电子科技大学
University of Electronic Science and Technology of China

University of Glasgow

UESTC1008: Microelectronic Systems

Digital to Analogue Conversion (DAC)

Lecture 6

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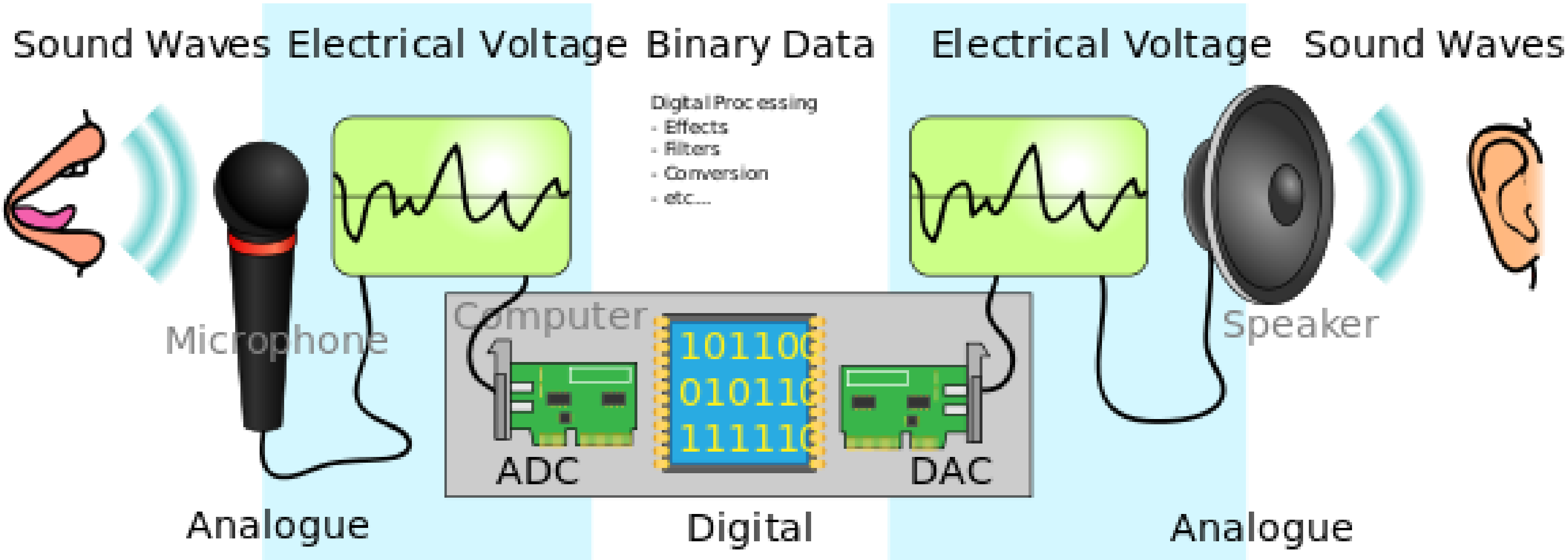
Why is conversion needed?

- The other day I went to the market to buy something. The sales girl would not understand English. How do we communicate then?
  - Use Translator >>> Language Converter
- Digital devices (PCs, Phones etc.) want to connect to real world but real world is Analogue and computer world is Digital. How to make them talk?

Why is conversion needed?

- Most signals in the world are analogue
- Microprocessors and most computers use digital signals
  - Analogue to Digital Converters (ADCs) change analogue signals to digital signals that are then used by the microprocessor
  - Digital to Analogue Converters (DACs) may be used to change digital signals to analogue signals that are then used by the peripherals attached to the microprocessor

Why is conversion needed?

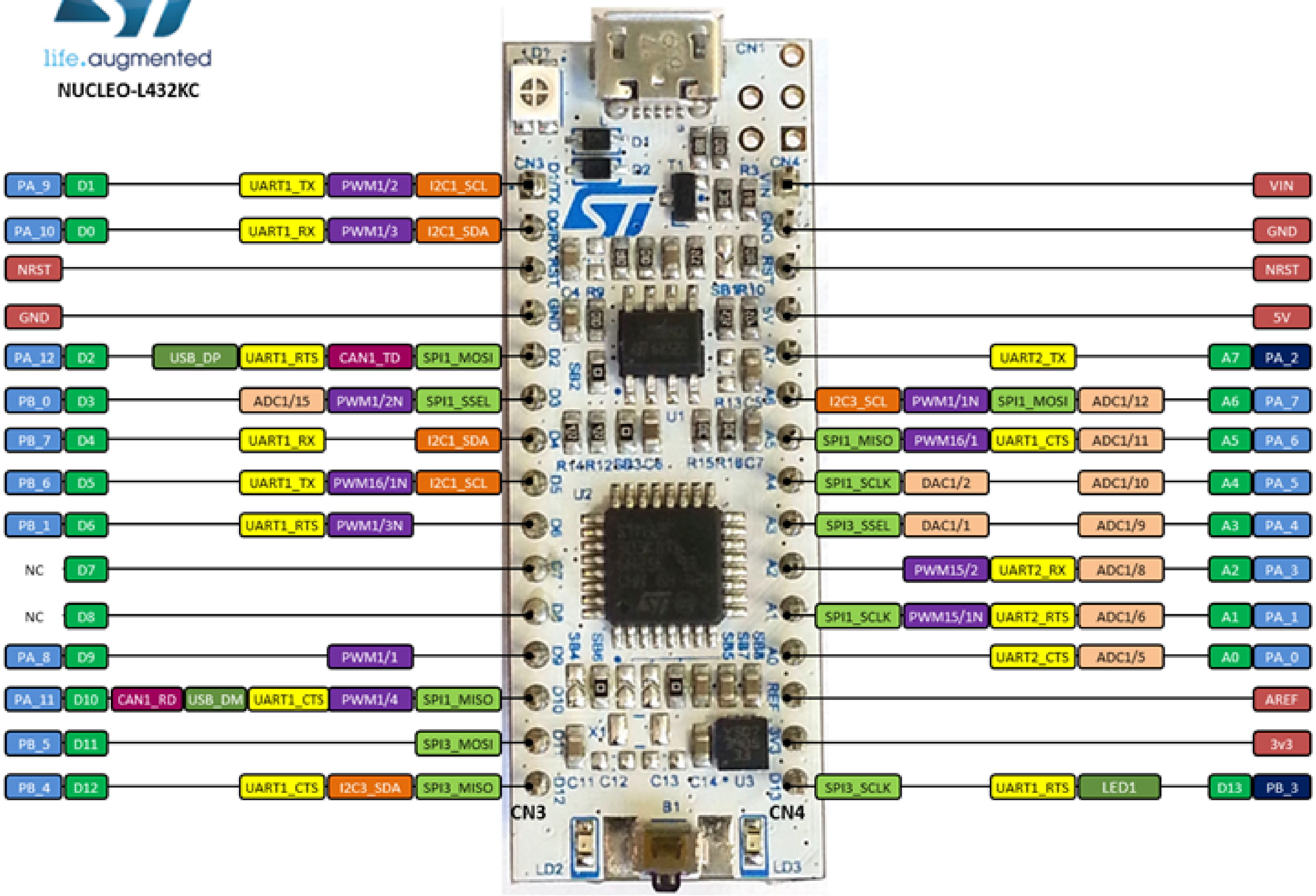


ADCs and DACs

- ADCs tend to be more common on a microprocessor.
  - The number of peripherals that have ADCs and DACs integrated inside is increasing so the microprocessor may not need this capability in the future.
    - Why? Because more peripherals are manufactured with integrated ADCs. However, you then need to decide type of format that the digitized data will be transferred to your microprocessor
      - Examples: I^2C, CAN, SPI, ethernet, USB

mbed – ADC and DAC pins

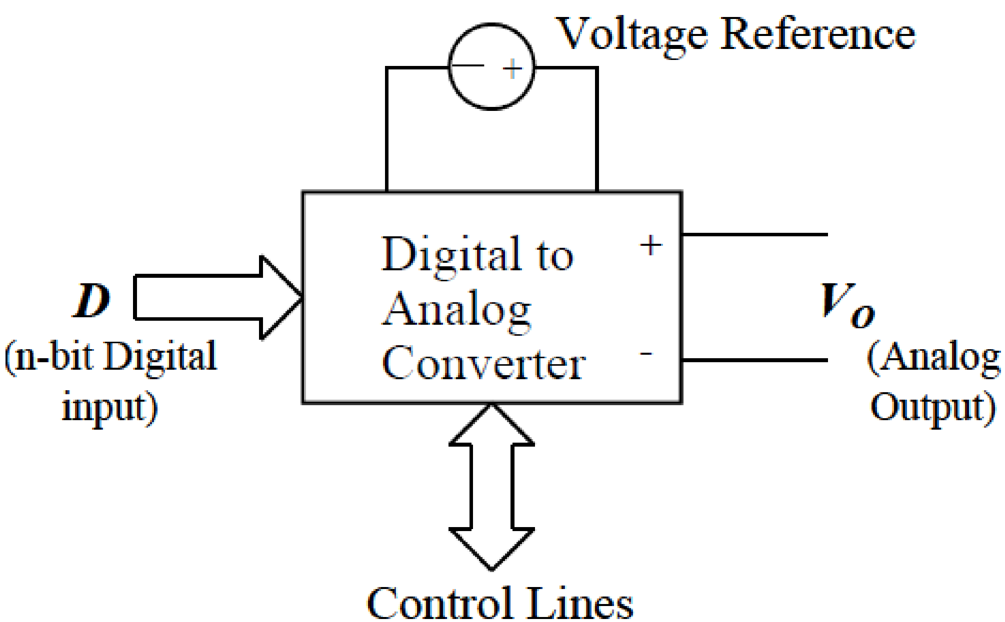
life.augmented
NUCLEO-L432KC



XXX AnalogIn (ADC) and AnalogOut pins (DAC)

Digital to Analogue Conversion (DAC)

- Want to convert a binary input number into an analogue output. As a block diagram, we are looking at something like



- D is the digital input.
- Vo is the Analog output.
- V_r is a precise, stable, known voltage reference,
- There are some control lines that are used to determine how often the DAC should convert the input signal, for example.

Digital to Analog Conversion (DAC)

For each digital input value, there is a corresponding analogue output voltage.

Number of possible output voltages is 2^n (is number of bits in the word)

Output step size, the **resolution**, is $\frac{V_r}{2^n}$

Maximum possible output value occurs when $D = (2^n-1)$, so value of V_r as an output is never reached. eg 3 bit DAC, V_r=3V

D	V_{OUT}	
000	0	
001	3/8 V	(0.375 V)
010	6/8 V	(0.75 V)
011	9/8 V	(1.125 V)
100	12/8 V	(1.5 V)
101	15/8 V	(1.875 V)
110	18/8 V	(2.25 V)
111	21/8 V	(2.625 V)

DAC - Example

- A bit sequence 010101011001110 (starts with 010) is given at the input of a 3-bit DAC. Draw the analogue output waveform.

D	V_{OUT}	
000	0	
001	3/8 V	(0.375 V)
010	6/8 V	(0.75 V)
011	9/8 V	(1.125 V)
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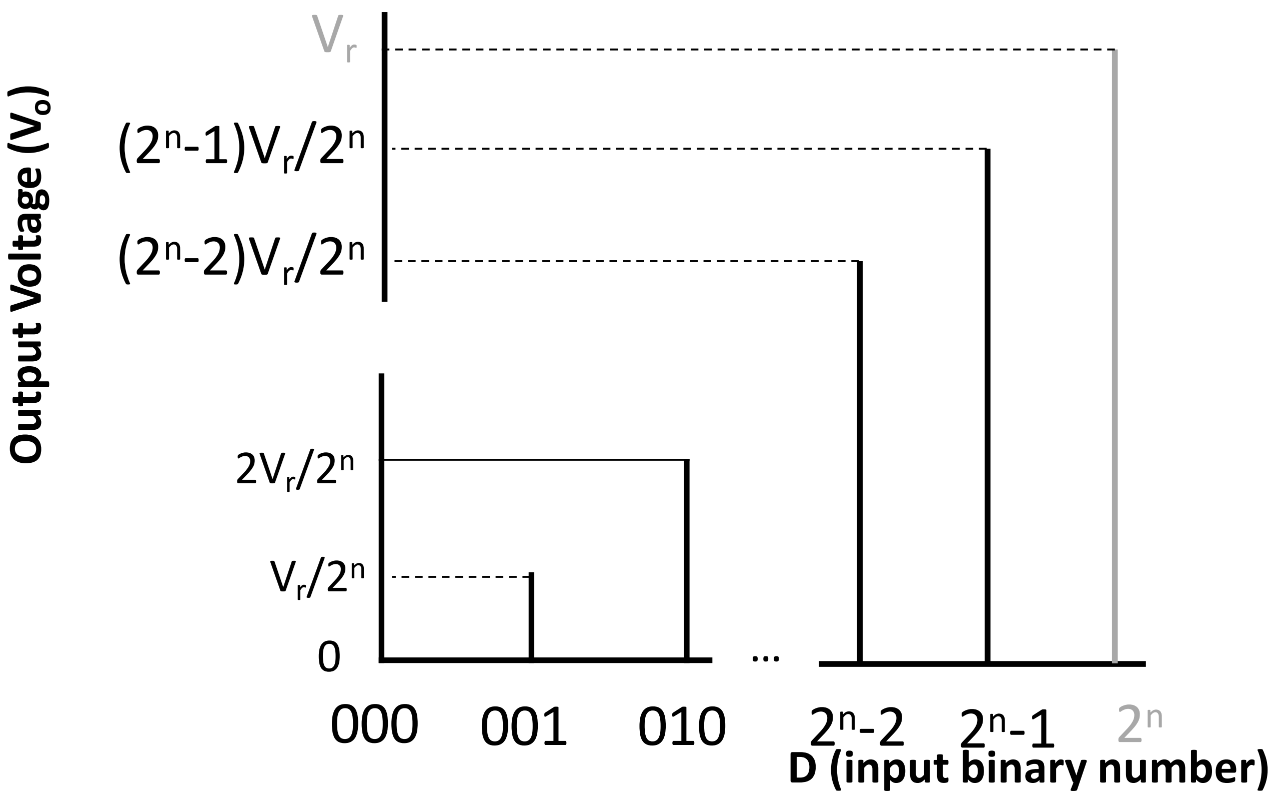
Output values

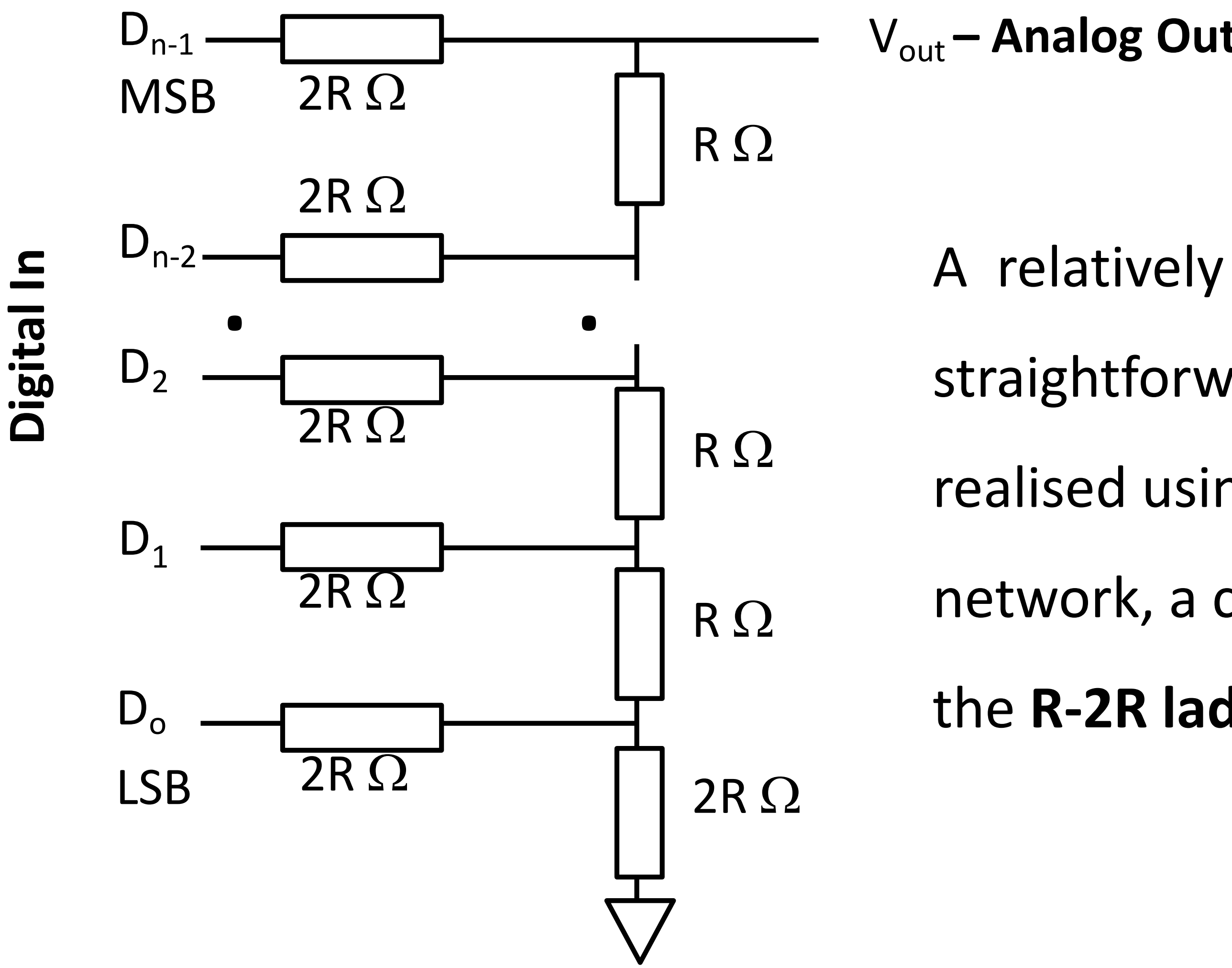
A simple relationship usually relates the digital input to the analog output, such as

$$V_o = \frac{D}{2^n} V_r$$

V_o is the analog output voltage
D is the value of the binary input word
n is the number of bits in the input word
V_r is the value of the voltage reference



Construction: R-2R ladder



A relatively straightforward DAC can be realised using a resistor network, a common type is the **R-2R ladder**

Analog Output

- The **range** of the DAC is the difference between the maximum and minimum output values

- The **resolution** of the DAC is the step size between each analog value

- **Conversion speed** is the inverse of the time that it takes the DAC to act on changes to the input

Key Features of the STM32L432KC

- Ultra-low-power with FlexPowerControl
    - 1.71 V to 3.6 V power supply
    - -40 ° C to 85/105/125 ° C temperature range
    - 8 nA Shutdown mode (2 wakeup pins)
    - 28 nA Standby mode (2 wakeup pins)
    - 280 nA Standby mode with RTC
    - 1.0 µA Stop 2 mode, 1.28 µA with RTC
    - 84 µA/MHz run mode
    - Batch acquisition mode (BAM)
    - 4 µs wakeup from Stop mode
    - Brown out reset (BOR)
    - Interconnect matrix
- Core: Arm® 32-bit Cortex®-M4 CPU with FPU, Adaptive real-time accelerator (ART Accelerator™) allowing 0-wait-state execution from Flash memory, frequency up to 80 MHz, MPU, 100DMIPS and DSP instruction

- Memories
    - Up to 256 KB single bank Flash, proprietary code readout protection
    - 64 KB of SRAM including 16 KB with hardware parity check
    - Quad SPI memory interface
- Rich analog peripherals (independent supply)
    - 1x 12-bit ADC 5 Msps, up to 16-bit with hardware oversampling, 200 µA/Msps
    - 2x 12-bit DAC output channels, low-power sample and hold
    - 1x operational amplifier with built-in PGA
    - 2x ultra-low-power comparators
- 14x communication interfaces
    - USB 2.0 full-speed crystal less solution with LPM and BCD
    - 1x SAI (serial audio interface)
    - 2x I2C FM+(1 Mbit/s), SMBus/PMBus

mbed - Example

- The L432kc has a 12 bit DAC, and uses its regulated 3.3 V power supply as the voltage reference.
  - What are
    a) the number of steps,
    b) the resolution,
    c) the range, and
    d) the conversion speed of the L432kc DAC? Assume that it takes 5μs per conversion.
    e) How many clock cycles does this conversion take?

mbed - Example

- The mbed L432kc chip has a 12-bit DAC (i.e. n = 12)
- The mbed uses its own 3.3 V power supply as voltage reference
  a) There will therefore be 2^n steps in the mbed DAC output characteristic, i.e. 4096.
  b) The step size, or resolution, is therefore be 3.3/4096, i.e. 0.8056mV per bit
  c) The range is $(2^{12} – 1)/ 2^{12} * 3.3 = 3.299$ V
  d) The conversion speed is 200,000/s.
  e) The clock speed is 80 MHz so the conversion time is equivalent to 400 clock cycles
- There is another specification called the sampling frequency. The maximum sampling frequency provides a limit to the speed at which the digital signal can be sent to the DAC

Digital to Analog Conversion (DAC)

It is relatively easy to check the resolution of the DAC.

For example, create an extremely slow sawtooth. In this case, it takes 10,000 steps to reach the max value with a 1 second interval between each step. The period of the waveform is about 2 hours 45 minutes, but this is not the point.

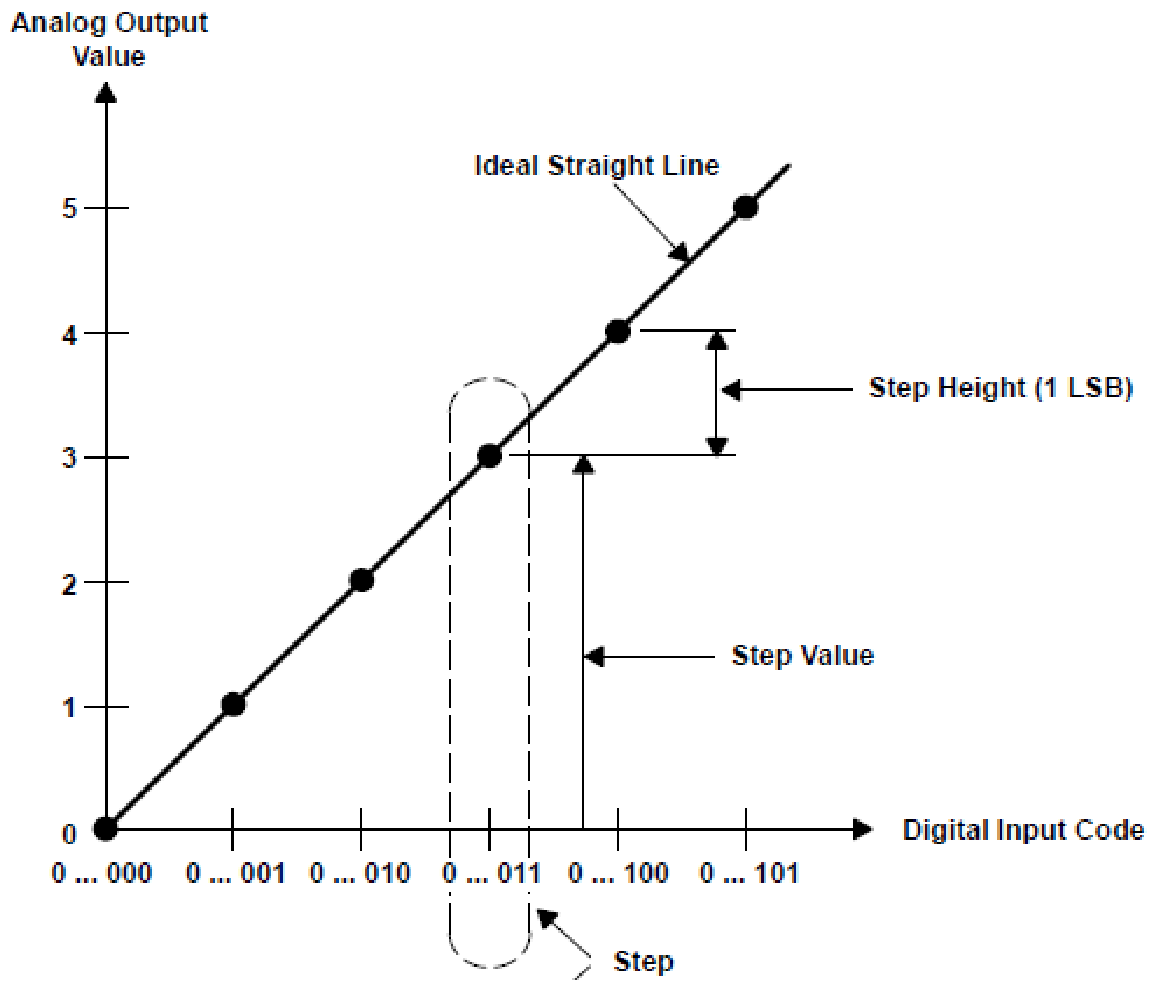
```
/* Program to check DAC resolution of mbed*/
#include "mbed.h"
AnalogOut Aout(A4);
DigitalOut led1(LED1);
float i;
int main(){
  while(1){
    for (i=0;i<1;i=i+0.0001){
      Aout=i;
      wait(1);
      led1=!led1;
    }
  }
}
```

Note: By the end of this course, you should be able to go through a simple program and describe what each line of code means and what the mbed will do as a result. You should also be able to write a simple program for the mbed .

Measurement

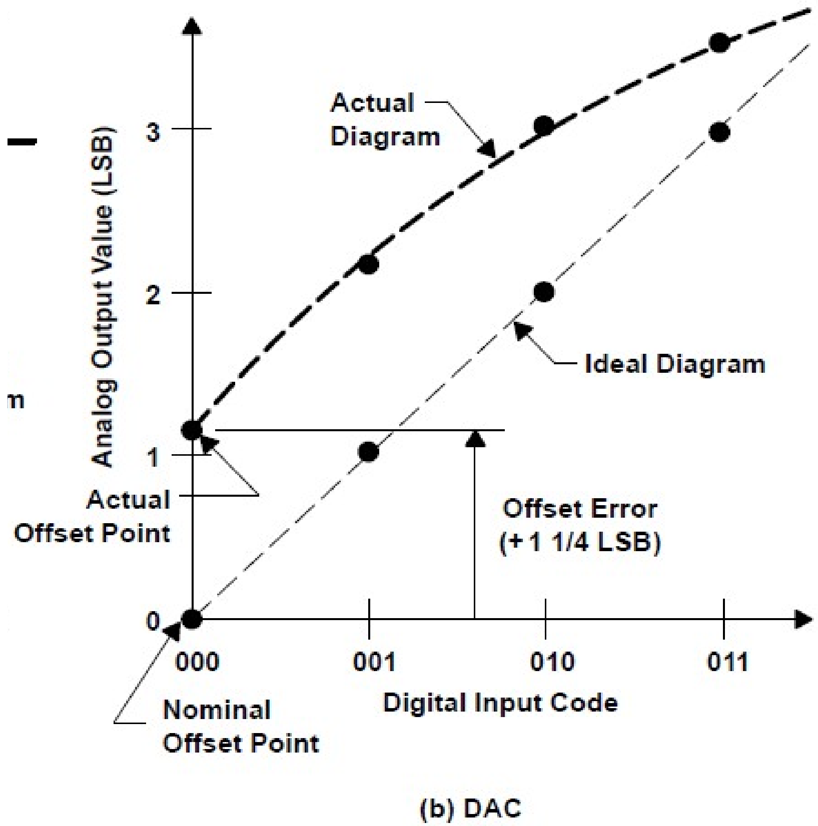
- Connect the AnalogOut pin to a voltmeter or an oscilloscope
- LED flashes each time that a new analog value is outputted by the DAC
- However, 10,000 is larger than the maximum number of steps for the mbed DAC
- So, the DAC output voltage only changes on approximately every 3rd step and when it does, the output voltage changes by about .80 mV
- The float value is rounded to the nearest digital input to the DAC

Ideal DAC



From Understanding Data Converters, Texas Instruments Application Note

Offset Error



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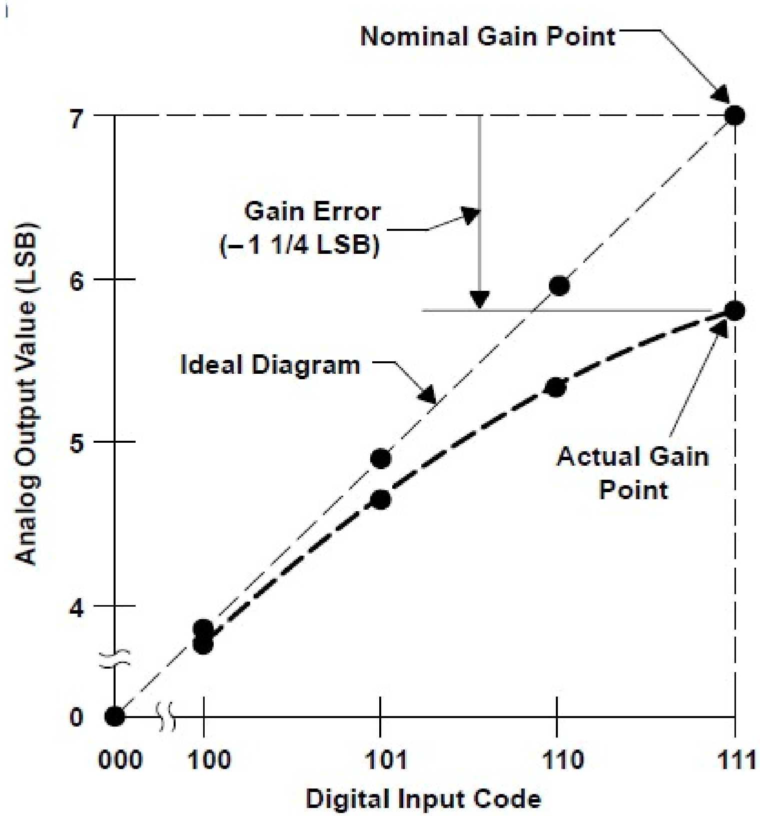
Gain Error

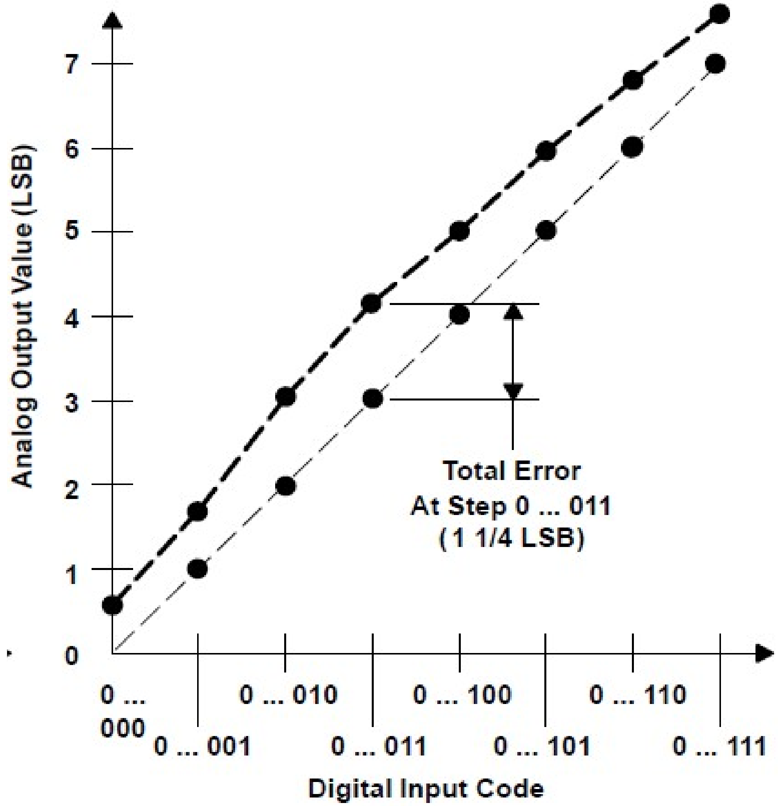


(b) DAC

From Understanding Data Converters, Texas Instruments Application Note

Total Error

Gain Error
Offset Error
Nonlinearity Error



(b) DAC

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