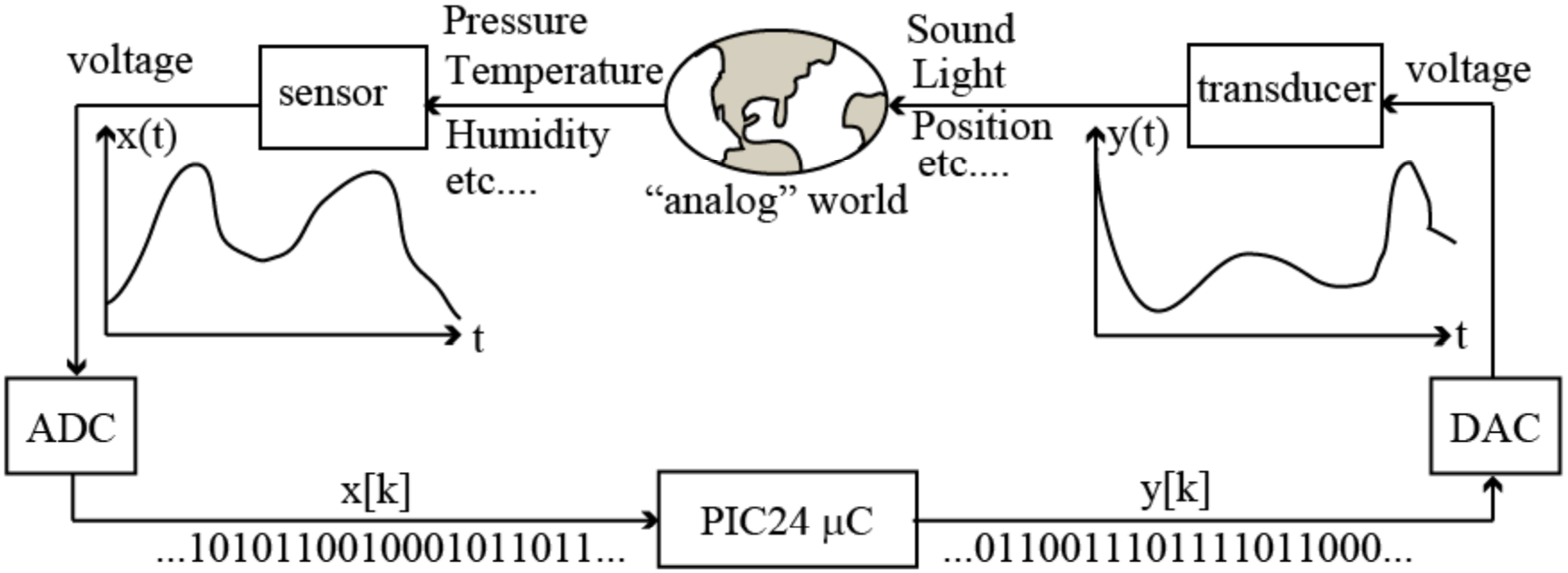
Digital Signal Processing



Analog-to-Digital Converter (ADC) converts an input analog value to an output digital representation.

This digital data is processed by a microprocessor and output to a Digital-to-Analog Converter (DAC) the converts an input binary value to an output voltage.

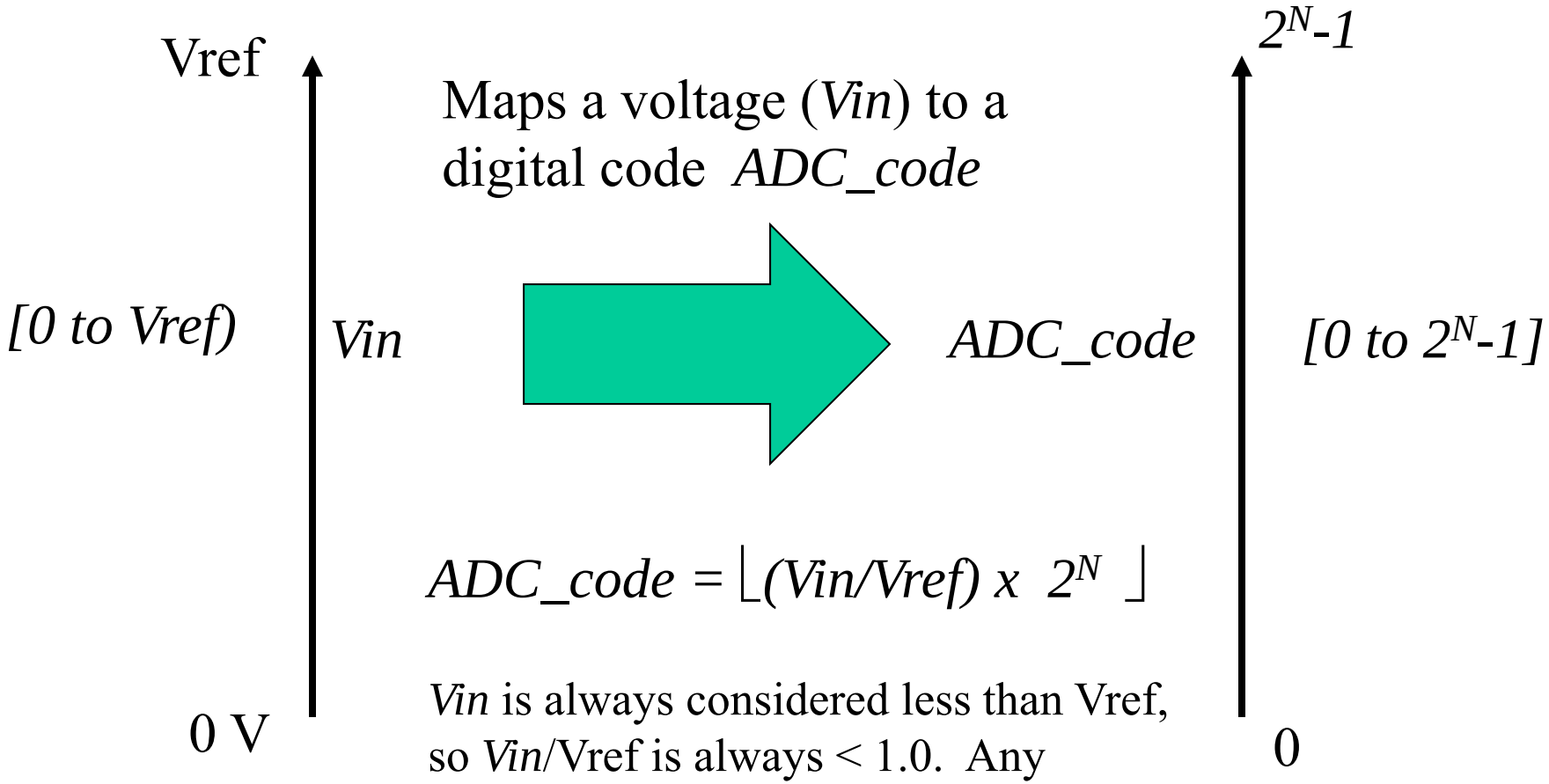
Applications

- Audio
  - Speech recognition
  - special effects (reverb, noise cancellation, etc)
- Video
  - Filtering
  - Special effects
  - Compression
- Data logging

Vocabulary

- ADC (Analog-to-Digital Converter) – converts an analog signal (voltage/current) to a digital code
- DAC (Digital-to-Analog Converter) – converts a digital code to an analog value (voltage/current)
- Sample period – for ADC, time between each conversion
  - Typically, samples are taken at a fixed rate
- Vref (Reference Voltage) – analog signal varies between 0 and Vref, or between +/- Vref
- Resolution – number of bits used for conversion (8 bits, 10 bits, 12 bits, 16 bits, etc).
- Conversion Time – the time it takes for an analog-to-digital conversion

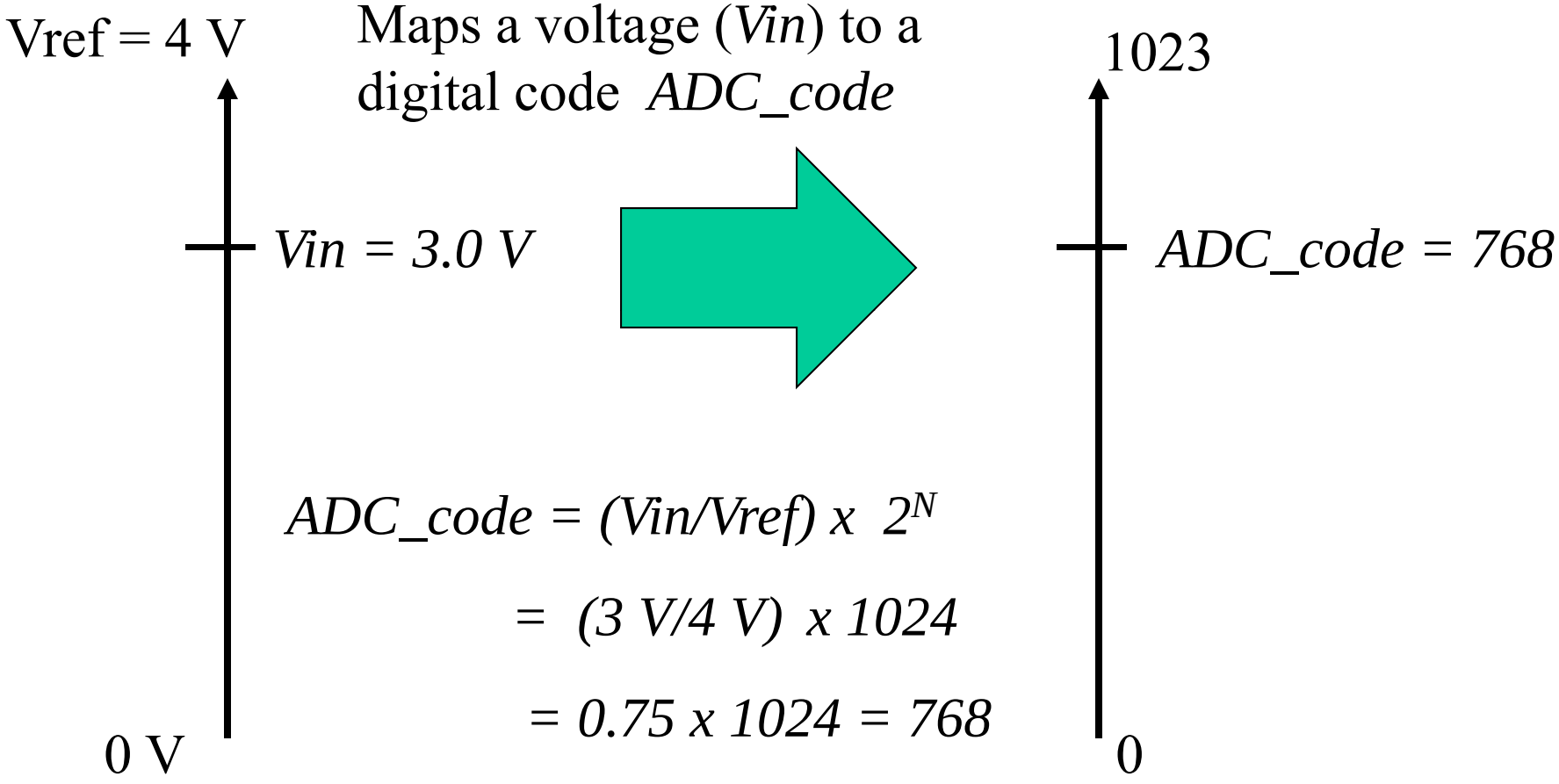
An N-bit ADC



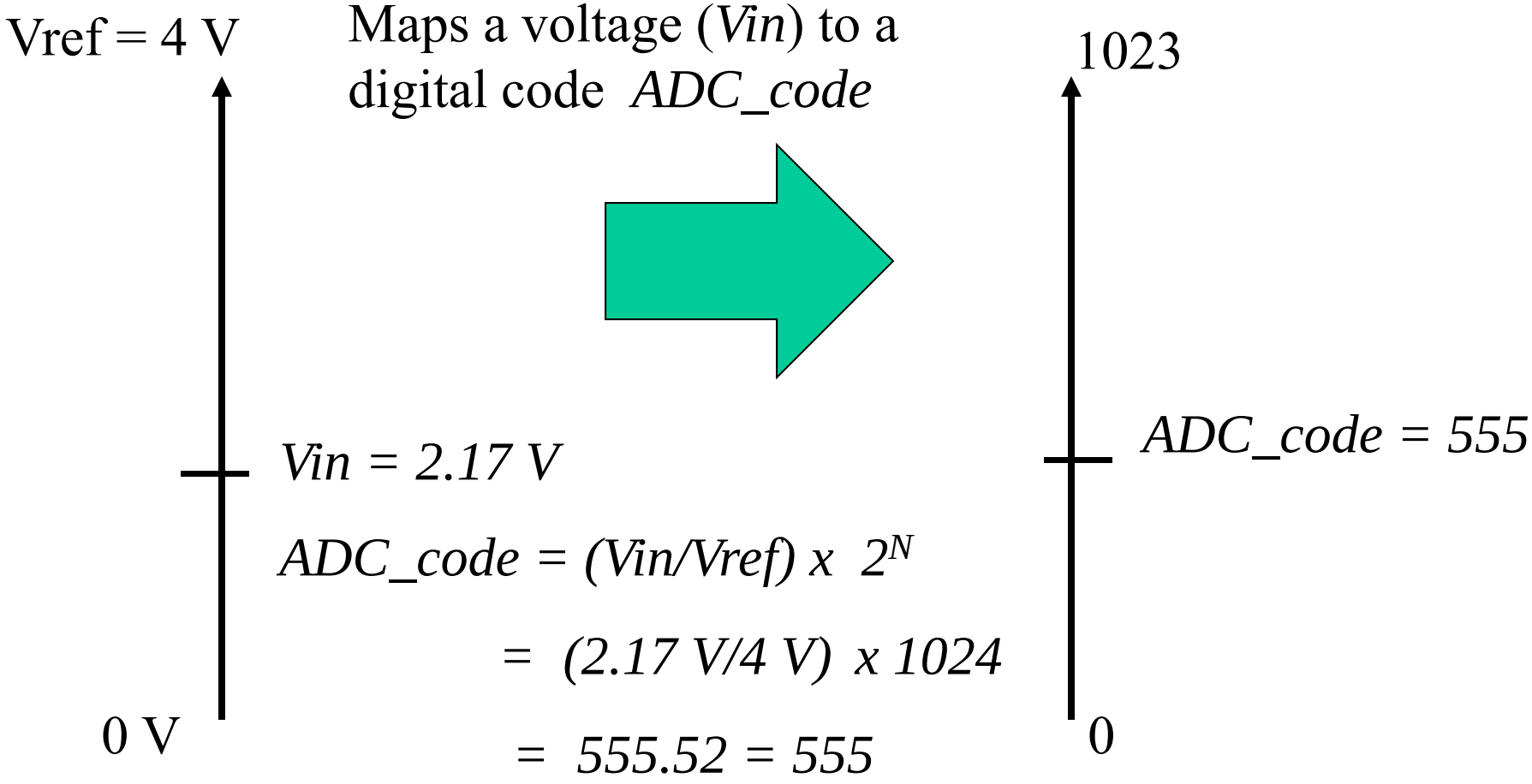
$$ADC\_code = \lfloor (Vin/Vref) \times 2^N \rfloor$$

Vin is always considered less than Vref, so *Vin*/Vref is always < 1.0. Any fractional part of the code is truncated.

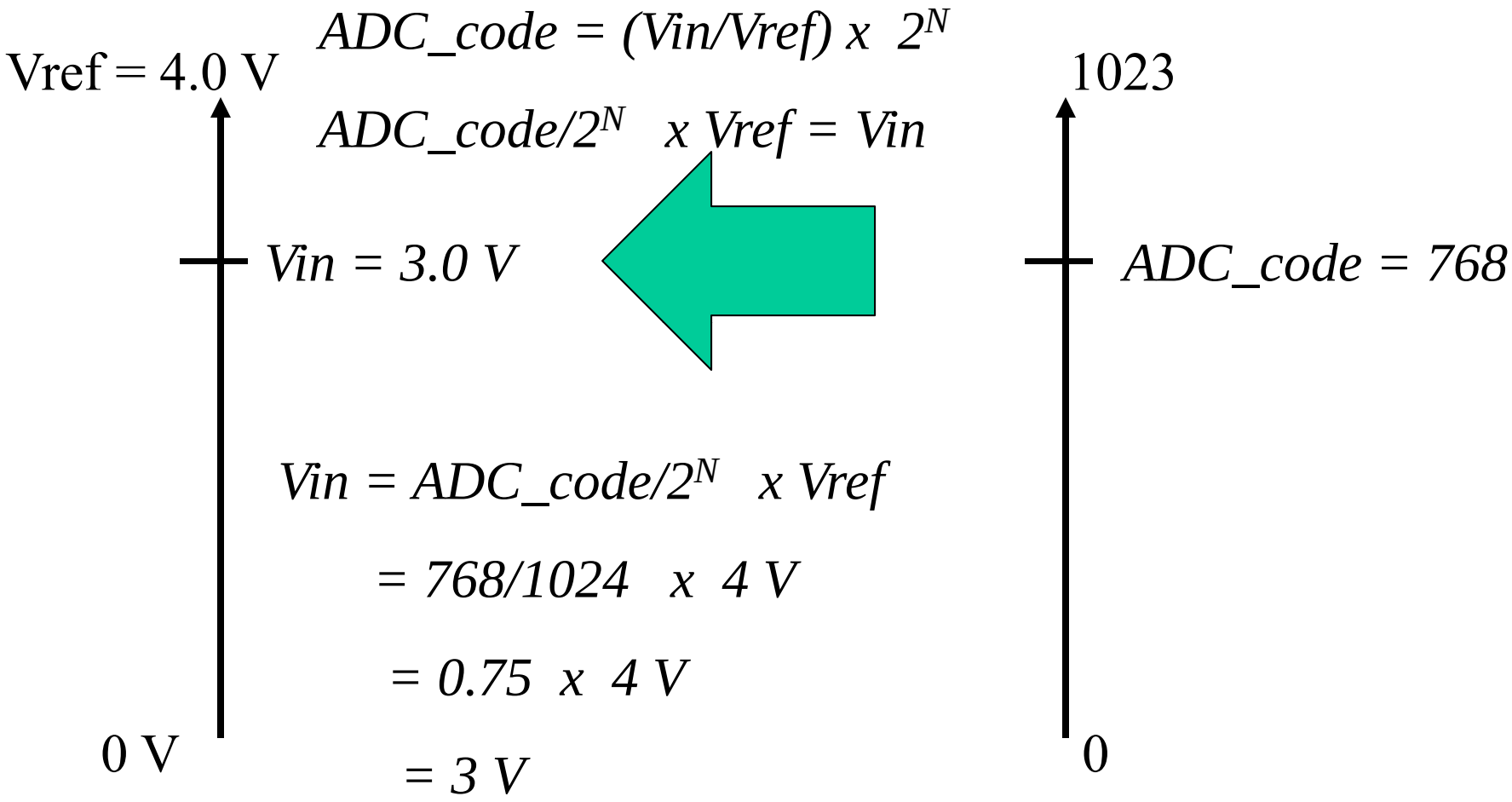
Example: A 10-bit ADC



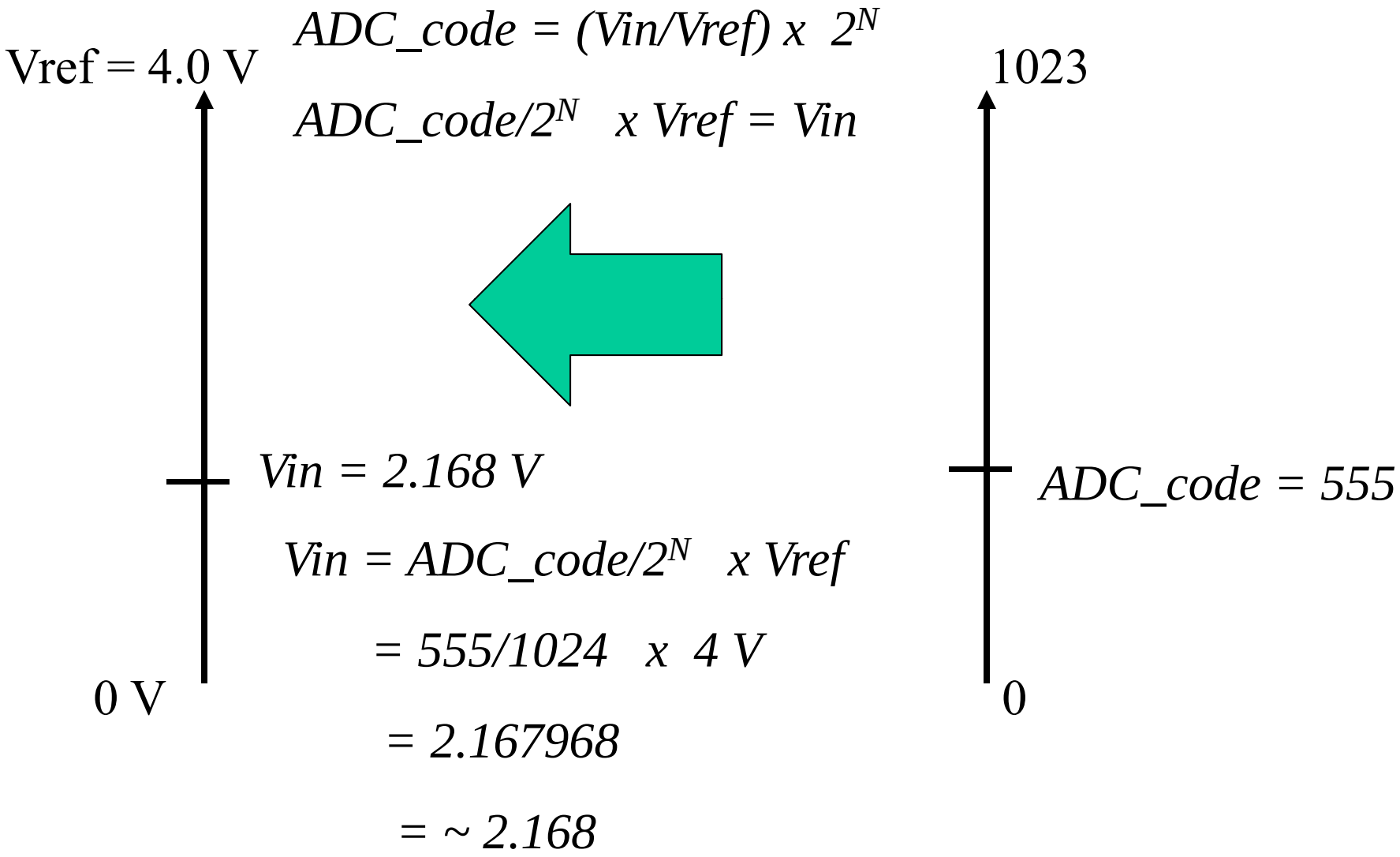
Example: A 10-bit ADC



Going from Code to Voltage



Going from Code to Voltage



ADC Resolution

For an N-bit ADC, the smallest input voltage that can be resolved is 1 LSb, or:

$1/2^N * (Vref+ - Vref-)$

Where Vref+ is the positive reference voltage and
Vref- is the negative reference voltage.

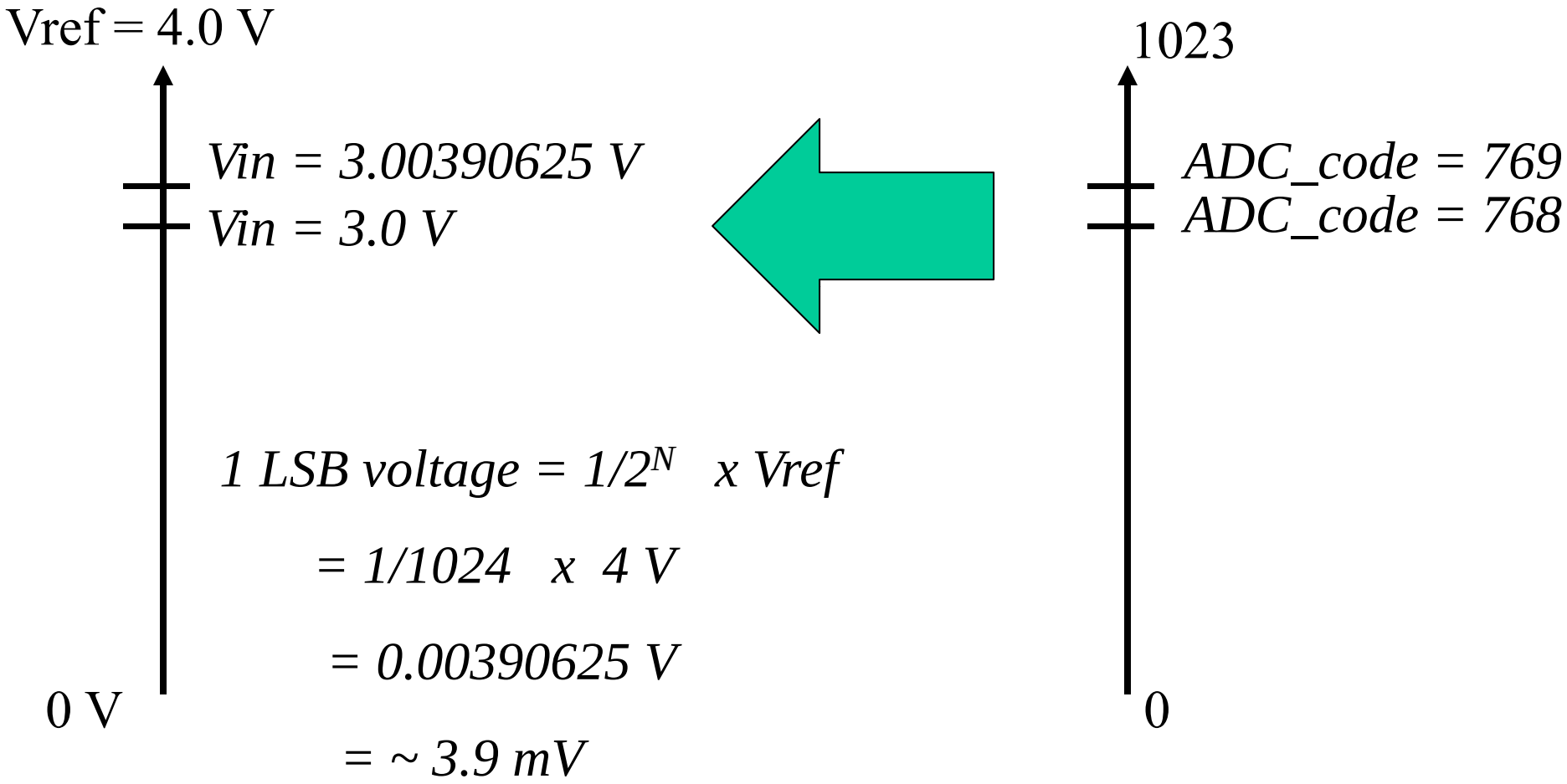
We will use Vref- = 0 V, and refer to Vref+ as simply Vref, so this simplifies to

$1/2^N * Vref.$

For Vref = 4 V, and N = 4, what is 1 LSb?

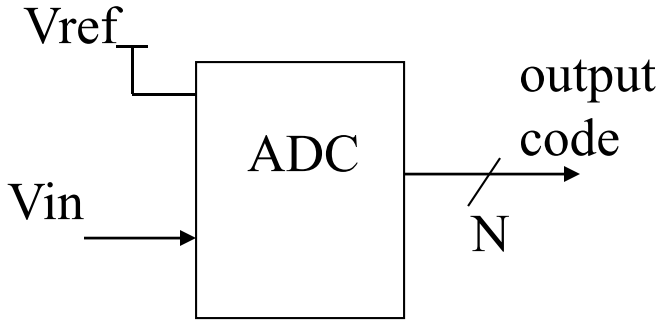
$1/2^4 * 4\ V = 1/16 * 4\ V = 0.25\ V.$

Example: 10-bit ADC Resolution



ADC, DAC Equations

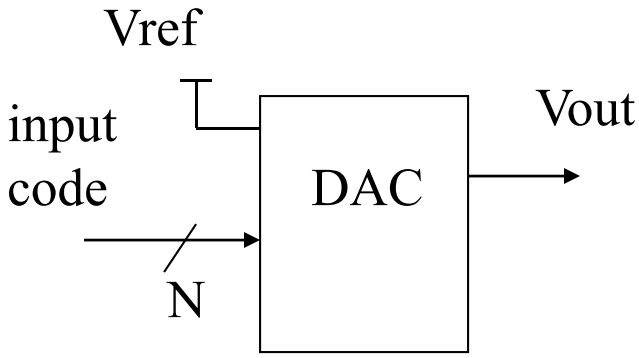
ADC: Vin = input voltage, Vref+ = reference voltage, Vref- = 0 V.
N = number of bits of precision



$$Vin/ Vref * 2^N = output\_code$$
$$output\_code/ 2^N * Vref = Vin$$

$$1\ LSB = Vref/2^N$$

DAC: Vout = output voltage, Vref = reference voltage,
N = number of bits of precision



$$Vout/ Vref * 2^N = input\_code$$
$$input\_code/ 2^N * Vref = Vout$$

$$1\ LSB = Vref/2^N$$

Sample ADC, DAC Computations

If Vref = 5V, and a 10-bit A/D output code is 0x12A, what is the ADC input voltage?

Vin = output_code/2^N * Vref = (0x12A)/2^{10} * 5 V

= 298/1024 * 5 V = 1.46 V (ADC Vin)

If Vref = 5V, and an 8-bit DAC input code is 0xA9, what is the DAC output voltage?

Vout = input_code/2^N * Vref = (0xA9)/2^8 * 5 V

= 169/256 * 5 V = 3.3 V (DAC Vout)

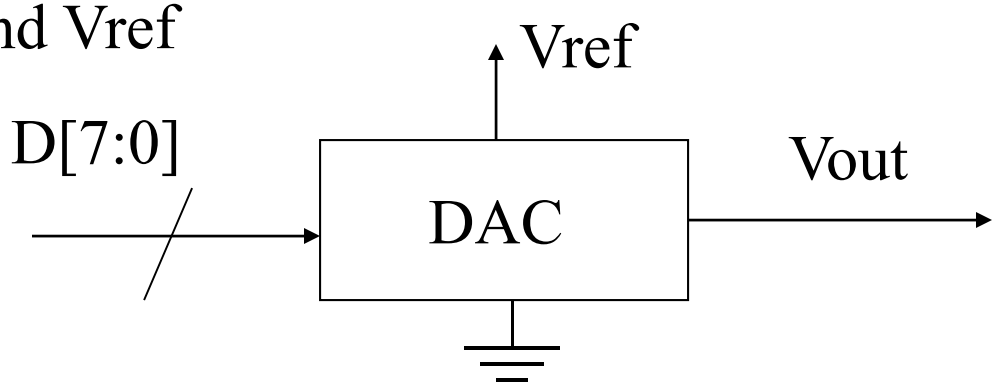
If Vref = 4V, and an 8-bit A/D input voltage is 2.35 V, what is the ADC output code?

output code = Vin/ Vref * 2^N = 2.35 V/ 4 V * 2^8

= .5875 * 256 = 150.4 = 150 = 0x96 (ADC output code)

Digital-to-Analog Conversion

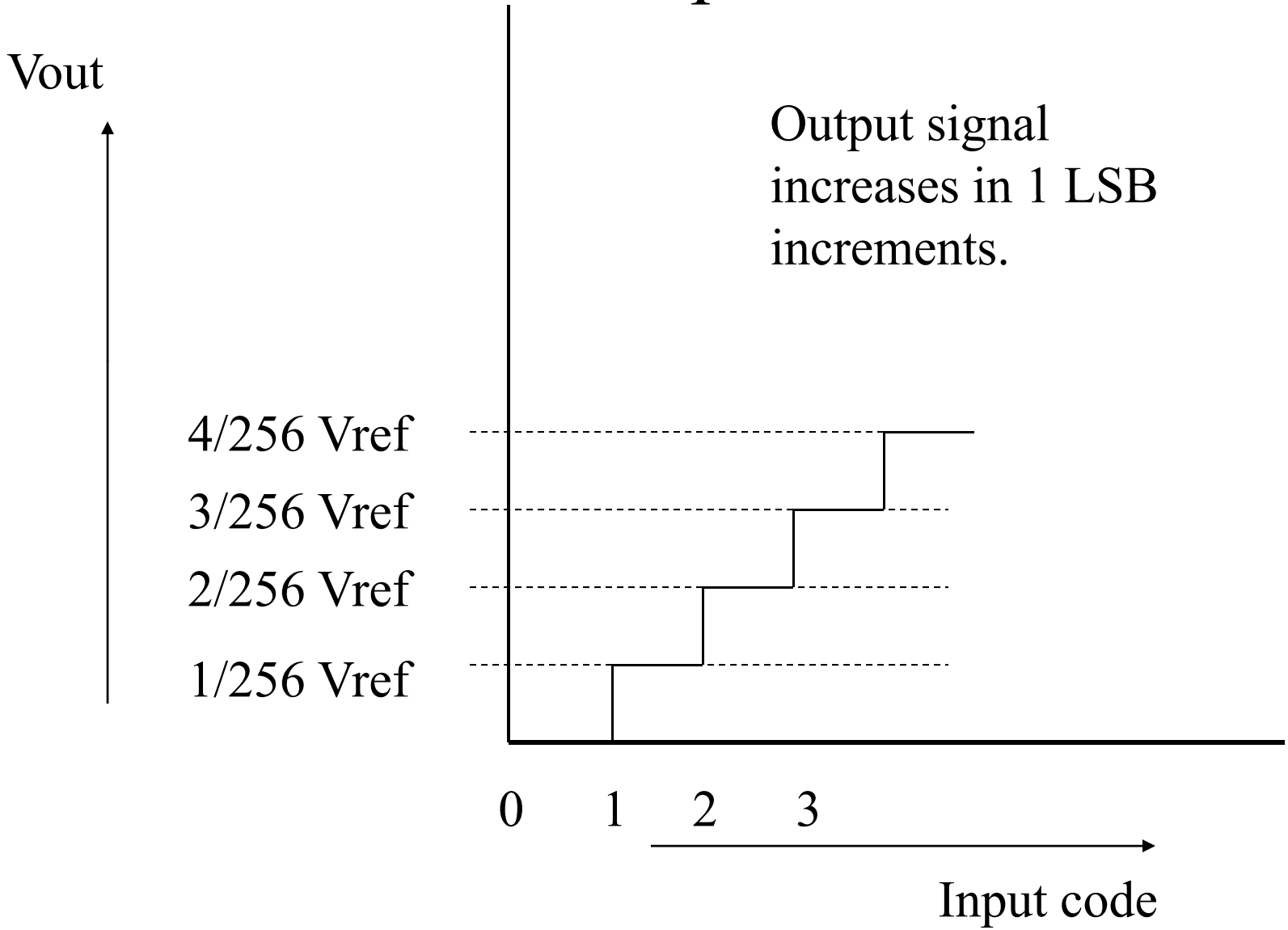
For a particular binary code, output a voltage between 0 and Vref



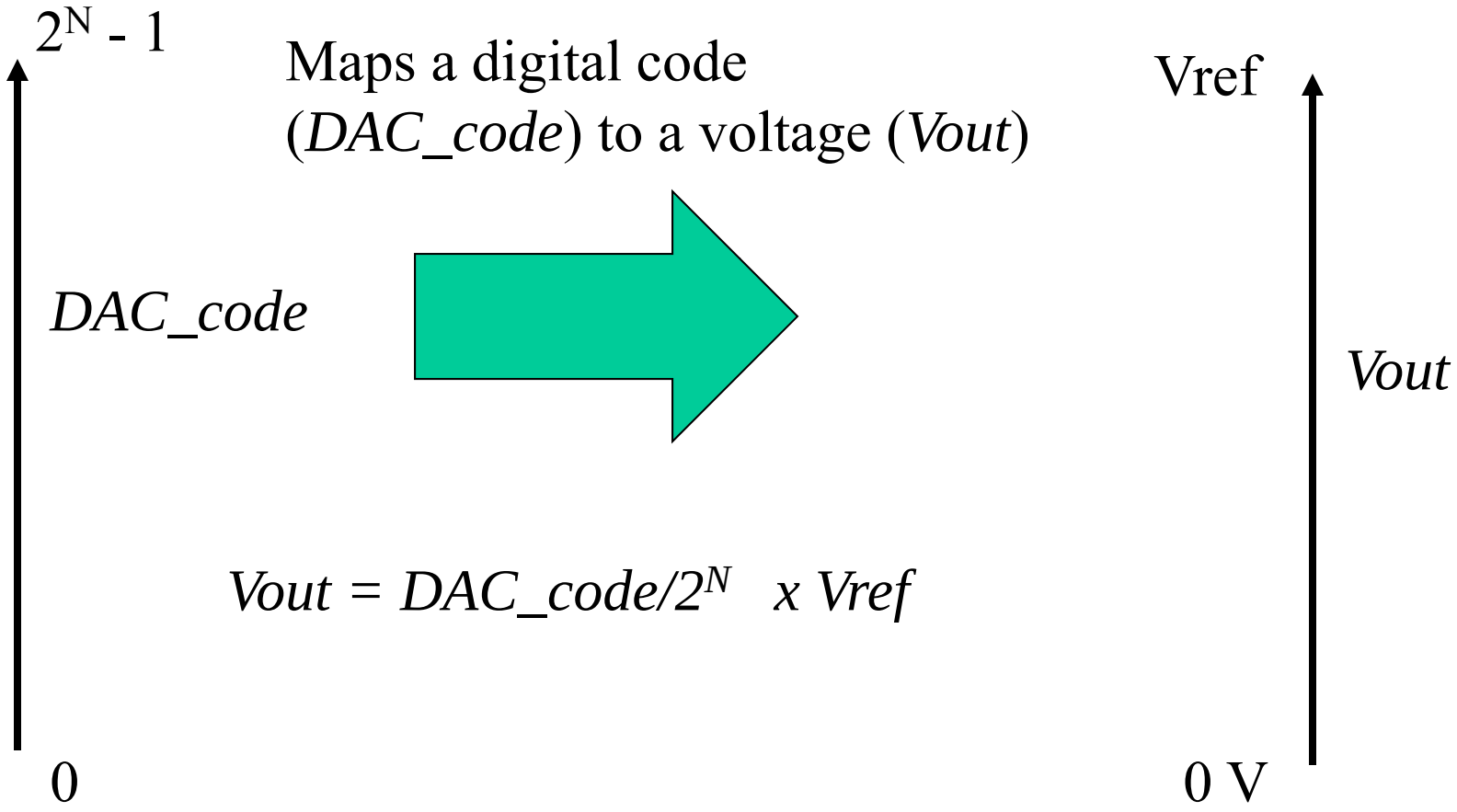
Assume a DAC that uses an unsigned binary input code, with $0 \leq$ Vout < Vref. Then

D= 0000 0000 Vout = 0V
D= 0000 0001 Vout = Vref(1/256) (one LSB)
D = 0000 0010 Vout = Vref(2/256)
...
D = 1111 1111 Vout = Vref(255/256) (full scale)

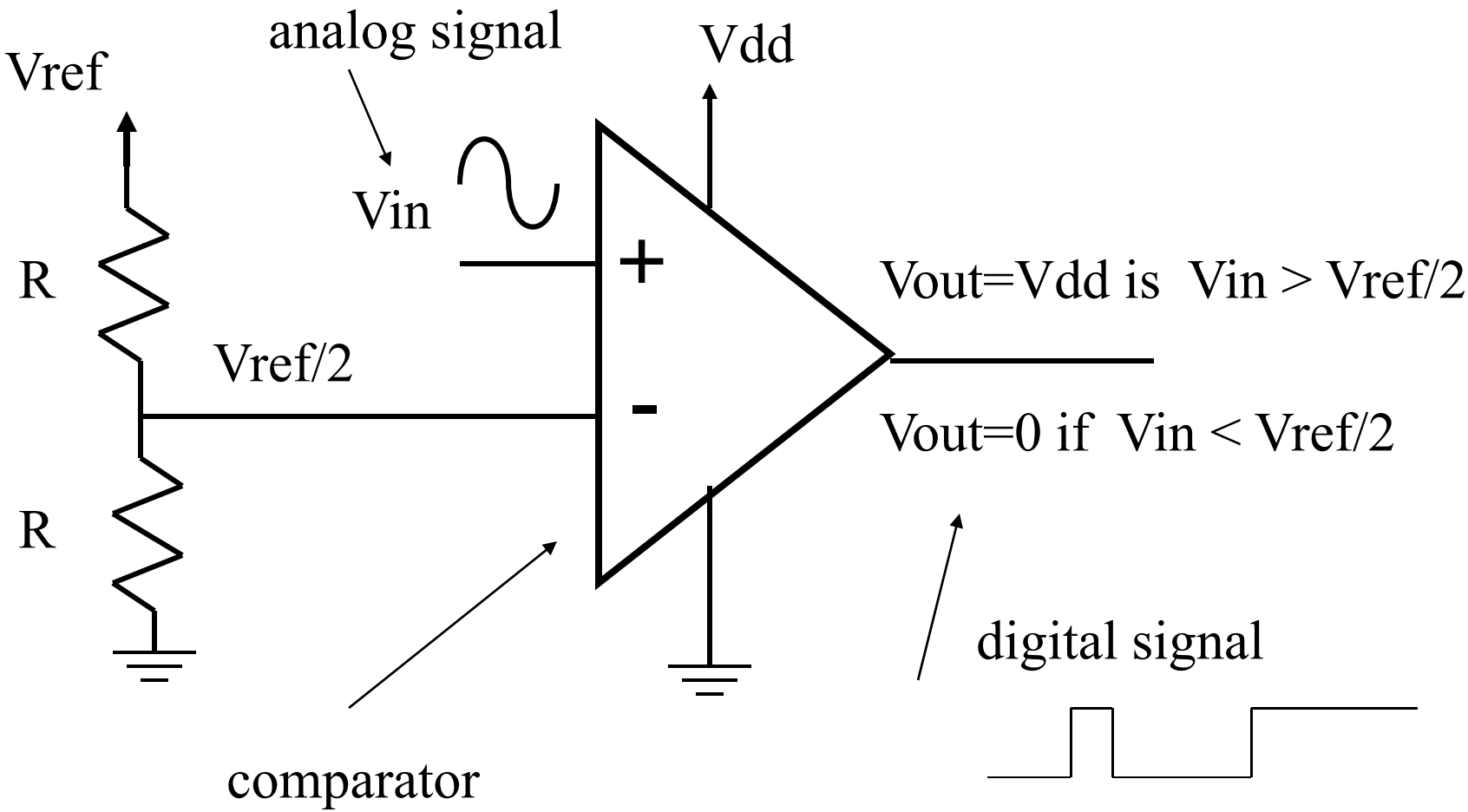
DAC Output Plot



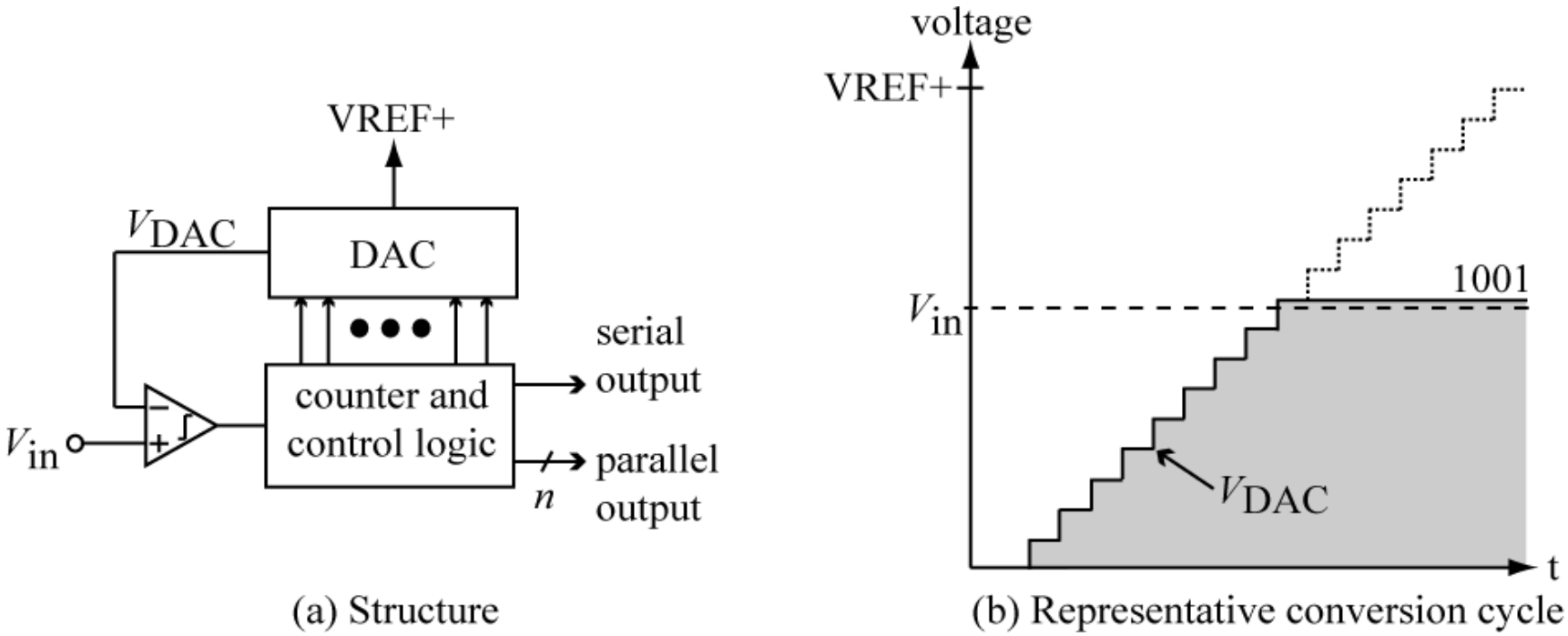
An N-bit DAC


$2^N - 1$
Maps a digital code
(*DAC_code*) to a voltage (*Vout*)
Vref
DAC_code
Vout
$Vout = DAC\_code/2^N \quad x\ Vref$
0
0 V

A 1-bit ADC

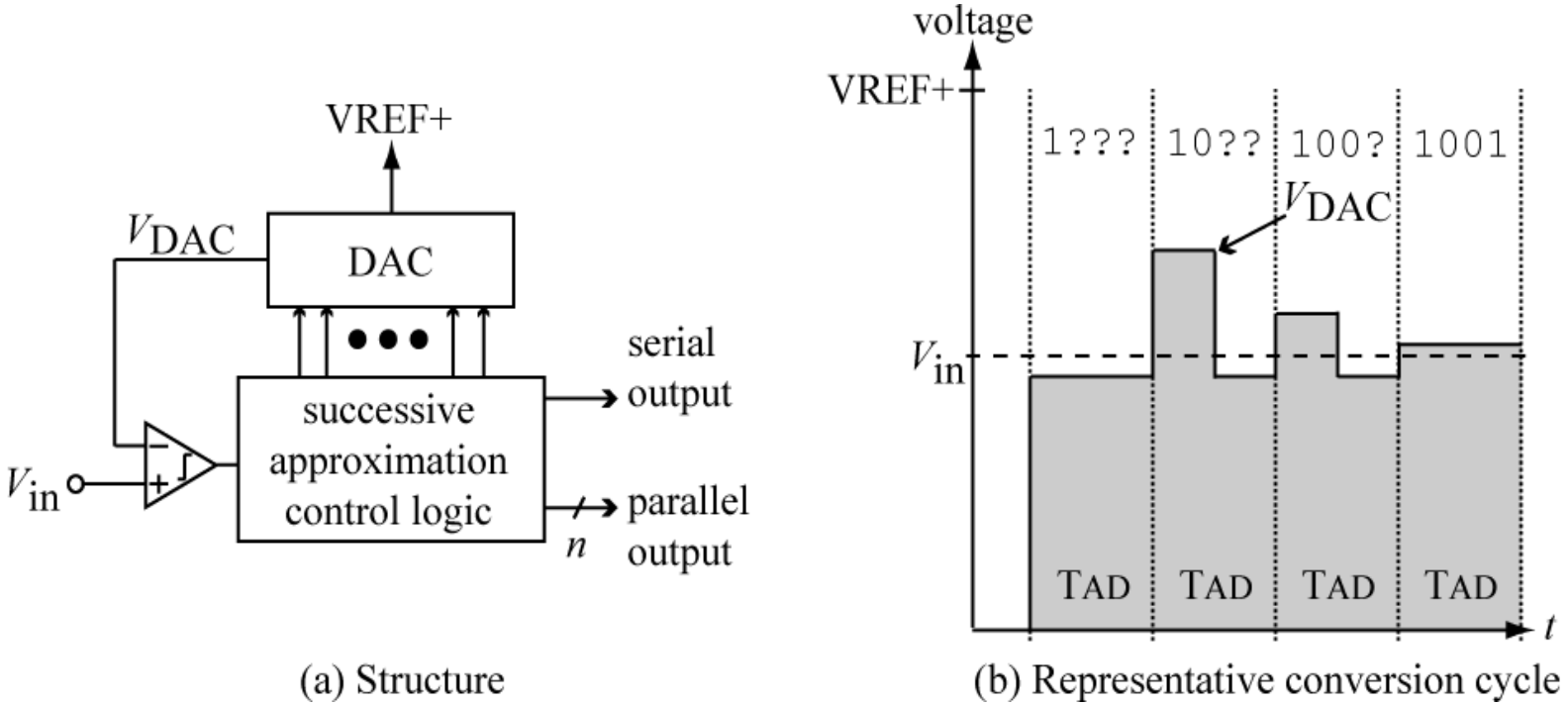

analog signal
Vdd
Vref
Vin
R
+
Vout=Vdd is Vin > Vref/2
Vref/2
-
Vout=0 if Vin < Vref/2
R
digital signal
comparator

Counter Ramp ADC



Control logic use a counter to apply successive codes 0,1,2,3,4... to DAC (Digital-to-Analog Converter) until DAC output is greater than Vin. This is SLOW, and have to allocate the worst case time for each conversion, which is 2^N clock cycles for an N-bit ADC.

Successive Approximation ADC



Initially set VDAC to ½ Vref, then see if Vin higher or lower tan VDAC. If > ½ Vref, then next guess is between Vref and ½ Vref, else next guess is between ½ Vref and GND. Do this for each bit of the ADC. Takes N clock cycles.

Successive Approximation Example

Given a 4-bit Successive Approximation ADC, and Vref = 4 V.
Let Vin = 3.14159 V. Clear DAC input to 0b0000.

1. First guess, DAC input = 0b1000 = 8, so Vdac = $8/2^4$* 4 V = 8/16 * 4 V = 2 V.
   Vdac (2 V) < Vin (3.14159 V), so guess of '1' for MSb of DAC was correct.

2. Set next bit of DAC to '1', DAC input = 0b1100 = 12, so Vdac = 12/16*4= 3V.
   Vdac (3 V) < Vin (3.14159 V), so guess of '1' for bit2 of DAC was correct.

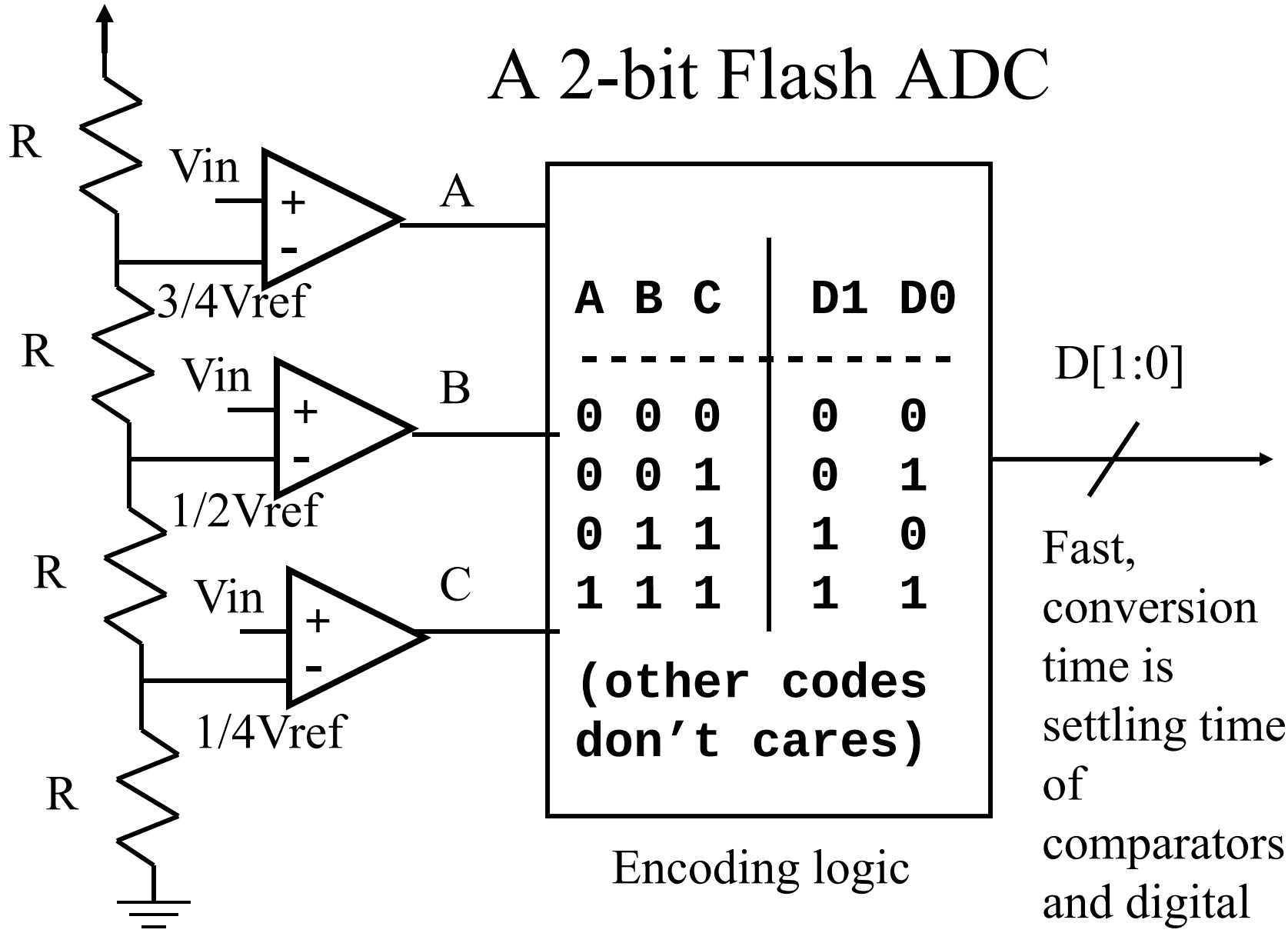
3. Set next bit of DAC to '1', DAC input = 0b1110 = 14, so Vdac = 14/16*4= 3.5V.
   Vdac (3.5 V) > Vin (3.14159 V), so guess of '0' for bit1 of DAC was incorrect.
   Reset this bit to '0'.

4. Set last bit of DAC to '1', DAC input = 0b1101 = 13, so Vdac = 13/16*4 = 3.25V.
   Vdac (3.25 V) > Vin (3.14159 V), so guess of '0' for bit0 of DAC was incorrect.
   Rest this bit to '0'.

Final ADC output code is 0b1100.

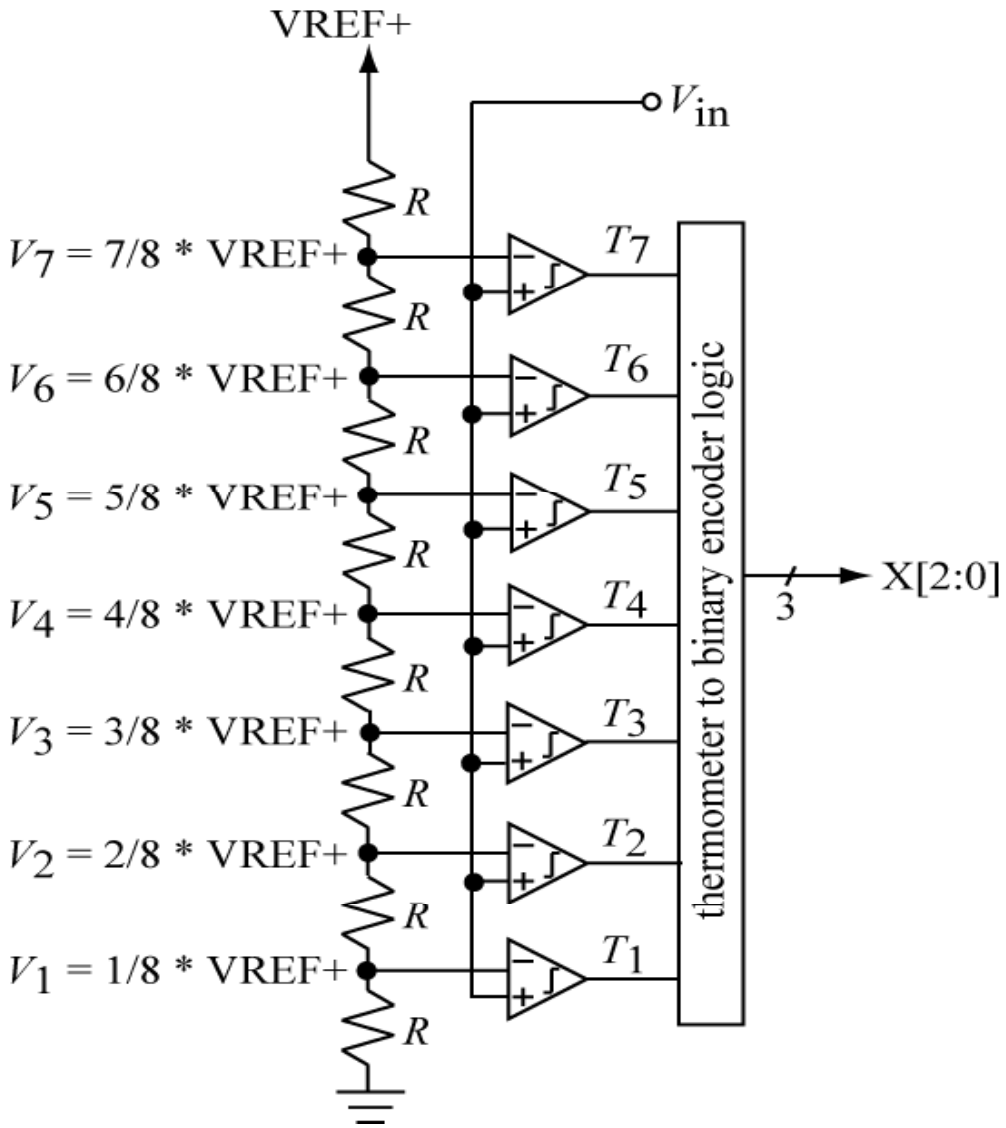
Check result: output code = Vin/Vref * 2^N = 3.14159/4 * 16 = 12.57 = 12 (truncated).

A 2-bit Flash ADC



Fast, conversion time is settling time of comparators and digital logic.

3-bit Flash ADC



ADC Architecture Summary

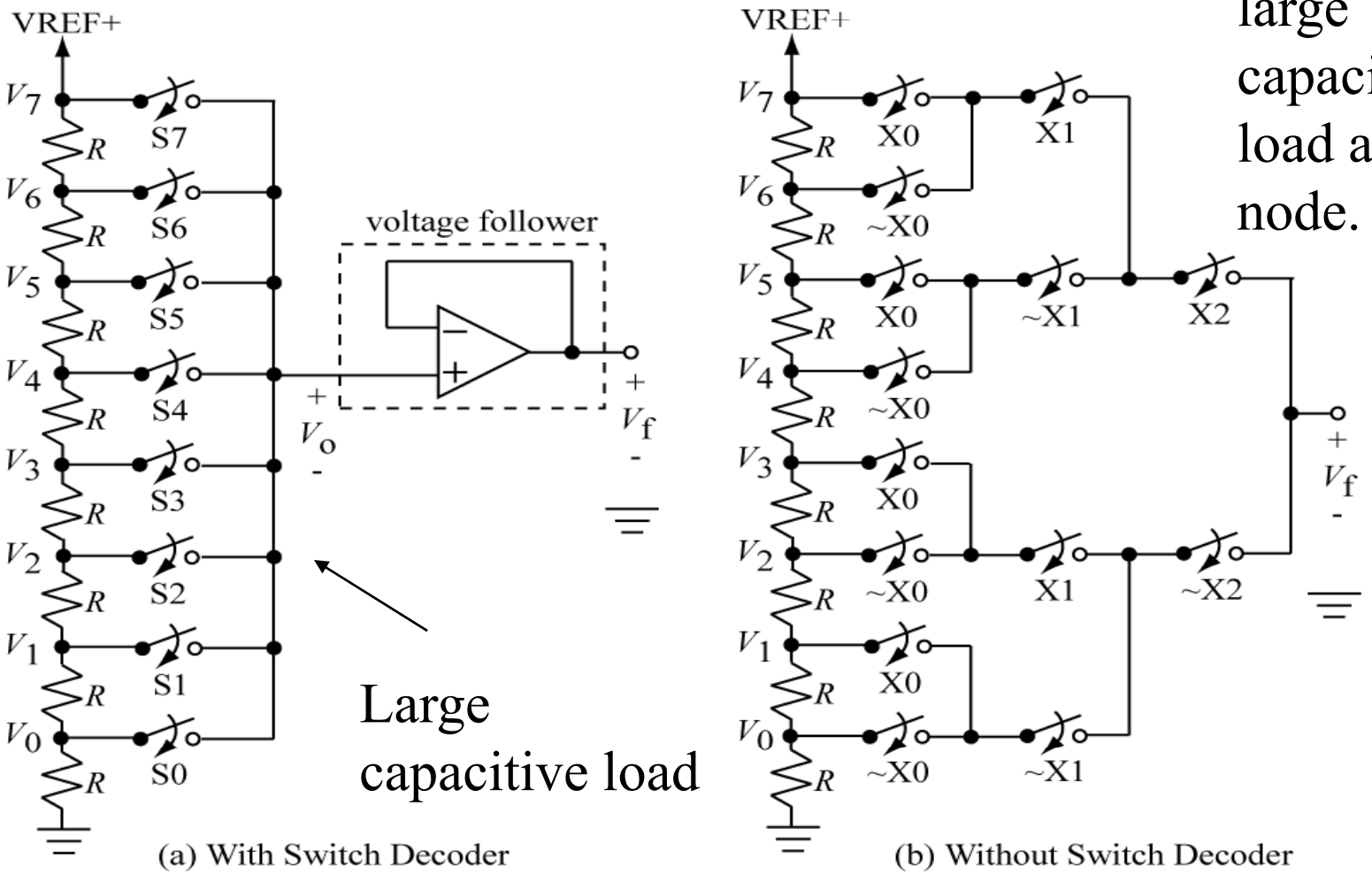
- ***Flash*** ADCs
  - Fastest possible conversion time
  - Requires the most transistors of any architecture
  - N-bit converter requires 2^N-1 comparators.
  - Commercially available flash converters up to 12 bits.
  - Conversion done in one clock cycle
- ***Successive approximation*** ADCs
  - Use only one comparator
  - Take one clock cycle per bit
  - High precision (16-bit converters are available)

Commercial ADCs

- Key timing parameter is ***conversion time*** – how long does it take to produce a digital output once a conversion is started
- Up to 16-bit ADCs available
- Separated into fast/medium/low speed families
  - Serial interfaces common on medium/low speed ADCs
- For high-precision ADCs, challenge is keeping system noise from affecting conversion
  - Assume a 16-bit DAC, and a 4.1V reference, then 1 LSB $= 4.1/2^{16} =$ 62 μV.

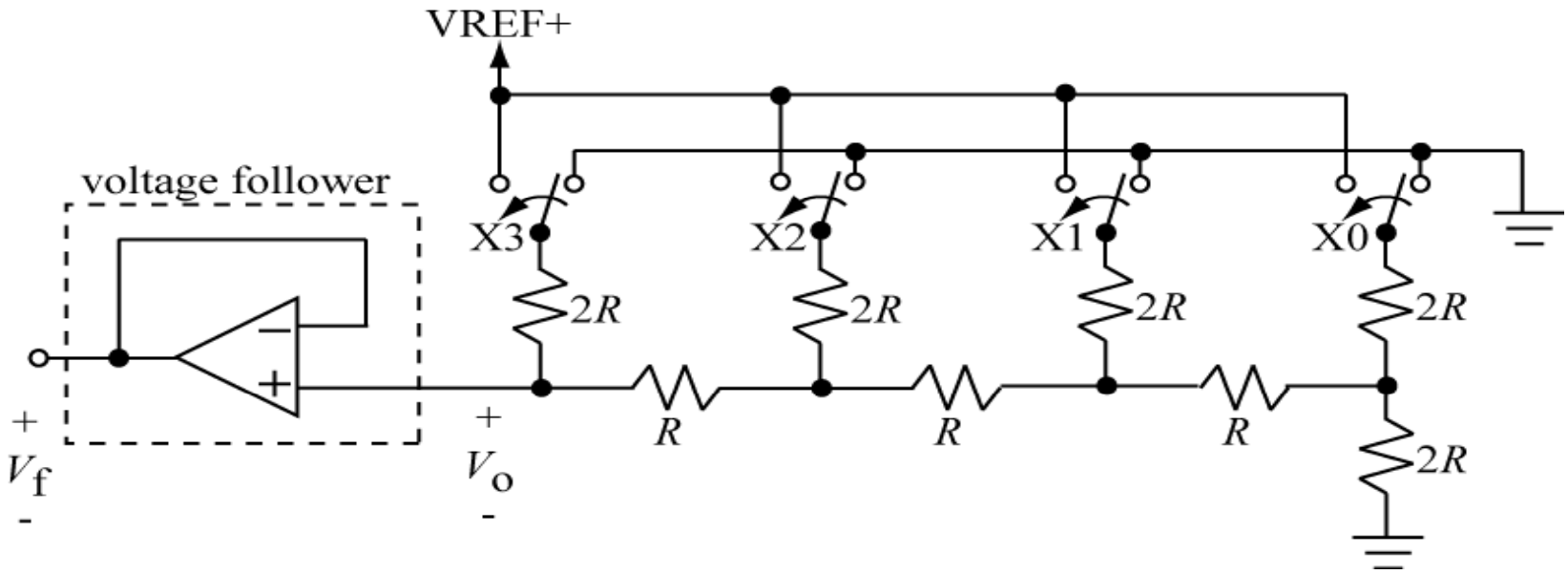
Flash DAC

Eliminates large capacitive load at one node.



N-bit DAC requires 2^N resistors!

R-2R Ladder DAC



Resistor ladder divides the Vref voltage to a binary weighted value 4-bit value, with the 4-bits equal to X3 X2 X1 X0

If the switch Xn is connected to Vref, then that bit value is '1', if the switch Xn is not connected to Vref, then that bit value is '0'.

Majority of DACs use this architecture as requires far less resistors than flash DACs.

Sample DAC Computations

If Vref = 5V, and the 8-bit input code is is 0x8A, what is the DAC output voltage?

$input\_code/2^N * Vref = (0x8A)/2^8 * 5\ V$

$= 138/256 * 5\ V = 2.70\ V$ (Vout)

If Vref = 4V, and the DAC output voltage is 1.25 V, what is the 8-bit input code?

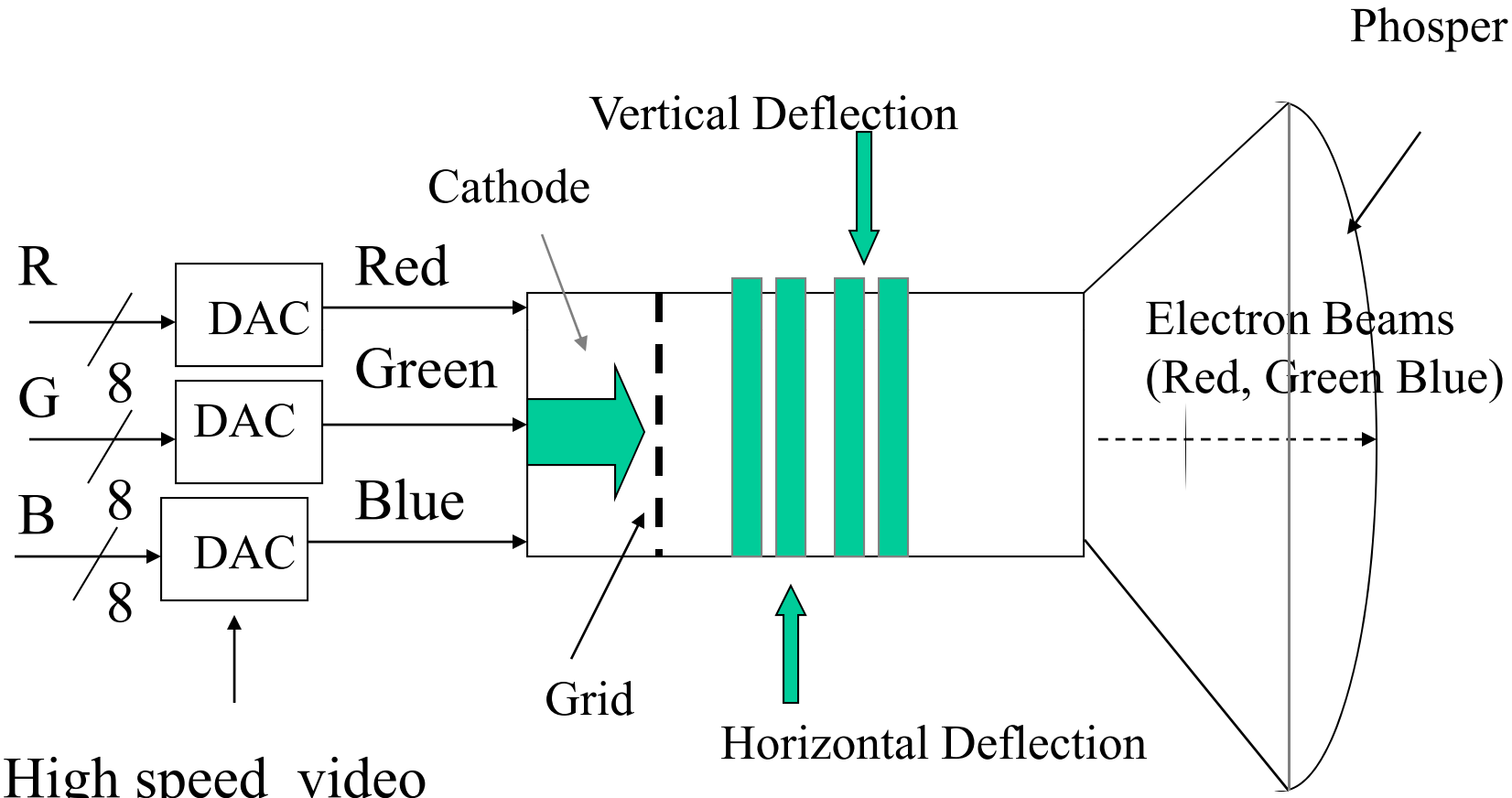
$Vout/ Vref * 2^N = 1.25\ V/4\ V * 2^8$

$= 0.3125 * 256 = 80 = 0x50$ (input_code)

Commercial DACs

- Either voltage or current DACs
  - Current DACs require an external operational amplifier to convert to voltage
- Precision up to 16 bits
- Key timing parameter is ***settling time*** - amount of time it takes to produce a stable output voltage once the input code has changed
- We will use an 8-bit voltage DAC with a SPI interface from Maxim semiconductor

DAC Application



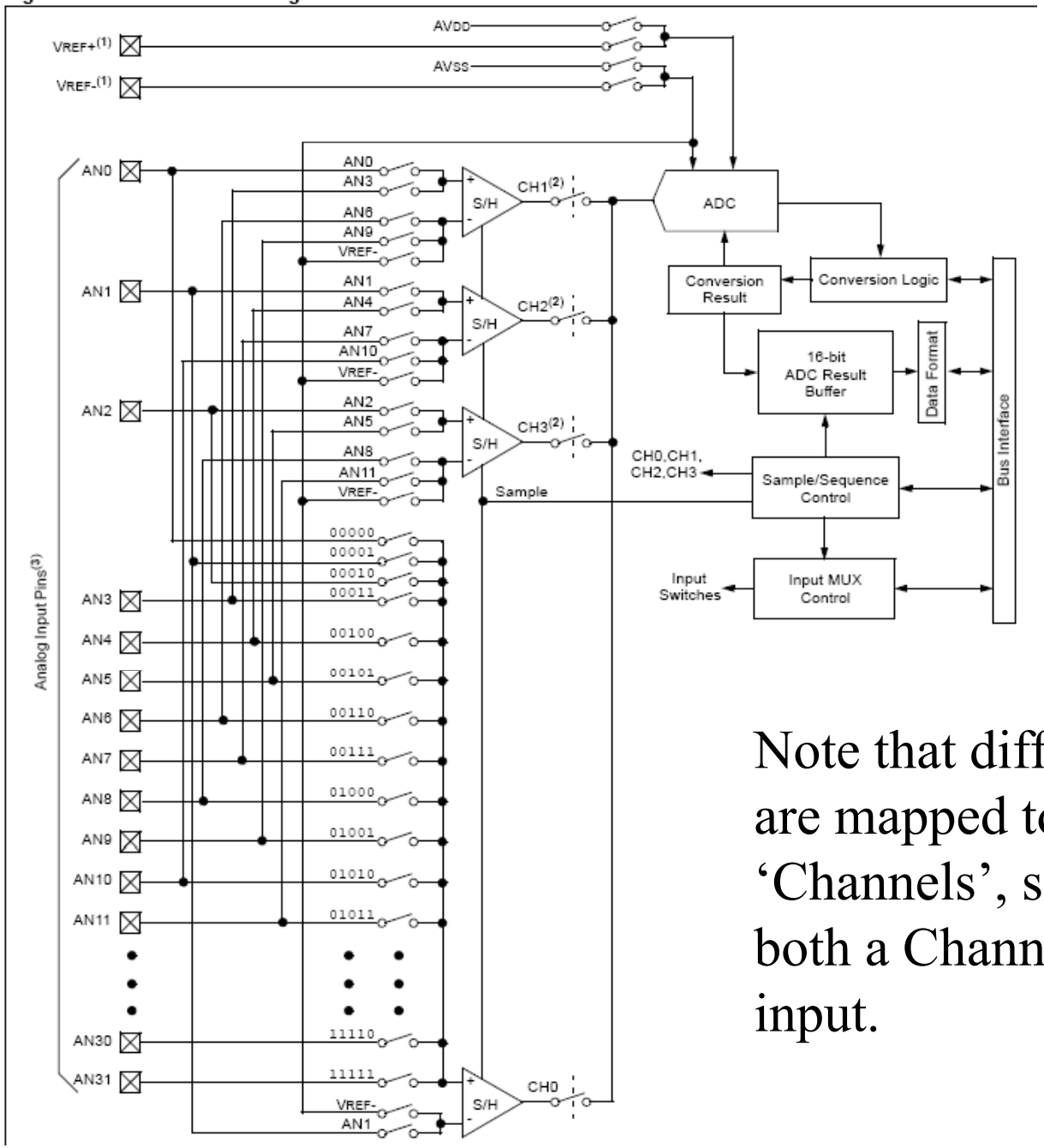
High speed video DACs produce RGB signals for color CRT

PIC24 ADC

- The PIC24 μC has an onboard ADC
  - Successive approximation
  - 10-bit (default) or 12-bit resolution
  - Reference voltage can be Vdd or separate voltage (min AVSS + 2.7 V)
  - Multiple input (more than one input channel)
  - Clock source for ADC is either a divided Fosc, or an internally generated clock. The ADC clock period (Tad) cannot be less than 76 ns for 10-bit mode, or 118 ns for 12-bit mode. The internally generated clock has a period of ~ 250 ns (~ 4 MHz).

Block Diagram

Figure 16-1: ADC Block Diagram

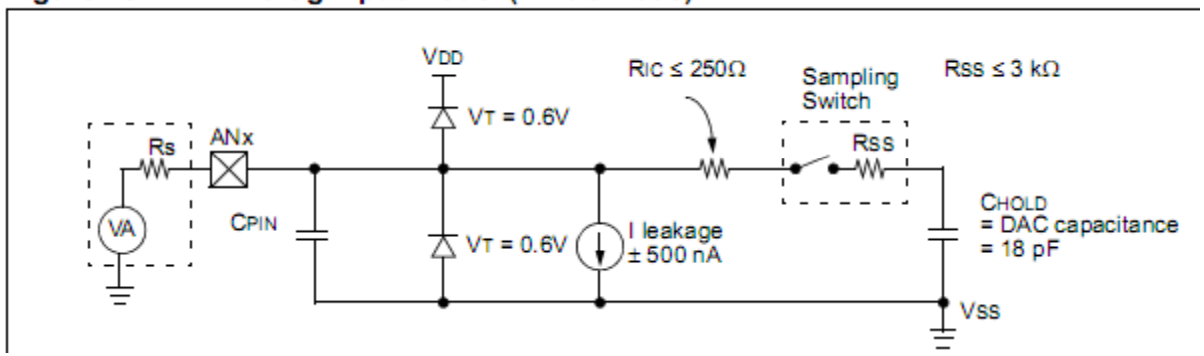


Note that different AN*x* inputs are mapped to different 'Channels', so have to select both a Channel and an AN*x* input.

Conversion Time

- Total conversion time is sampling time + conversion time
- Sampling looks at the input voltage and uses a storage capacitor to acquire the input.
  - This time is configurable; we will use a conservative 31 Tad periods which is the maximum for the PIC24HJGP202.
- Conversion time is Number of bits + 31 Tad periods.
- So, for these settings, takes 31 (sampling) + 12 (bits) + 2 = 45 clock periods.
- Using the internal clock (250 ns), one conversion takes about 11.25 µs (88.9 kHz).

Figure 28-17: Analog Input Model (12-bit Mode)



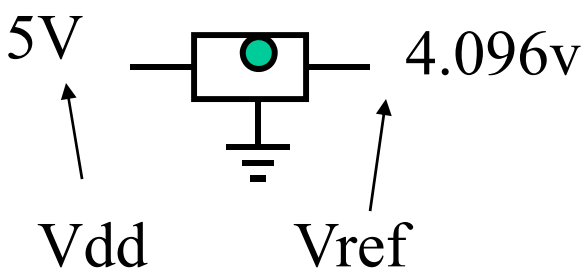
Ric = 250 Ω
Rs = 200 Ω
Rss = 3 kΩ
Chold = 18 pF
RC = 3.45 kΩ*18 pF=61.2 n
½ LSB error = .5/4096 = 0.0122 m = 9.01 RC
9.01 RC * 61.2 n = 0.56 µs
0.56 µs/250 ns = 2.2 Tad, so round up to 3 Tad.

Voltage References

Stability of voltage reference is critical for high precision conversions.

We will use Vdd as our voltage reference for convenience, but will be throwing away at least two bits of precision due to Vdd fluctuations.

Example commercial voltage reference: 2.048v, 2.5v , 3v, 3.3v, 4.096v, 5v (Maxim 6029). The PIC24H can only use a voltage reference of either 3.0 V or 3.3 V.



Key parameter for a voltage is stability over temperature operating range. Need this to be less than ½ of a LSB value.

Configuring the ADC

```
  void configADC1_ManualCH0(uint16 u16_Ch0PositiveMask,
                    uint8 u8_autoSampleTime, uint8 u8_Use12bits) {

  if (u8_autoSampleTime > 31) u8_autoSampleTime=31;
  AD1CON1bits.ADON = 0;   // turn off ADC (changing setting while ADON is
not allowed)

  /** Configure the internal ADC **/
  AD1CON1 = ADC_CLK_AUTO + ADC_AUTO_SAMPLING_OFF;
  if (u8_Use12bits) AD1CON1 |= ADC_12BIT;
  AD1CON3 = ADC_CONV_CLK_INTERNAL_RC + (u8_autoSampleTime<<8);
  AD1CON2 = ADC_VREF_AVDD_AVSS;
  AD1CHS0 = ADC_CH0_NEG_SAMPLEA_VREFN + u16_Ch0PositiveMask;
  AD1CON1bits.ADON = 1;   //turn on the ADC

}
```

Configures for internal ADC clock, uses manual sample start/auto conversion, and **`u16_Ch0PositiveMask`** selects the ANx input from Channel 0 to convert. Uses AVDD, AVSS as references. Parameter **`u8_autoSampleTime`** sets the number of sample clocks, and **`u8_Use12bits`** determines if 12-bit or 10-bit conversion is done.

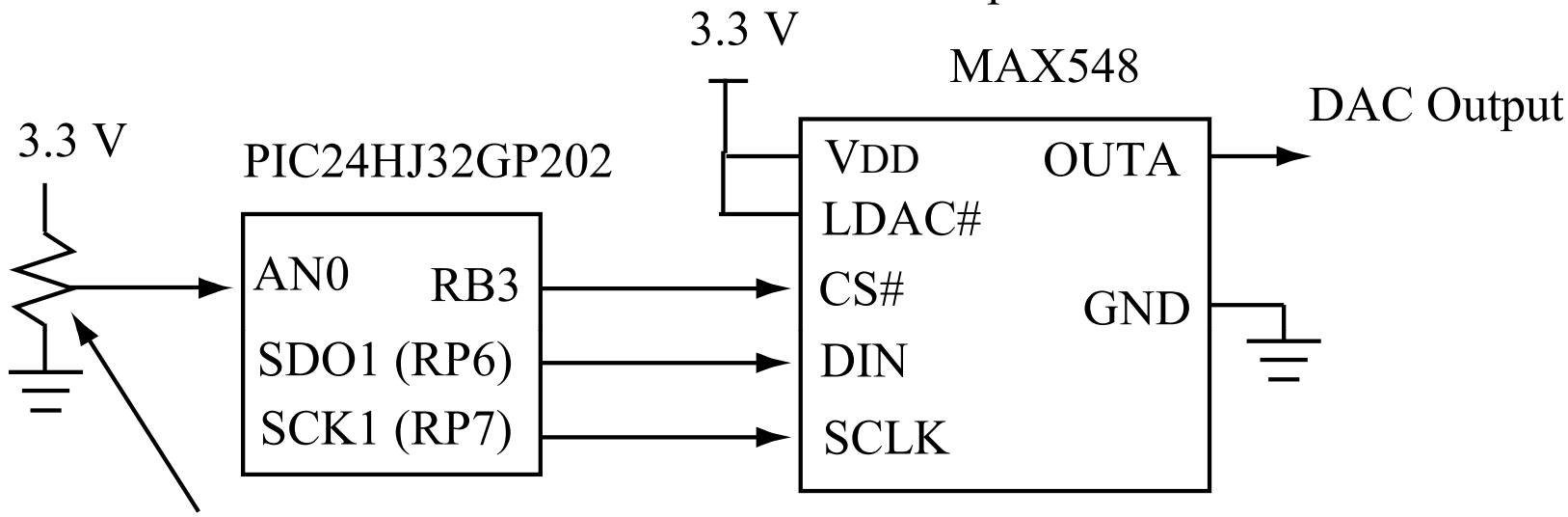
Starting a Conversion, Getting result:

```
int16 convertADC1(void) {
 SET_SAMP_BIT_AD1();   //start sampling
 WAIT_UNTIL_CONVERSION_COMPLETE_AD1(); //wait for conversion to finish
 return(ADC1BUF0);
}
```

In this mode, tell ADC to start sampling, after sampling is done the ADC conversion is started, and then a status bit is set when the conversion is finished.

Testing the ADC and DAC

The MAX548 is an 8-bit DAC with a SPI port

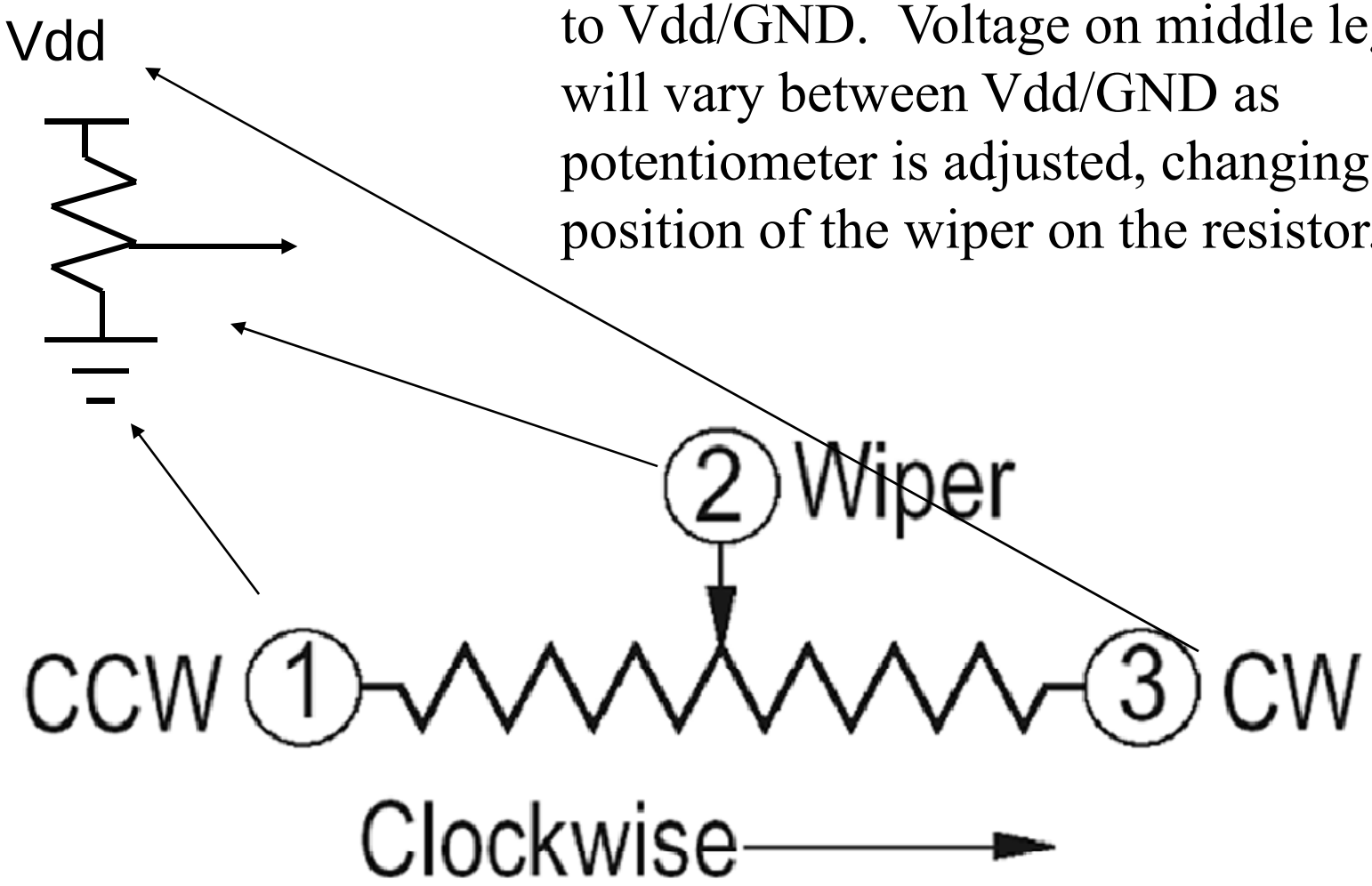


Potentiometer has three pins - middle pin is the wiper, connect the end pins to Vdd/Gnd (ordering does not matter).

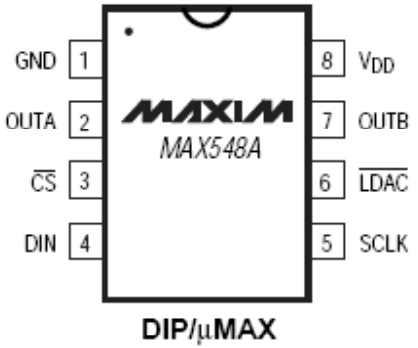
Read the voltage from the potentiometer via the PIC24 ADC, write this digital value to the DAC. The DAC output voltage should match the potentiometer voltage.

Potentiometer

A variable resistor. Tie outer two legs to Vdd/GND. Voltage on middle leg will vary between Vdd/GND as potentiometer is adjusted, changing the position of the wiper on the resistor.

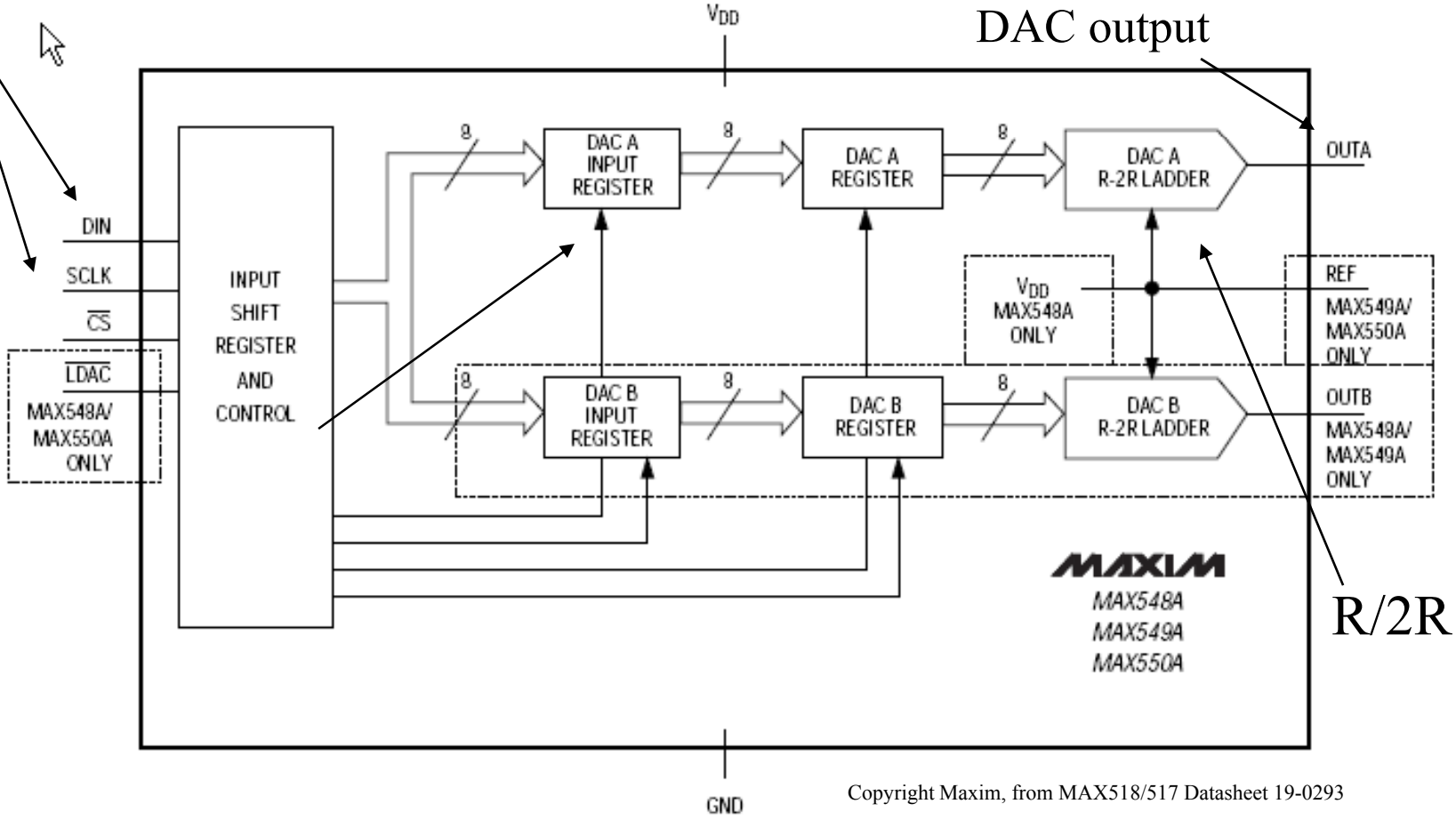


MAXIM 548 DAC



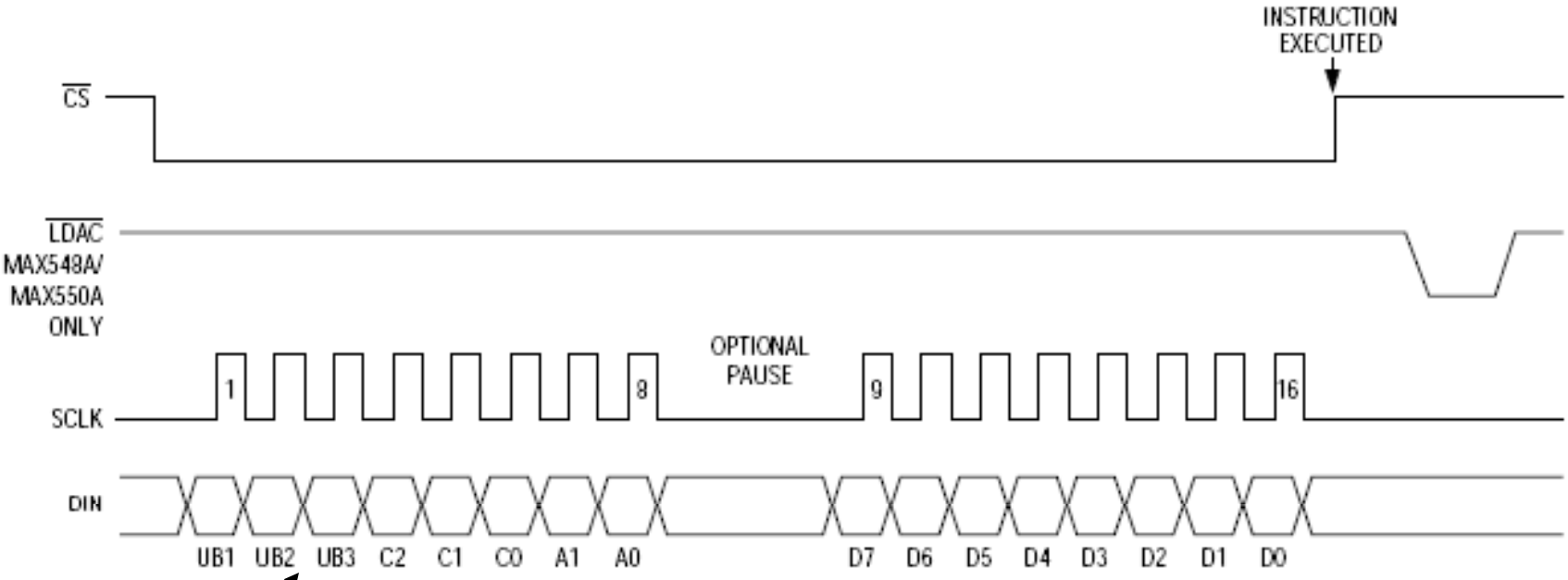
SPI interface

DAC output



R/2R DAC

Max548A SPI Command Format



First Byte: DAC command byte

Second Byte: Command data

Command byte to do conversion: 0x09 (0b00001001)

Data is the value to convert.

Function for doing a DAC conversion:

```
#define CONFIG_SLAVE_ENABLE() CONFIG_RB8_AS_DIG_OUTPUT()
#define SLAVE_ENABLE()        _LATB8 = 0  //low true assertion
#define SLAVE_DISABLE()       _LATB8 = 1

void writeDAC (uint8 dacval) {
  SLAVE_ENABLE();          //assert Chipselect line to DAC
  ioMasterSPI1(0b00001001)  //control byte that enables DAC A
  ioMasterSPI1(dacval);     //write DAC value
  SLAVE_DISABLE();
}
```

adc_spidac_test.c

```
void configDAC() {
 CONFIG_SLAVE_ENABLE();        //chip select for DAC
 SLAVE_DISABLE();              //disable the chip select
}

int main(void) {
  uint16 u16_adcVal;
  uint8 u8_dacVal;
  float f_adcVal;
  float f_dacVal;

  configBasic(HELLO_MSG);
  CONFIG_AN0_AS_ANALOG();
  configADC1_ManualCH0(ADC_CH0_POS_SAMPLEA_AN0, 31, 1);
  configSPI1();
  configDAC();
  while (1) {
```

Use input AN0 on Channel 0 as ADC input

Number of sampling periods, 31 is maximum for PIC24HJ32GP202

Support function, configures for manual sampling, auto conversion

Value of '1' selects 12-bit mode, '0' selects 10-bit mode.

adc_spidac_test.c (cont)

```
while (1) {
    u16_adcVal = convertADC1();   //get ADC value
    u8_dacVal = (u16_adcVal>>4) & 0x00FF;  //upper 8 bits to DAC value
    writeDAC(u8_dacVal);
    f_adcVal = u16_adcVal;
    f_adcVal = f_adcVal/4096.0 * VREF;  //convert to float 0.0 to VREF
    f_dacVal = u8_dacVal;
    f_dacVal = f_dacVal/256.0 * VREF;
    printf("ADC in: %4.3f V (0x%04x), To DAC: %4.3f V (0x%02x) \n",
    (double) f_adcVal, u16_adcVal, (double) f_dacVal, u8_dacVal);
    DELAY_MS(300);   //delay so that we do not flood the UART.
  } //end while(1)
}
```

u16_adcVal is 12-bit ADC value.

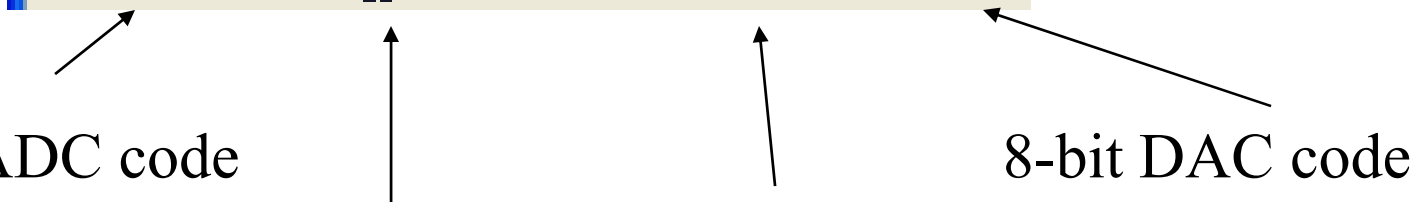
f_adcVal is **u16_adcVal** converted to a voltage between 0 – 3.3V using a float data type.

u8_dacVal is the 8-bit value to send to the DAC (upper 8 bits of **u16_adcVal**).

f_dacVal is **u8_dacVal** converted to a voltage between 0 – 3.3V using a float data type.

Program Output

```
ADC in: 1.764 V (0x088d), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088d), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088e), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088d), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088e), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088e), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088e), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088e), To DAC: 1.753 V (0x88)
ADC in: 1.764 V (0x088e), To DAC: 1.753 V (0x88)
```



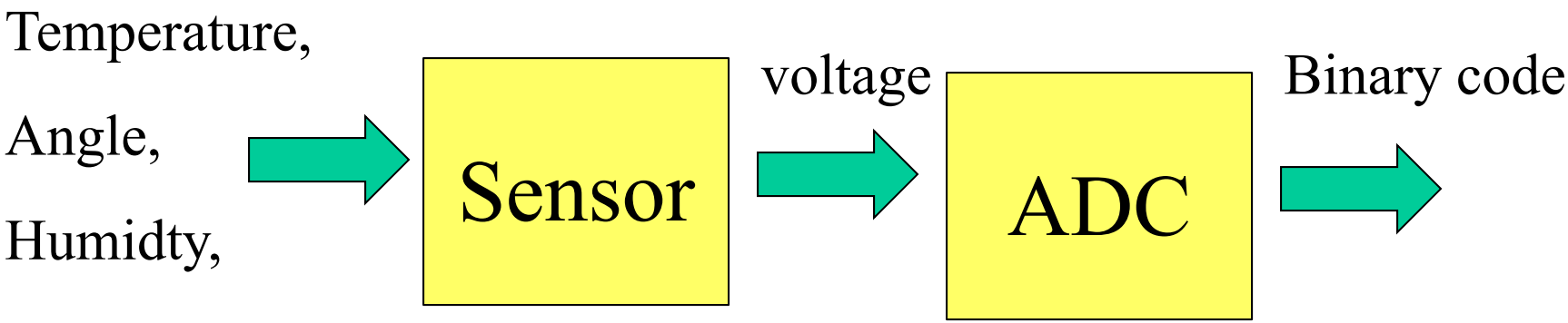
12-bit ADC code as voltage

12-bit ADC code

8-bit DAC code as voltage

8-bit DAC code

Sensors



y = f(x)

Voltage = F (*real_world_quantity*)

The sensor has some function that maps the real world quantity into a voltage; the function can be either linear or non-linear.

A linear function is characterized by:

y = m * x + b

voltage = m * *real_world_quantity* + offset

Example 1

An LM60 temperature sensor produces 6.25 mV for every 1° C and has a DC offset of 424 mV.

Voltage (mV) = 6.25 mV * Tcelsius + 424 mV

Question: Using a 10-bit ADC with Vref = 3.3V, what is the ADC code value for a temperature of -10 Celsius?

Step 1: Convert temperature to voltage:
Voltage (mV) = 6.25 mV * (-10) + 424 mV = 361.5 mV = 0.3615 V

Step 2: Convert voltage to ADC code:

$Vin/Vref * 2^N = 0.3615/3.3 * 2^{10} = 112.17 = 112$

Example 1 (cont)

Can reduce the computations needed by simplifying the equation by combining steps:

Question: Using a 10-bit ADC with Vref = 3.3V, what is the ADC code value for a temperature of -10 Celsius?

Step 1: Convert temperature to voltage:

Voltage (mV) = 6.25 mV * (Tcelsius) + 424 mV

ADC code = (0.00625 * Tcelsius) + 0.424)/ 3.3 V * 1024

ADC code = (6.4 * Tcelsius) + 434.176)/ 3.3 V

For Tcelsius = -10

ADC code = ((6.4 * -10) + 434.176)/3.3

= 112.17 = 112

Example 2

A Freescale MPX5050 pressure sensor outputs 0.2 V at 0 kPa and has a sensitivity of 90 mV/kPa.

Voltage (mV) = 90 mV * Pressure_kPa + 200 mV

Question: A 10-bit ADC with a Vref = 3.3 V returns a code value of 420. What pressure is being sensed by the pressure sensor?

Step 1: Convert ADC code to a voltage:

$adc\_code/2^N * Vref = 420/ 2^{10} * 3.3\ V = 1.354\ V.$

Step 2: Convert Volts to pressure (solve the above equation for pressure):

Pressure (kPa) = (voltage (mV) – 200 mV) / 90 mV
= (1354 mV – 200 mV)/90 mV
= 12.8 kPa

What do you have to know?

- Vocabulary
- DAC R/2R architecture
- ADC Flash, Successive approximation architectures
- PIC24 ADC
  - How to configure
  - Acquisition, Conversion time
  - How to start do conversion, read result
- MAX548A DAC usage