split across two 8 bit registers, ADCH and ADCL. By default, the lowest 8 bits of the ADC value are found in ADCL, with the upper two being the lowest two bits of ADCH. By setting the ADLAR bit in the ADMUX register, we can left align the ADC value. This puts the highest 8 bits of the measurement in the ADCH register, with the rest in the ADCL register. If we then read the ADCH register, we get an 8 bit value that represents our 0 to 5 volt measurement as a number from 0 to 255. We're basically turning our 10 bit ADC measurement into an 8 bit one. Here's the code to set the ADLAR bit:

Code:

```
ADMUX |= (1 << ADLAR);
```

That completes the setup of the ADC hardware for this example. Two more bits need to be set before the ADC will start taking measurements. To enable the ADC, set the ADEN bit in ADCSRA:

Code:

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

To start the ADC measurements, the ADSC bit in ADCSRA needs to be set:

Code:

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

At this point, the ADC would begin continuously sampling the voltage presented on ADC0. The code to this point would look like this:

Code:

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

int main (void)
{
   DDRE |= (1 << 2); // Set LED1 as output
   DDRG |= (1 << 0); // Set LED2 as output

   ADCSRA |= (1 << ADPS2) | (1 << ADPS1) | (1 << ADPS0); // Set ADC prescalar to 128 - 125KHz sample rate @ 16MHz

   ADMUX |= (1 << REFS0); // Set ADC reference to AVCC
   ADMUX |= (1 << ADLAR); // Left adjust ADC result to allow easy 8 bit reading

   // No MUX values needed to be changed to use ADC0

   ADCSRA |= (1 << ADFR);  // Set ADC to Free-Running Mode
```

```
    ADCSRA |= (1 << ADEN);  // Enable ADC
    ADCSRA |= (1 << ADSC);  // Start A2D Conversions

    for(;;)  // Loop Forever
    {
        // TODO: Test ADC Value and set LEDs
    }
}
```

The only thing left to do is test the ADC value and set the LEDs to display a high / low indication. Since the ADC reading in ADCH has a maximum value of 255, a test value of 128 was chosen to determine whether the voltage was high or low. A simple IF/ELSE statement in the FOR loop will allow us to turn the correct LED on:

Code:

```
if(ADCH < 128)
        {
            PORTE |= (1 << 2); // Turn on LED1
            PORTG &= ~(1 << 0); // Turn off LED2
        }

        else
        {
            PORTE &= ~(1 << 2); // Turn off LED1
            PORTG |= (1 << 0); // Turn on LED2
        }
```

Again, if the notation used above is unclear, the Programming 101 tutorial at AVRFreaks forum gives a great explanation.

Here's the finished program with comments. When compiled and downloaded to an ATMega128, LED1 will be lit for roughly half the rotation of the potentiometer, indicating a low voltage reading. Near the halfway point of the potentiometer's rotation, LED1 will go out and LED2 will light. Indicating a high voltage reading. By changing the tests in the FOR loop, one could get different voltage indications with two or more LEDs.

Code:

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

int main (void)
{
    DDRE |= (1 << 2); // Set LED1 as output
    DDRG |= (1 << 0); // Set LED2 as output

    ADCSRA |= (1 << ADPS2) | (1 << ADPS1) | (1 << ADPS0); // Set ADC prescalar to 128 - 125KHz sample rate @ 16MHz

    ADMUX |= (1 << REFS0); // Set ADC reference to AVCC
    ADMUX |= (1 << ADLAR); // Left adjust ADC result to allow easy 8 bit reading

    // No MUX values needed to be changed to use ADC0

    ADCSRA |= (1 << ADFR);  // Set ADC to Free-Running Mode
    ADCSRA |= (1 << ADEN);  // Enable ADC
    ADCSRA |= (1 << ADSC);  // Start A2D Conversions

    for(;;)  // Loop Forever
    {
        if(ADCH < 128)
        {
            PORTE |= (1 << 2); // Turn on LED1
            PORTG &= ~(1 << 0); // Turn off LED2
        }

        else
        {
            PORTE &= ~(1 << 2); // Turn off LED1
            PORTG |= (1 << 0); // Turn on LED2
        }

    }

}
```

Part 2 An Interrupt-Driven Example

Let's improve the first example so that we can run the LED IF loop in the background. It takes 13 cycles of the ADC clock to perform one A2D conversion in free-running mode according to the datasheet. With a prescaler of 128 as in the previous example, there are 13x128, or 1664, system clock cycles between each A2D conversions. If our short IF loop can be run only after an A2D conversion, this allows considerable processing time to be dedicated to other tasks.

Microcontrollers allow this kind of program execution using something called interrupts. Certain pieces of hardware within the microcontroller can signal that a certain task has been completed. Normal program execution can be interrupted when one of these signals (the interrupt) is asserted. Depending on the interrupt signal, different user-defined programs, called interrupt service routines or ISRs, can be run. After the ISR completes, normal program execution resumes.

The AVR ADC has an interrupt associated with it that is asserted when an A2D conversion completes. There are several changes that need to make to the first example to utilize this interrupt. First, let's write the ISR that will be run when the interrupt is asserted.

The first step in using interrupts in our application is to add the standard library header avr/interrupt.h. This file defines functions and macros needed to utilize interrupts on the AVR. The following line should be added below the io.h define in our original program.

Code:

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

Next, we'll define the ISR itself. To do this, we need the name of the interrupt we are connecting to the ISR. Referring to the datasheet, we find the name of the interrupt we want to use ADC, which is asserted when an A2C conversion completes. Here is the proper format for an ISR using the ADC interrupt:

Code:

```
ISR(ADC_vect)
{
   // Code to be executed when ISR fires
}
```

Now, we place the IF statement originally in the infinite loop inside the ISR, so it will only be run when the ADC interrupt indicates a conversion has been completed:

Code:

```
ISR(ADC_vect)
{
   if(ADCH < 128)
      {
         PORTE |= (1 << 2); // Turn on LED1
         PORTG &= ~(1 << 0); // Turn off LED2
      }

      else
      {
         PORTE &= ~(1 << 2); // Turn off LED1
         PORTG |= (1 << 0); // Turn on LED2
      }
}
```

At this point, the program has an ISR defined. However, the ISR will never execute. Interrupts on the AVR need to be enabled before they will run. This is done in two steps. First, the interrupt capability of the microprocessor needs to be enabled. This is done with the sei() function call, defined in interrupt.h to simplify this process. Next, the ADC interrupt needs to be enabled. This is done by setting the ADIE bit in the ADCSRA register. The following two lines enable the ADC interrupt:

Code:

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

We can now combine the new interrupt code with our first example. We will insert the ISR after the main loop. The interrupt enable lines will be inserted before we start the A2D conversions. The FOR loop is now empty, as the code we had there originally has been moved to the ISR. Other code could be inserted here to run between ISR calls. The full code is shown below.

Code:

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

int main (void)
{
   DDRE |= (1 << 2); // Set LED1 as output
   DDRG |= (1 << 0); // Set LED2 as output

   ADCSRA |= (1 << ADPS2) | (1 << ADPS1) | (1 << ADPS0); // Set ADC prescaler to 128 - 125KHz sample rate @ 16MHz

   ADMUX |= (1 << REFS0); // Set ADC reference to AVCC
   ADMUX |= (1 << ADLAR); // Left adjust ADC result to allow easy 8 bit reading

   // No MUX values needed to be changed to use ADC0

   ADCSRA |= (1 << ADFR);  // Set ADC to Free-Running Mode
   ADCSRA |= (1 << ADEN);  // Enable ADC

   ADCSRA |= (1 << ADIE);  // Enable ADC Interrupt
   sei();    // Enable Global Interrupts

   ADCSRA |= (1 << ADSC);  // Start A2D Conversions

   for(;;)  // Loop Forever
   {
   }
}

ISR(ADC_vect)
{
   if(ADCH < 128)
   {
      PORTE |= (1 << 2); // Turn on LED1
      PORTG &= ~(1 << 0); // Turn off LED2
   }

   else
   {
      PORTE &= ~(1 << 2); // Turn off LED1
      PORTG |= (1 << 0); // Turn on LED2
```

```
    }
}
```