XMUT202 Digital Electronics

Analogue to digital and Digital to Analog Conversion.

Week 15 Lecture

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A-D/D-A

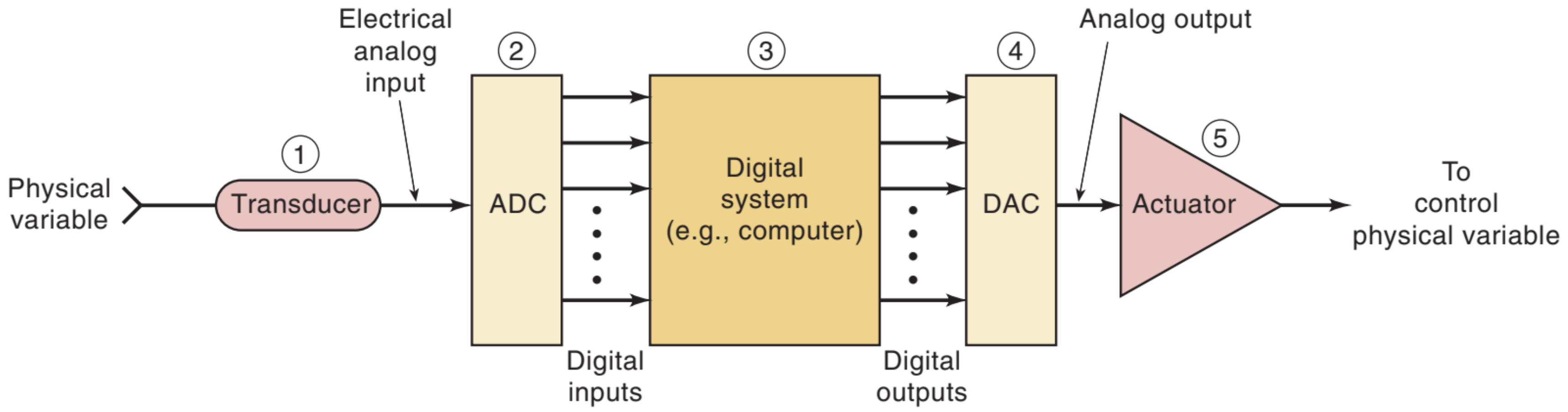
- Conversion between analogue and digital signals is common. The following aspects will be examined:
  – DAC and ADC
  – Different conversion methods
  – Sampling
  – Analogue multiplexing
  - Analogue interfacing

Interfacing With the Analog World

- A review of the difference between digital and analog quantities
  - Digital quantities – values can take on one of several discrete values. Discrete
  - Analog quantities – values can take on an infinite number of values. Continuous.

Interfacing With the Analog World

- Transducer
- ADC
- Computer
- DAC
- Actuator



Digital to Analog Conversion

- The conversion process:

–Digital code is converted to a voltage or current proportional to the digital code

– Voltage reference used to determine the full scale O/P.

– Analog O/P = K x digital I/P
  where K is the proportionality factor

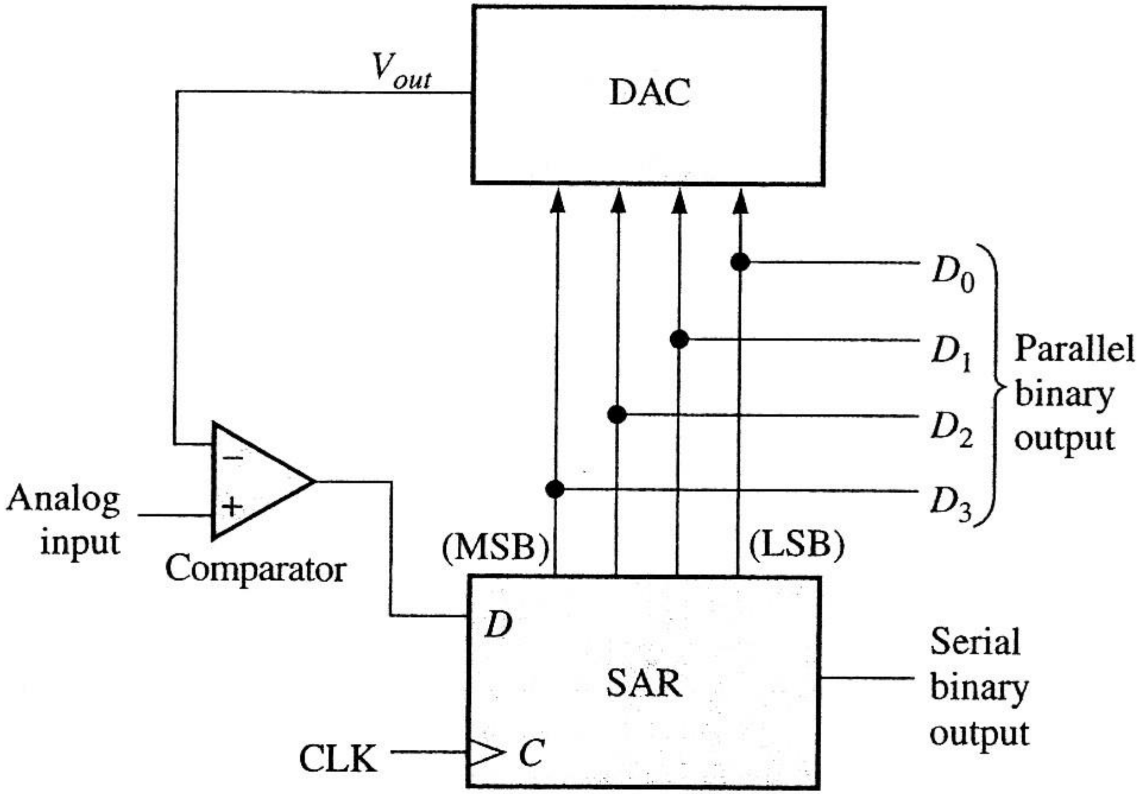
– "Pseudo analog" as O/P cannot take on continuous values

–Bipolar DAC's: Use 2's compliment to represent negative voltages

DAC **Digital to Analog**

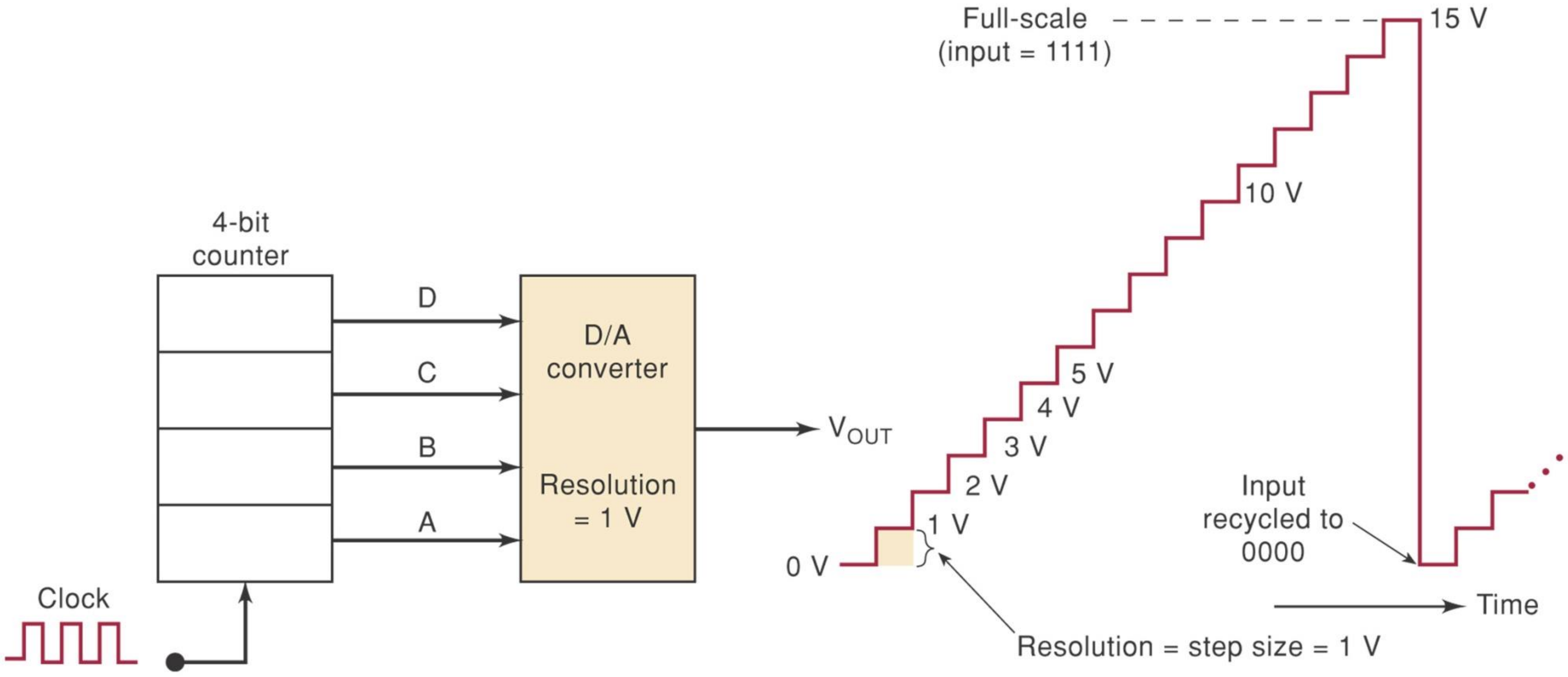
What would we use a DAC for?

Use case one: As part of a Analog to Digital Converter.



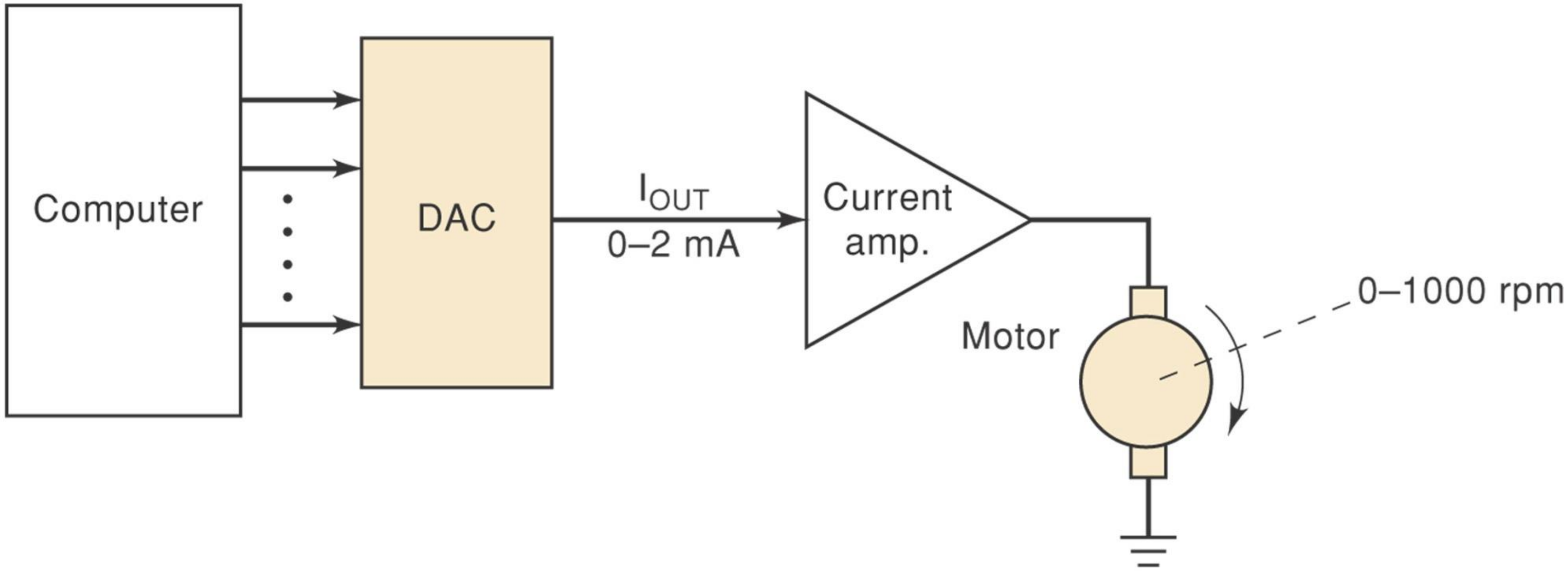
What would we use a DAC for?

Use case two: To generate a digital waveform



What would we use a DAC for?

Use case three: To control the current or voltage output and drive a transducer or process.

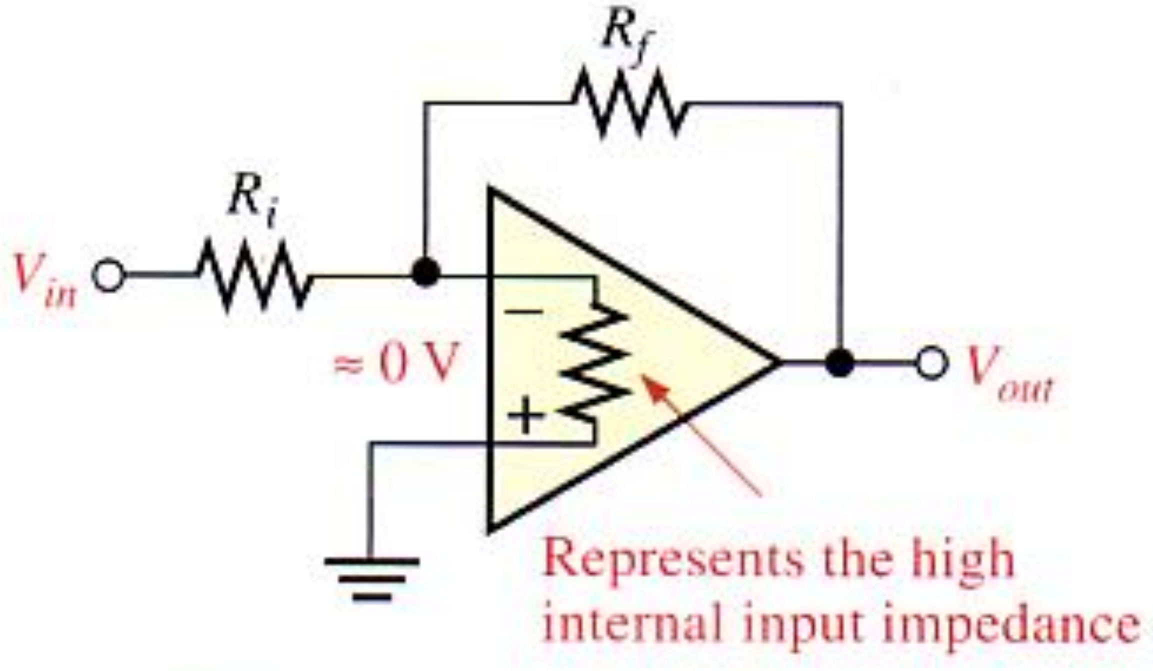


How would we construct a DAC?

Option one: A binary weighted input DAC circuit

Start with an inverting Op-Amp

Gain: $$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$



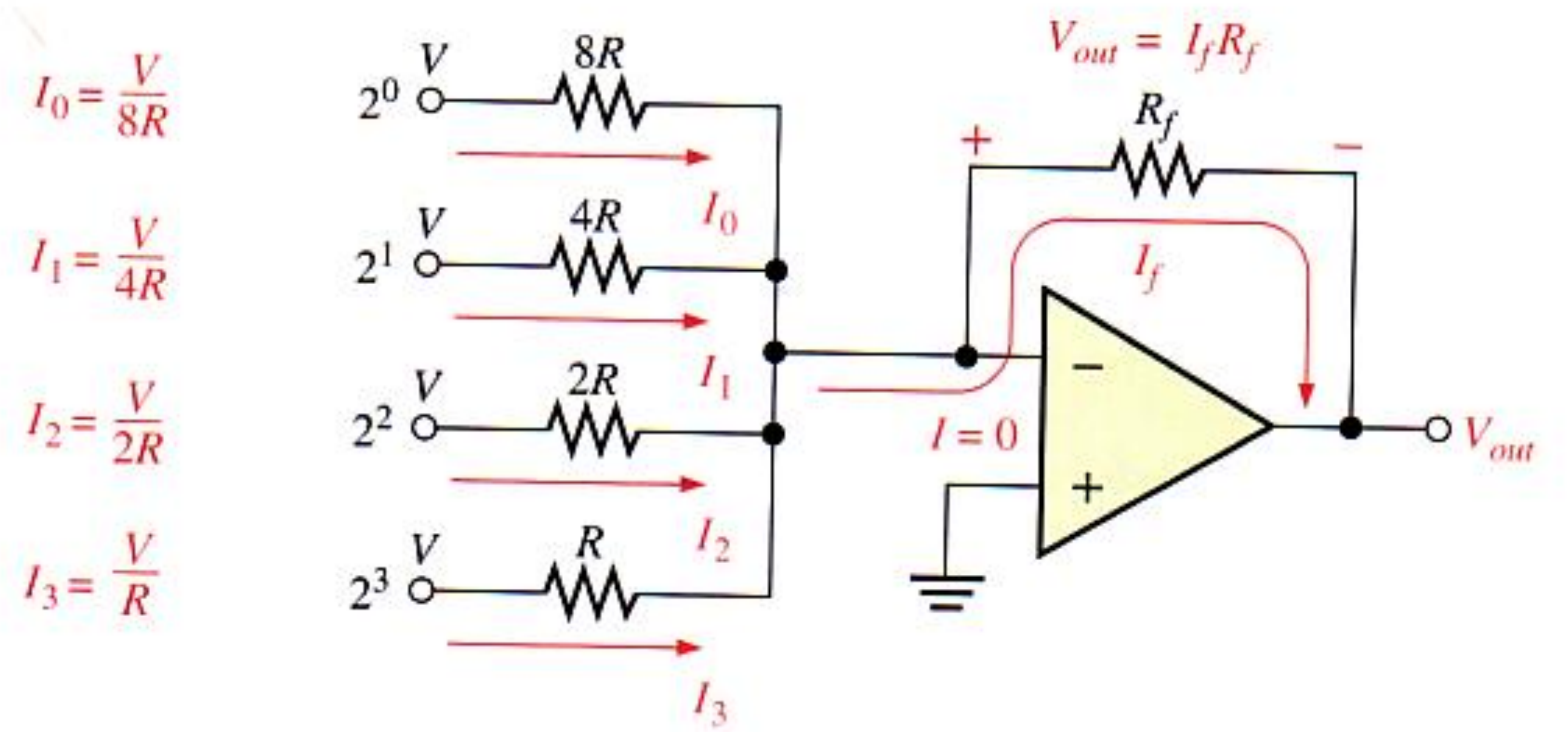
(b) Op-amp as an inverting amplifier with gain of R_f/R_i

Output Voltage: $V_{out} = -\frac{V_{in}R_f}{R_i}$

$$V_{out} = I_f R_f$$

How would we construct a DAC?

Option one: A binary weighted input DAC circuit

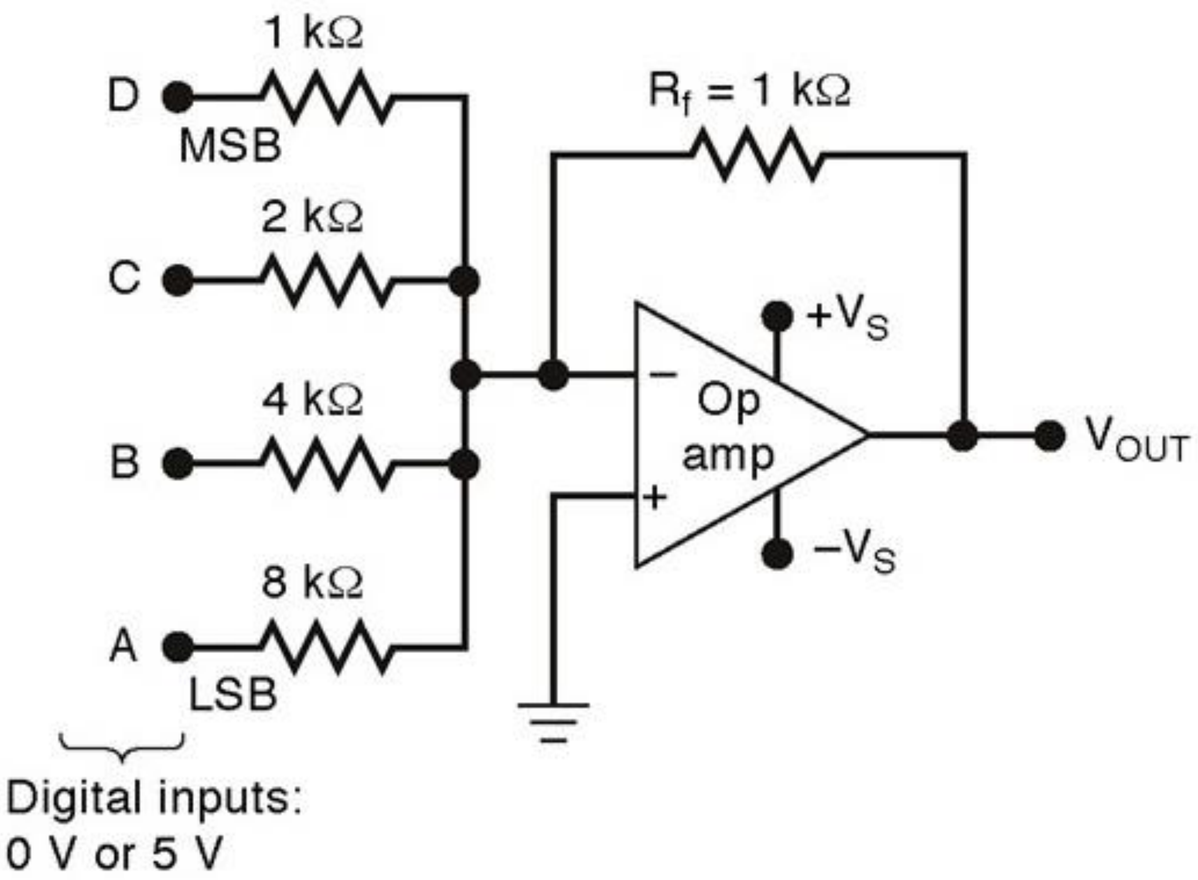


Adjusting the resistance R_i changes the current flow and the voltage output V_{out}

$$V_{out} = I_f R_f = \left(\frac{V}{8R} + \frac{V}{4R} + \frac{V}{2R} + \frac{V}{R}\right) R_f$$

DAC implementation 1

- This summing amplifier has a resolution of 0.625V



Input code

D	C	B	A	V_{OUT} (volts)
0	0	0	0	0
0	0	0	1	–0.625 ← LSB
0	0	1	0	–1.250
0	0	1	1	–1.875
0	1	0	0	–2.500
0	1	0	1	–3.125
0	1	1	0	–3.750
0	1	1	1	–4.375
1	0	0	0	–5.000
1	0	0	1	–5.625
1	0	1	0	–6.250
1	0	1	1	–6.875
1	1	0	0	–7.500
1	1	0	1	–8.125
1	1	1	0	–8.750
1	1	1	1	–9.375 ← Full-scale

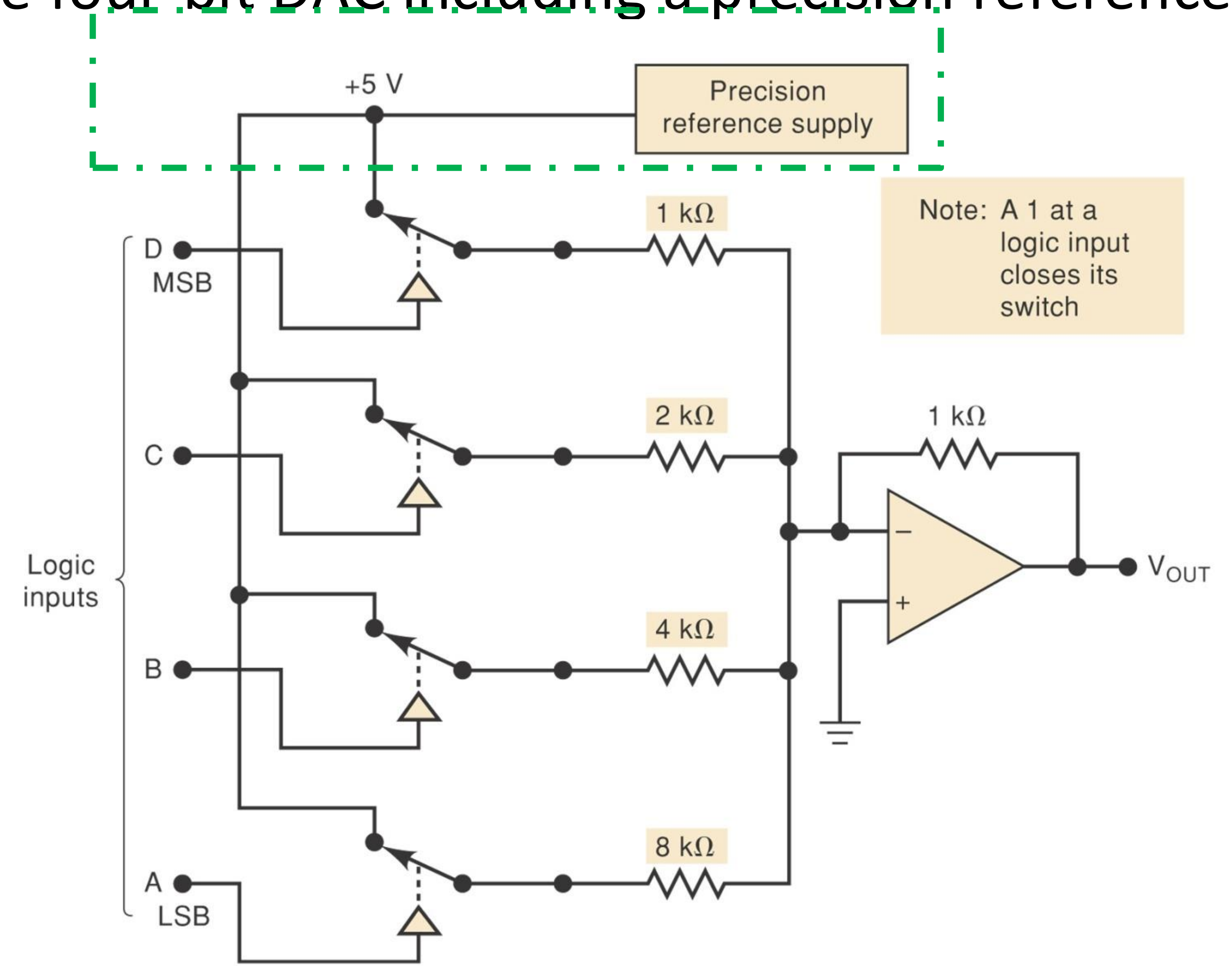
Limitations of implementation one

The output voltage depends on:

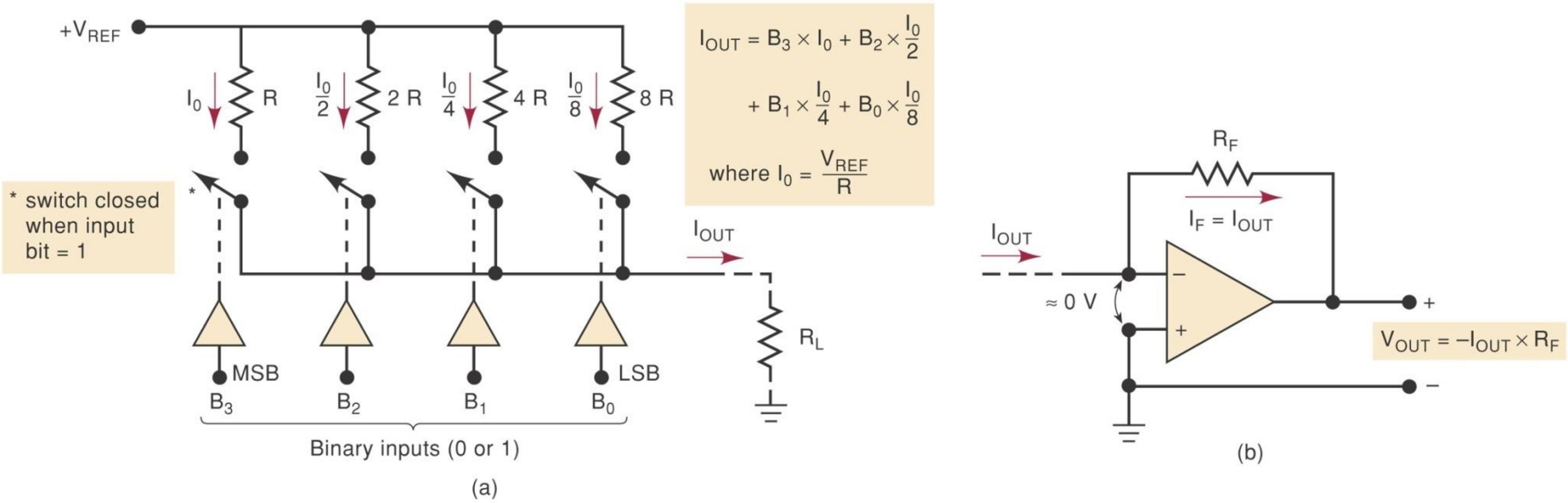
- The precision of the resistors, these can be made very accurate but a wide range of resistance values is required.

- The precision of the input voltages. This implementation requires better precision than a typical digital voltage supply. Therefore, need to use a precision voltage supply.

Complete four-bit DAC including a precision reference supply.



Calculation of the output.



Practical DAC circuitry

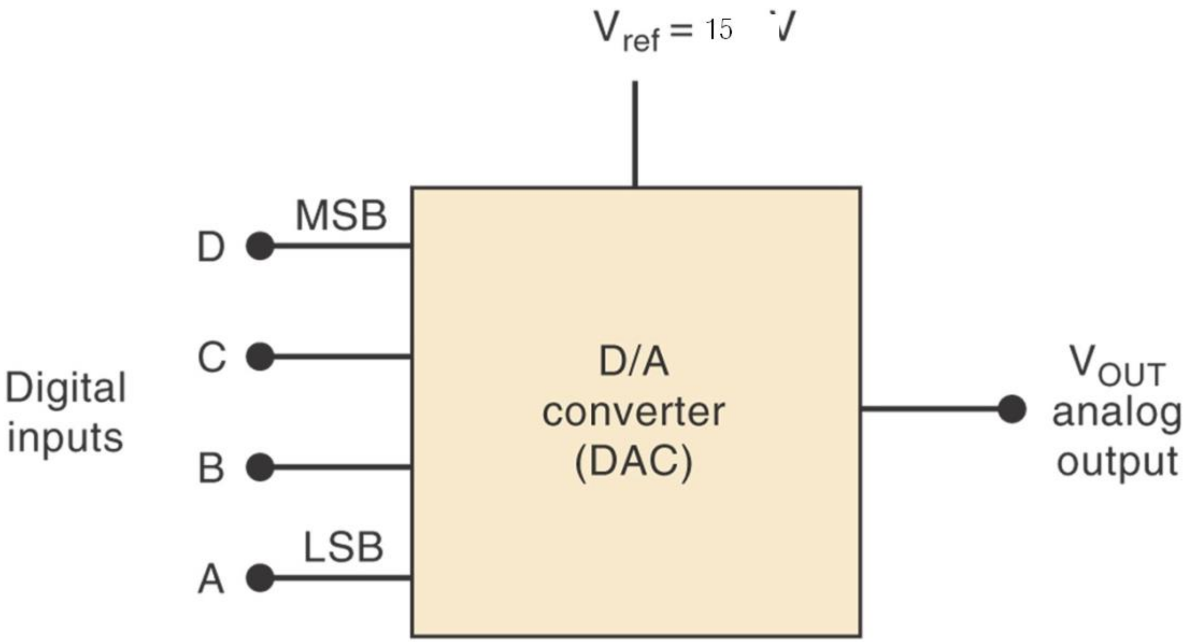
Circuits with binary weighted resistors have some problems due to the large difference in R values between the LSB and MSB.

- For a 12-bit DAC R can increase from 1 kΩ (MSB) to > 2 MΩ (LSB). Scaling this design is difficult!

Use a R-2R ladder in practice

The R-2R ladder uses resistances that span only a 2 to 1 range.

Four-bit DAC with voltage output.



(a)

D	C	B	A	V_{OUT}	
0	0	0	0	0	Volts
0	0	0	1	1	
0	0	1	0	2	
0	0	1	1	3	
0	1	0	0	4	
0	1	0	1	5	
0	1	1	0	6	
0	1	1	1	7	
1	0	0	0	8	
1	0	0	1	9	
1	0	1	0	10	
1	0	1	1	11	
1	1	0	0	12	
1	1	0	1	13	
1	1	1	0	14	
1	1	1	1	15	Volts

(b)

Problem 1

A 5-bit DAC has a current O/P. For a digital I/P of 10100 an O/P current of 10 mA is produced. What is:

(i) I_{out} for a digital I/P of 11101 ?

(ii) The full scale O/P ?

Problem 1

10100

Convert binary to decimal.

Each bit represents a power of 2:

Bit	Power of 2	Value
1	2^4	16
0	2^3	0
1	2^2	4
0	2^1	0
0	2^0	0

Add them:

16+4=20

So:

$10100_2=20_{10}$

Problem 1

$$\text{Output} = (\textit{Decimal value of binary input}) \times (\textit{Current per step})$$

$$\text{Current per step} = \frac{\textit{Known output}}{\textit{Known decimal input}}$$

Decimal input 20 gives output current 10 mA.
So each decimal step produces:

$$K = \frac{10\ mA}{20}$$

$$K = 0.5\ mA\ per\ step$$

This means:
every increase of 1 in the digital number increases output current by 0.5 mA.

Problem 1

Part (i): Find Output for 11101

Convert 11101 to Decimal

Bit	Power of 2	Value
1	2^4	16
1	2^3	8
1	2^2	4
0	2^1	0
1	2^0	1

16+8+4+1=29

$11101_2 = \mathbf{29}_{\mathbf{10}}$

Problem 1

Part (i): Find Output for 11101

Multiply by the Scale Factor

Each count = 0.5 mA.

So:

$$I_{out} = 29 \times 0.5\ mA$$
$$I_{out} = 14.5\ mA$$

Problem 1

Part (ii): Find the full scale output

A 5-bit DAC can represent:

$$00000_2 \; to \; 11111_2$$

The maximum is:

$$11111_2$$

Convert it to decimal:

$$16 + 8 + 4 + 2 + 1 = 31$$

So:

$$11111_2 = 31_{10}$$

Multiply by the Scale Factor

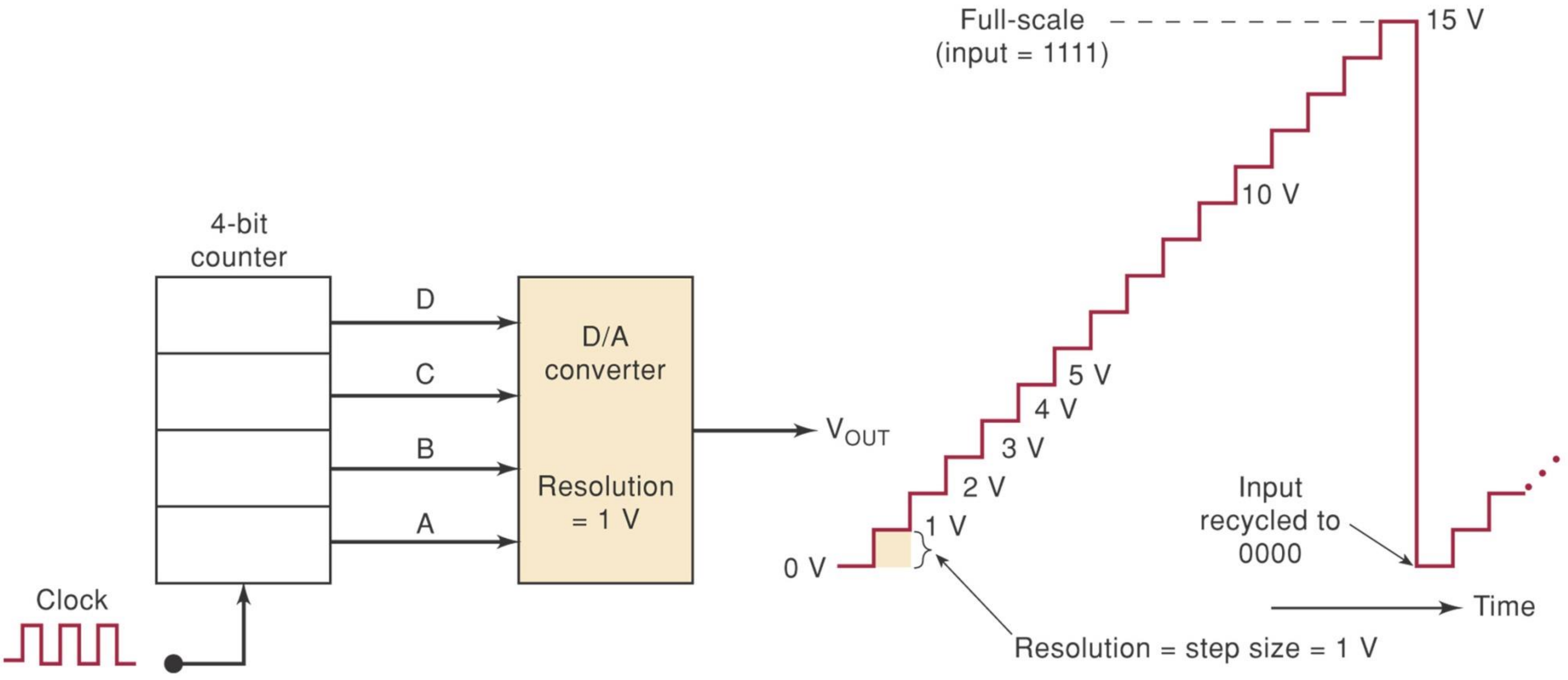
$$I_{FS} = 31 \times 0.5 \; mA$$
$$I_{FS} = 15.5 \; mA$$

Resolution (Step size)

The smallest change that can happen in the analog output as a result of change in the digital input.

The resolution is always equal to the weight of the LSB and is also referred to as the <u>step size</u> because it is the amount that V_{OUT} will change as the digital input value is changed from one step to the next.

Output waveforms of a DAC as inputs are provided by a binary counter



Resolution

Difference in O/P voltage caused by a single code bit change on the I/P.

$$\text{Resolution} = \frac{\text{Full scale analog output}}{2^n - 1}$$

$$= K$$

Percentage Resolution

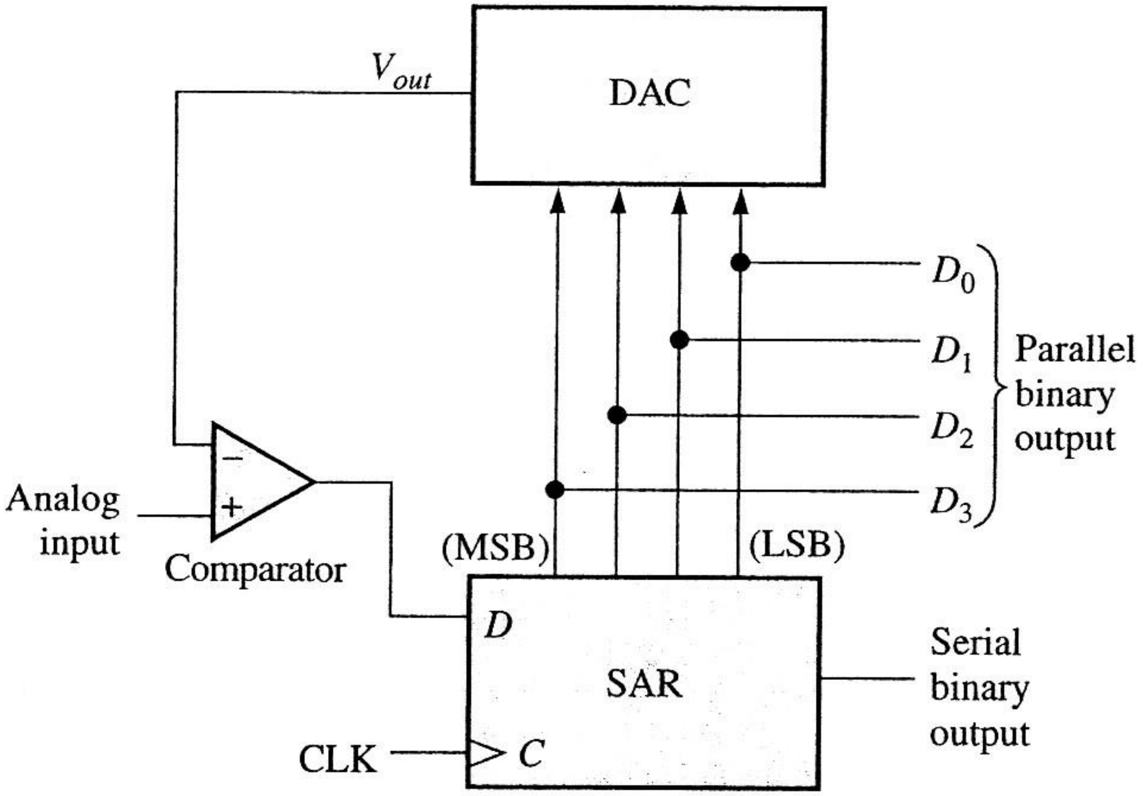
Often useful to express resolution as a % of the full scale output:

Resolution = Step Size/Full Scale x 100%

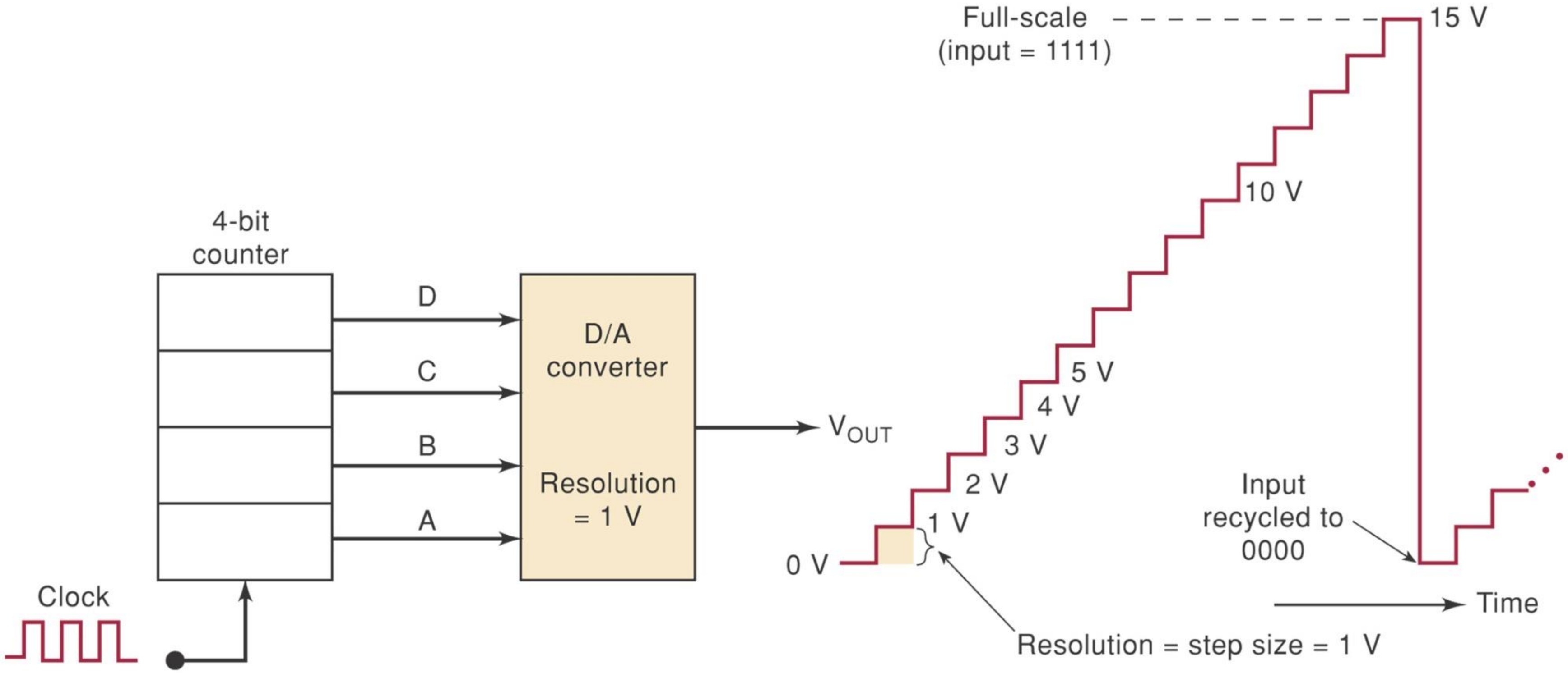
E.g.: 1V step/15 V Full scale x 100% = 6.67%

What are DACs useful for?

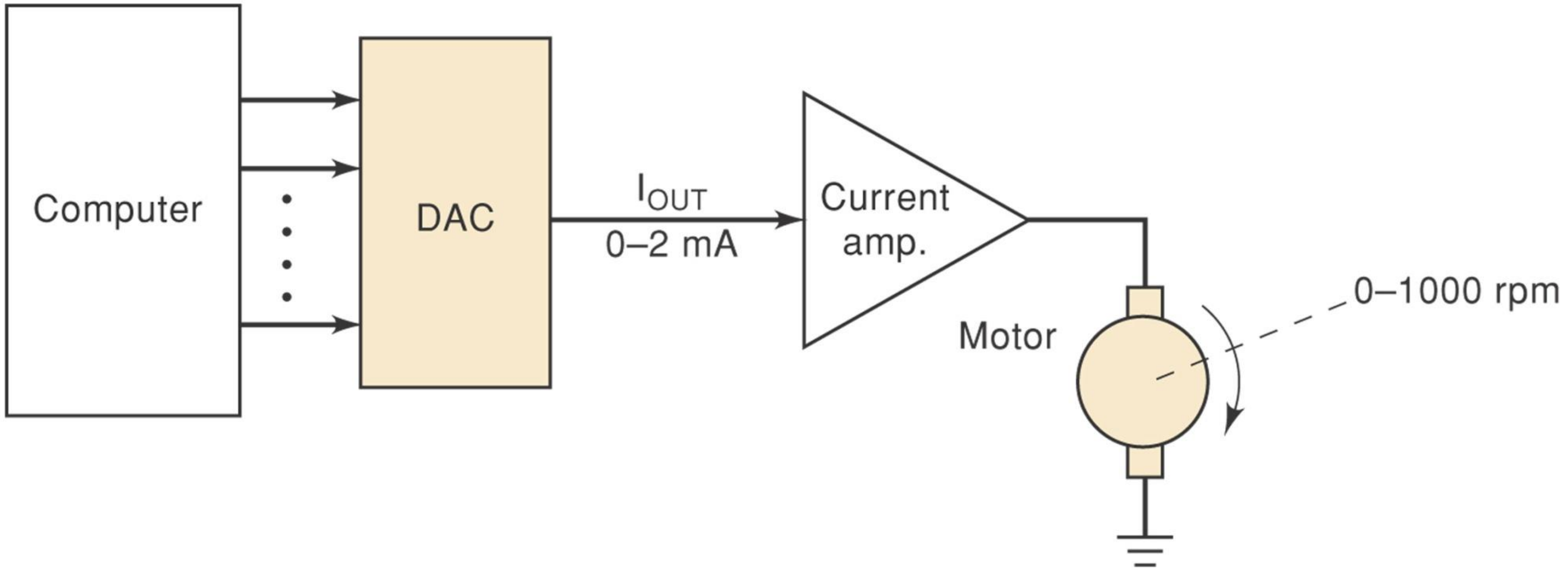
1. Essential part of many A/D converters – e.g. SAC



2. Digital waveform generators.



3. Control current/voltage output to drive a transducer or process.

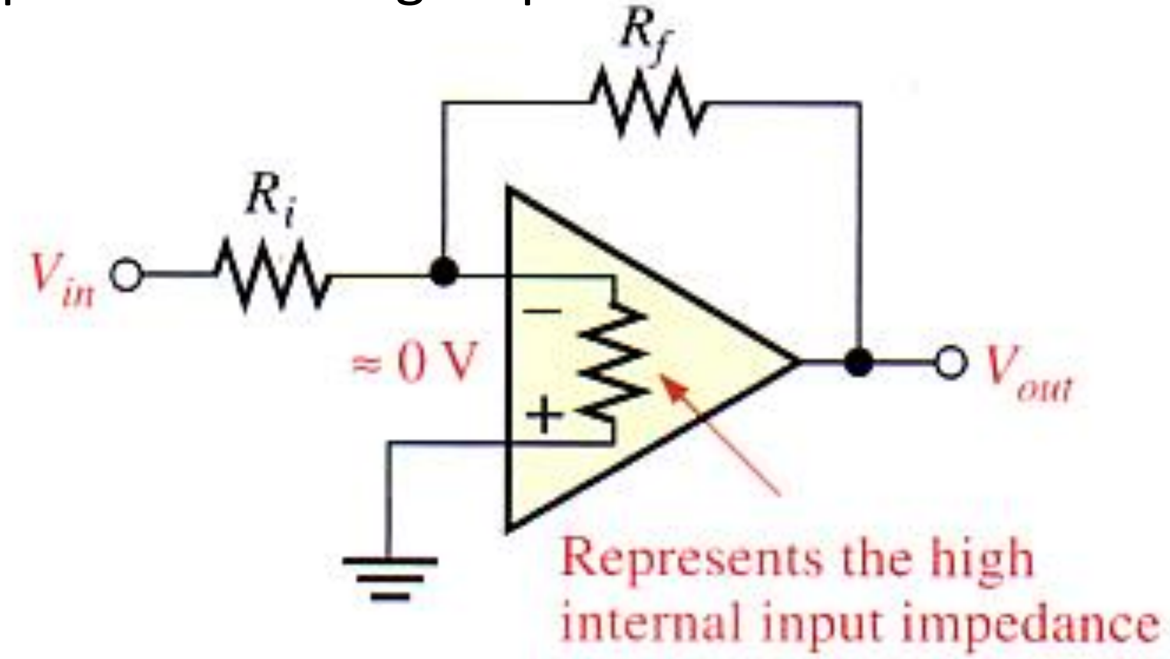


A computer controlling the speed of a motor. The 0- to 2-mA analog current from the DAC is amplified to produce motor speeds from 0 to 1000 rpm (revolutions per minute).
How many bits should be used if the computer is to be able to produce a motor speed that is within 2 rpm of the desired speed?

Using nine bits, how close to 326 rpm can the motor speed be adjusted?

Basic Construction of a Digital to Analog Converter

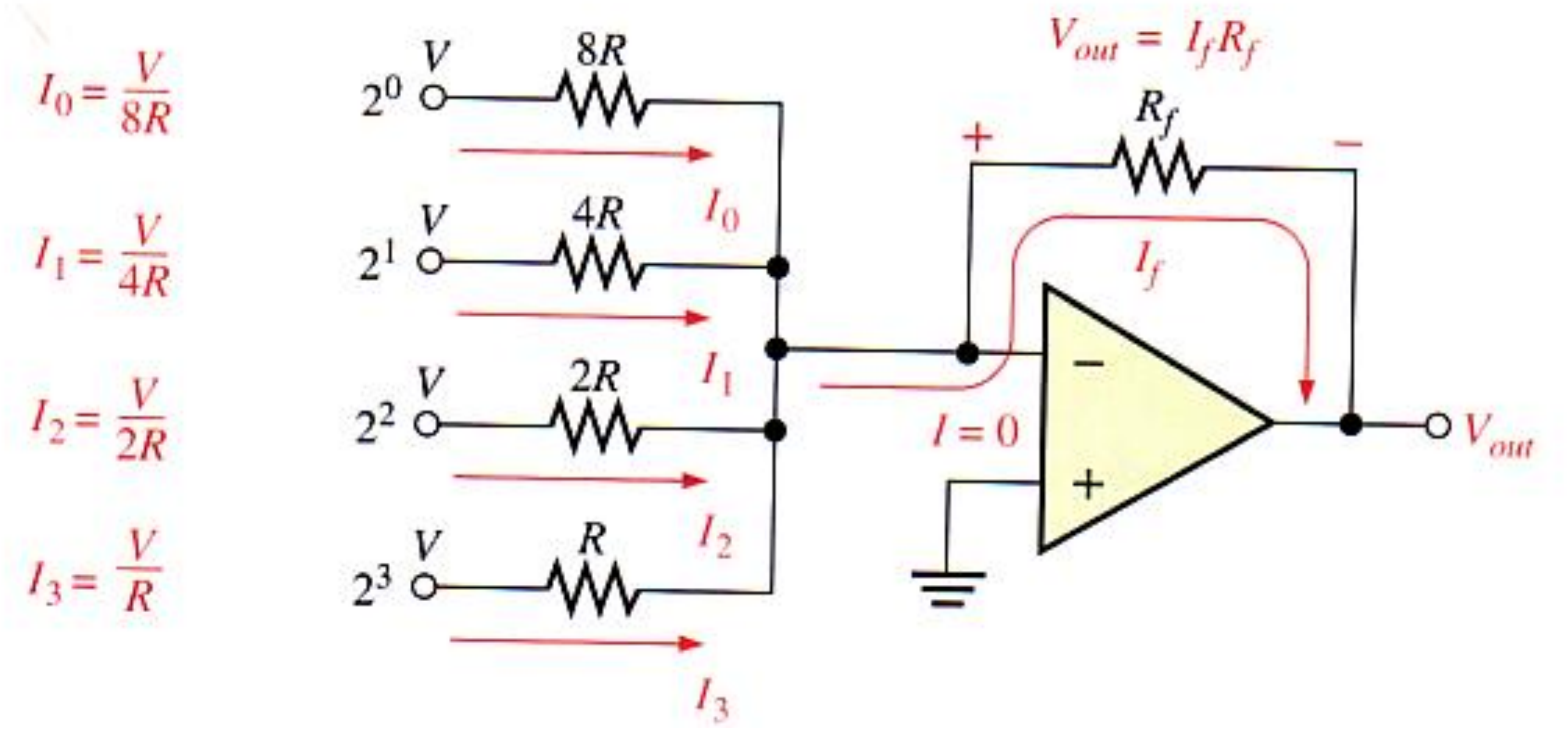
Consider the Op-amp as an inverting amplifier:



(b) Op-amp as an inverting amplifier with gain of R_f/R_i

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

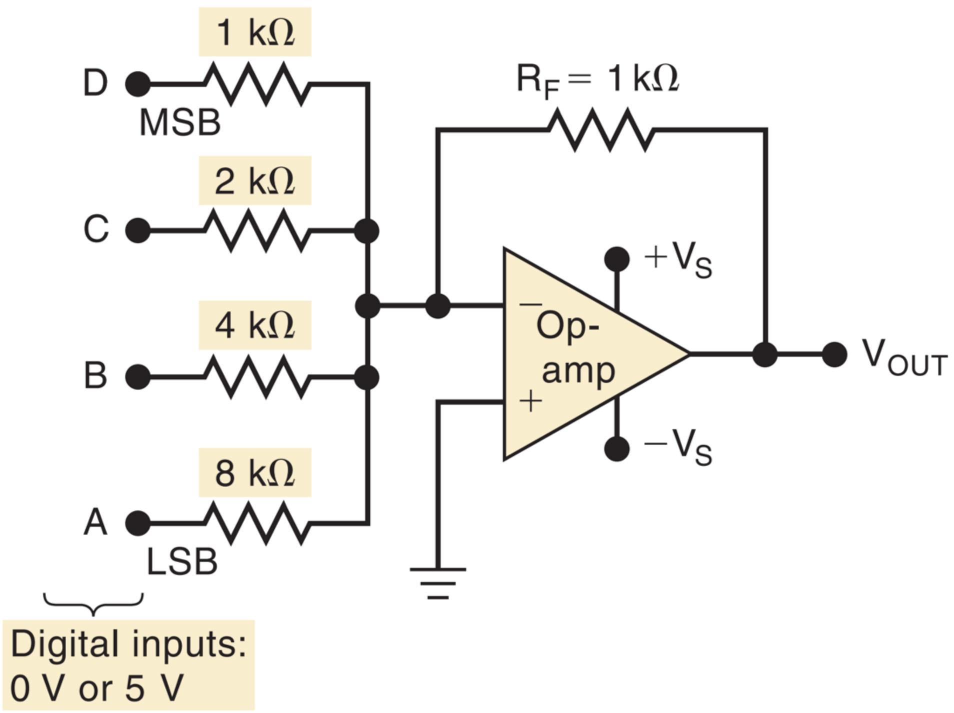
A binary weighted input D/A converter circuit



$$V_{out} = I_f R_f = \left(\frac{V}{8R} + \frac{V}{4R} + \frac{V}{2R} + \frac{V}{R}\right) R_f$$

D/A Converter Circuitry

- A summing operational amplifier with a resolution of .625 V



Input code					
D	C	B	A	V_{OUT} (volts)	
0	0	0	0	0	
0	0	0	1	−0.625	← LSB
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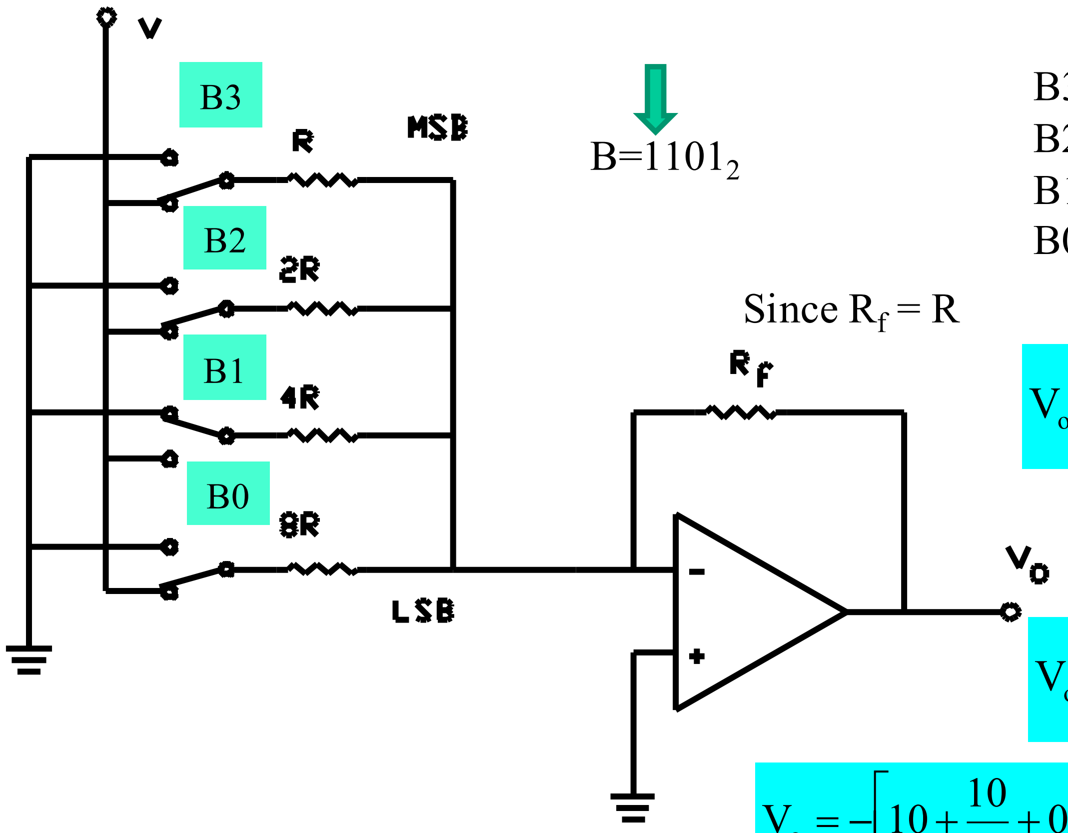
1	0	1	1	−6.875	
1	1	0	0	−7.500	
1	1	0	1	−8.125	
1	1	1	0	−8.750	
1	1	1	1	−9.375	← Full-scale

Binary Weighted DAC Example

- Example: For the binary-weighted resistor DAC below find the output when the input word is 1101_2 V = 10 Vdc, R_f = R



$B=1101_2$

n=4

B3=1 MSB
B2=1
B1=0
B0=1 LSB

Since $R_f = R$

$$V_o = -R\cdot\left[\frac{B3\cdot V}{2^{1-1}R}+\frac{B2\cdot V}{2^{2-1}R}+\frac{B1\cdot V}{2^{3-1}R}+\frac{B0\cdot V}{2^{4-1}R}\right]$$

$$V_o = -\frac{R}{R}\cdot\left[\frac{1\cdot V}{2^0}+\frac{1\cdot V}{2^1}+\frac{0\cdot V}{2^2}+\frac{1\cdot V}{2^3}\right]$$

$$V_o = -1\cdot\left[\frac{1\cdot 10}{2^0}+\frac{1\cdot 10}{2^1}+\frac{0\cdot 10}{2^2}+\frac{1\cdot 10}{2^3}\right]$$

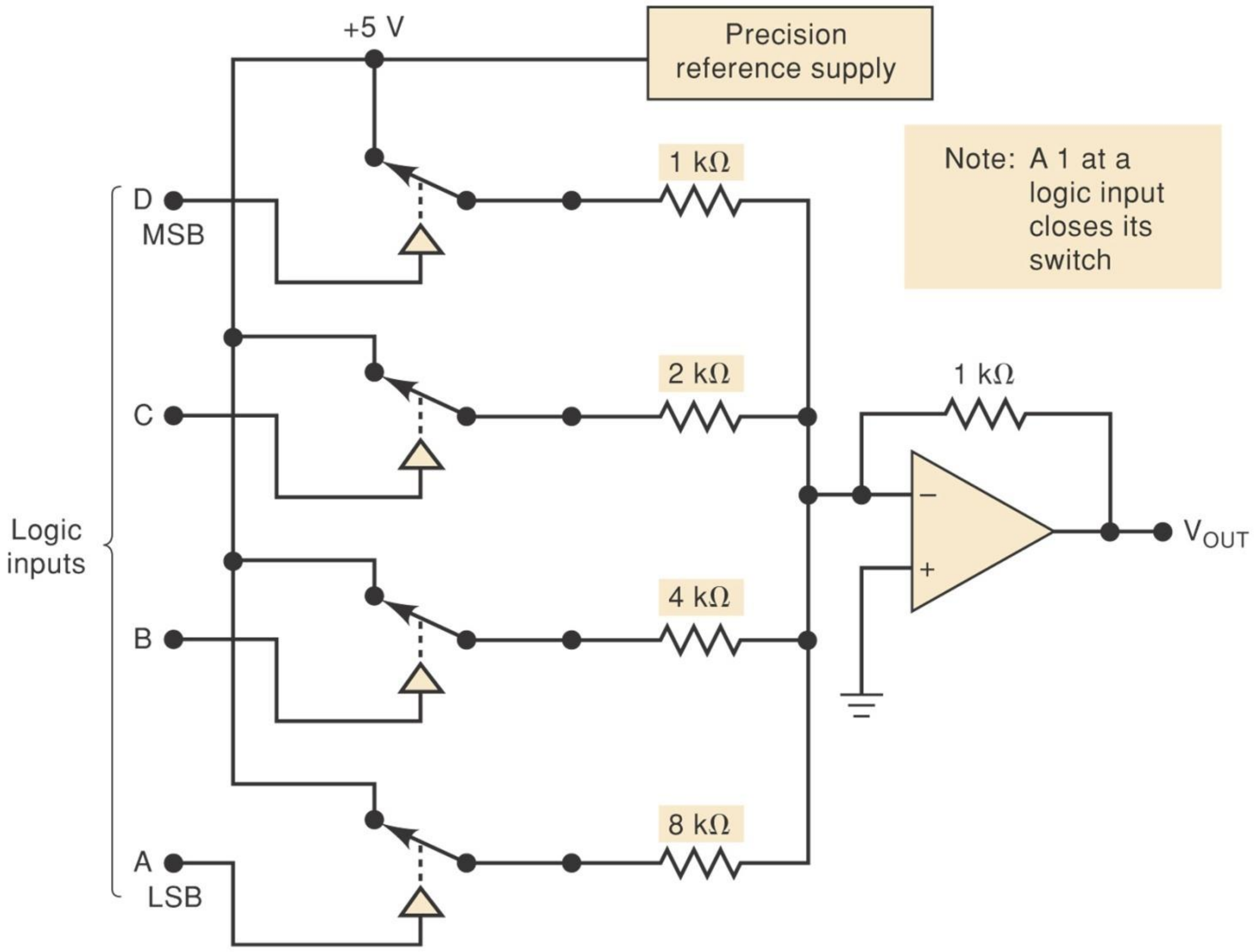
$$V_o = -\left[10+\frac{10}{2}+0+\frac{10}{8}\right] = -[10+5+1.25] = -16.25$$

Precision of the O/P voltage depends on:

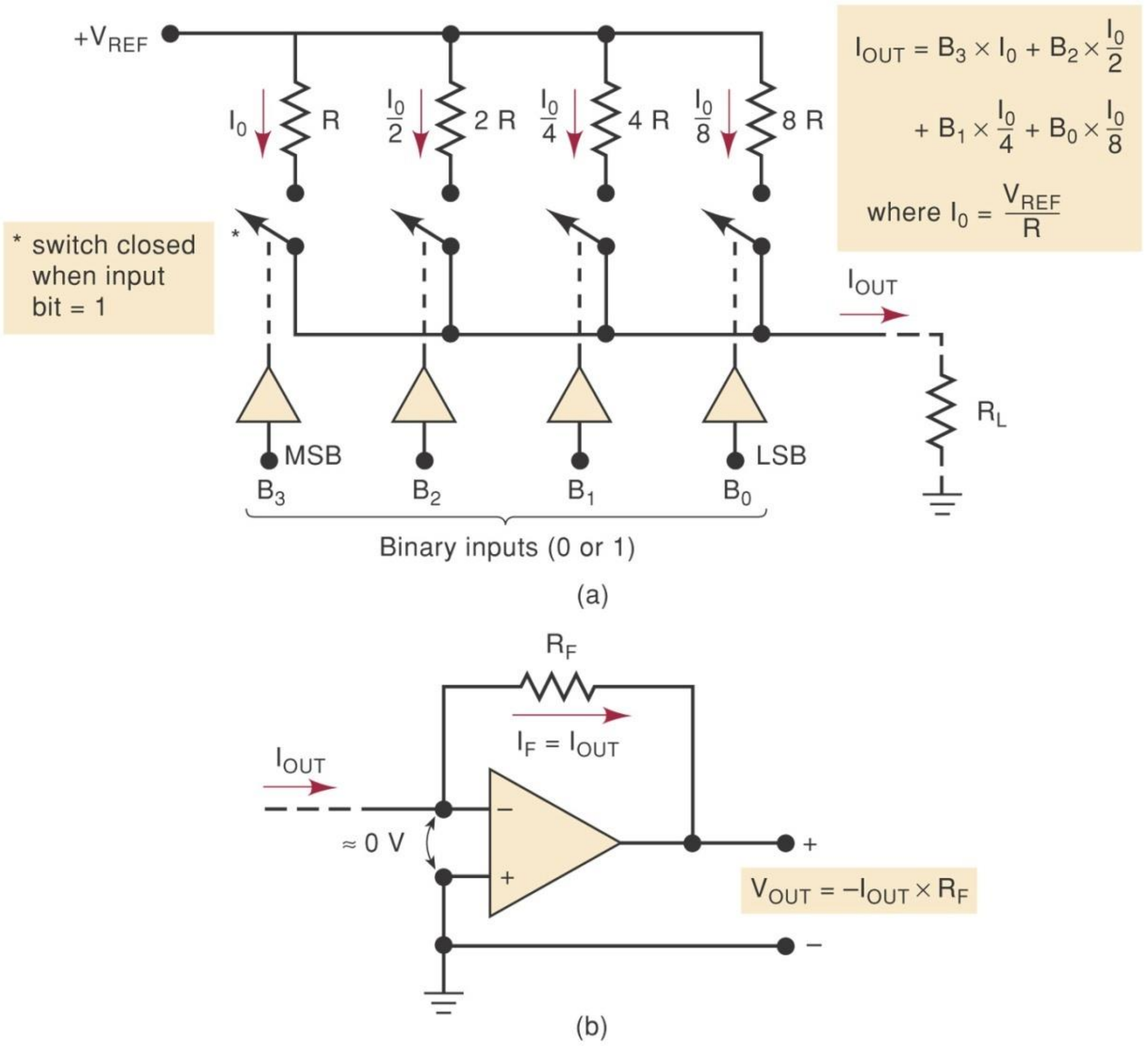
1) Precision of the resistors – can be made very accurate by trimming (But wide range needed !)
2) Precision of the I/P voltages. Need better precision than typical digital voltages. Use digital signals to select a precision voltage supply

Need additional circuitry

Complete four-bit DAC including a precision reference supply.



(a) Basic current-output DAC; (b) connected to an op-amp current-to-voltage converter.



Problem 1: Assume that V_{REF} = 10 V and R = 10 k Ω
Determine the resolution and the full-scale output for this DAC. Assume that RL is much smaller than R.

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Solution: $I_0 = V_{REF}/R$ = 1 mA. This is the weight of the MSB. The other three currents will be 0.5, 0.25, and 0.125 mA. The LSB is 0.125 mA, which is also the resolution.

The full-scale output will occur when the binary inputs are all HIGH so that each current switch is closed and

I_{OUT} = 1 + 0.5 + 0.25 + 0.125 = 1.875 mA

Note that the output current is proportional to V_{REF}. If V_{REF} is increased or decreased, the resolution and the full-scale output will change proportionally.

Practical D/A Converter Circuitry

- R/2R ladder
  - Circuits with binary weighted resistors cause a problem due to the large difference in R values between LSB and MSB
  - e.g. for 12 bits can span from 1k (MSB) to >2M for LSB
  - Rather use R/2R ladder in practice
  - The R/2R ladder uses resistances that span only a 2 to 1 range

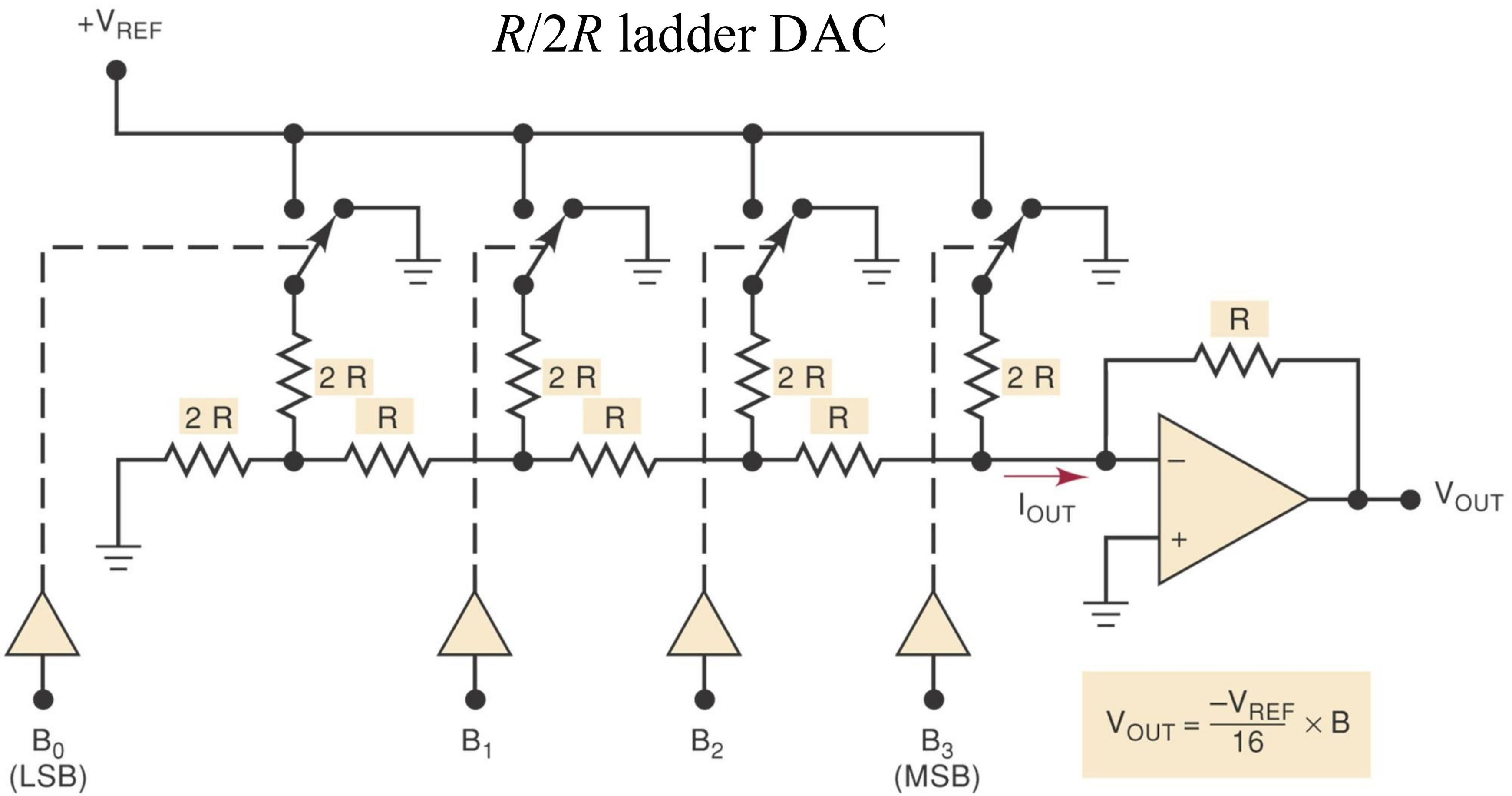
R-2R ladder

A DAC converts a **binary digital number** into an **analog voltage**.
In this example:
•It is a **4-bit DAC**

•Inputs are:
- B3 = MSB (Most Significant Bit)

- B0 = LSB (Least Significant Bit)

$R/2R$ ladder DAC

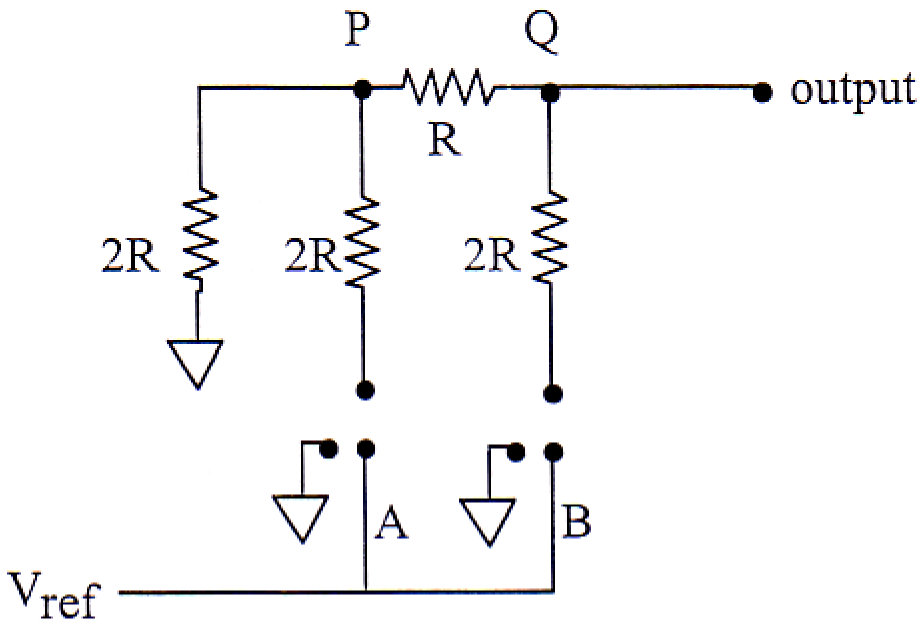


where B is the value of the binary I/P's from 0000 to 1111

$$V_{out} = \frac{V_{ref}}{2^4}\left(2^3 B_3 + 2^2 B_2 + 2^1 B_1 + 2^0 B_0\right)$$

let's look at a two-bit version.

It converts the 2-bit binary input:
AB
into an analog output voltage.



Resistors
Only two resistor values are used:

Type	Value
R	Base resistance
2R	Double resistance

$$V_{out} = \frac{V_{ref}}{2^2}(2^1 B + 2^0 A)$$

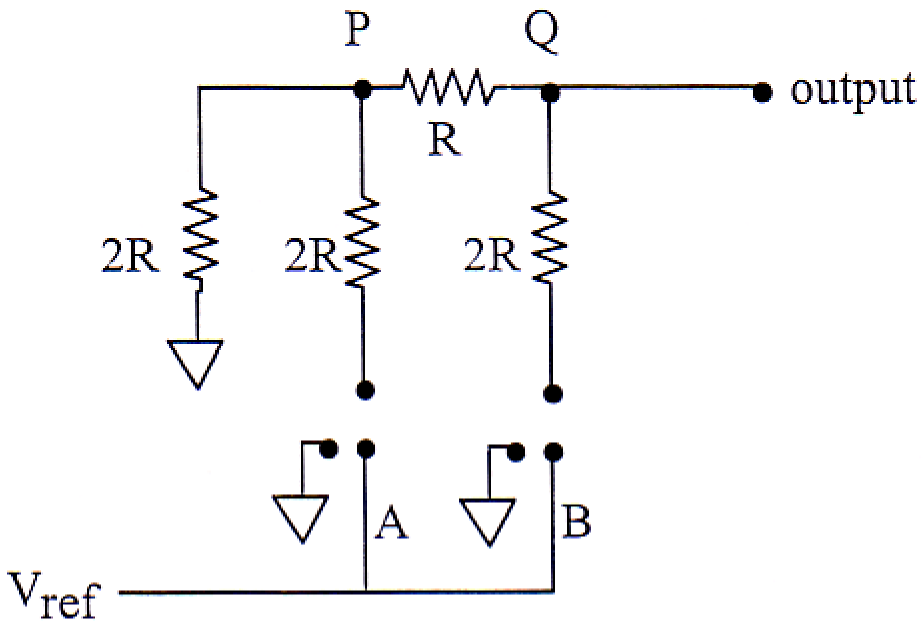
R-2R Ladder DAC (2-bit)

This circuit:

1. Uses switches to represent binary bits
2. Uses resistor ladder for binary weighting
3. Produces proportional analog voltage
4. Converts digital data → analog signal

It is the basic idea behind many DAC systems used in:

- audio devices
- microcontrollers
- signal generation
- embedded system



$$V_{out} = \frac{V_{ref}}{2^2}(2^1 B + 2^0 A)$$

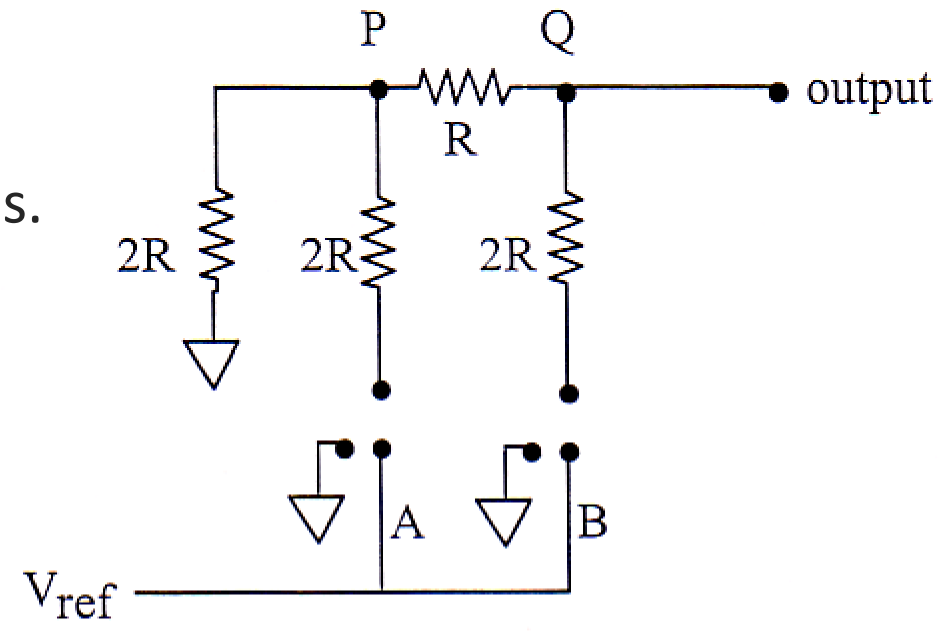
R-2R Ladder DAC (2-bit)

Each switch connects either to:
The resistor ladder creates weighted voltages.

Switch Position	Meaning
VREF	Bit = 1
Ground	Bit = 0

Bits

- A = LSB (Least Significant Bit)
- B = MSB (Most Significant Bit)



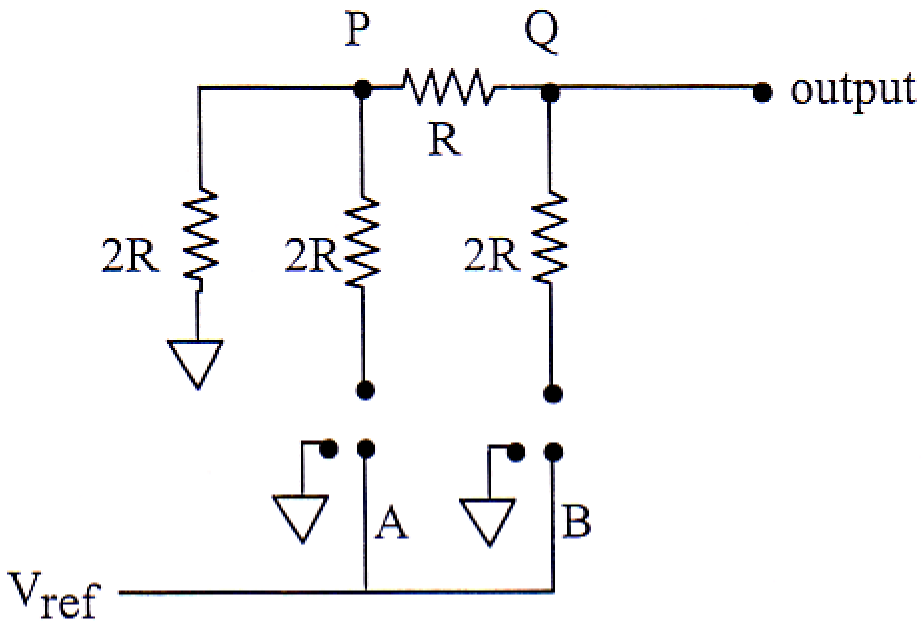
$$V_{out} = \frac{V_{ref}}{2^2}(2^1 B + 2^0 A)$$

R-2R Ladder DAC (2-bit)

$$V_{out} = \frac{V_{ref}}{2^2}(2^1 B + 2^0 A)$$

or

$$V_{out}=V_{ref}(B/2+A/4)$$



Bit	Weight
B (MSB)	1/2
A (LSB)	1/4

So:

- •MSB contributes more
- •LSB contributes less

That is how binary weighting works in an R-2R DAC.

2-bit converter

Consider the cases: B=0, A=0

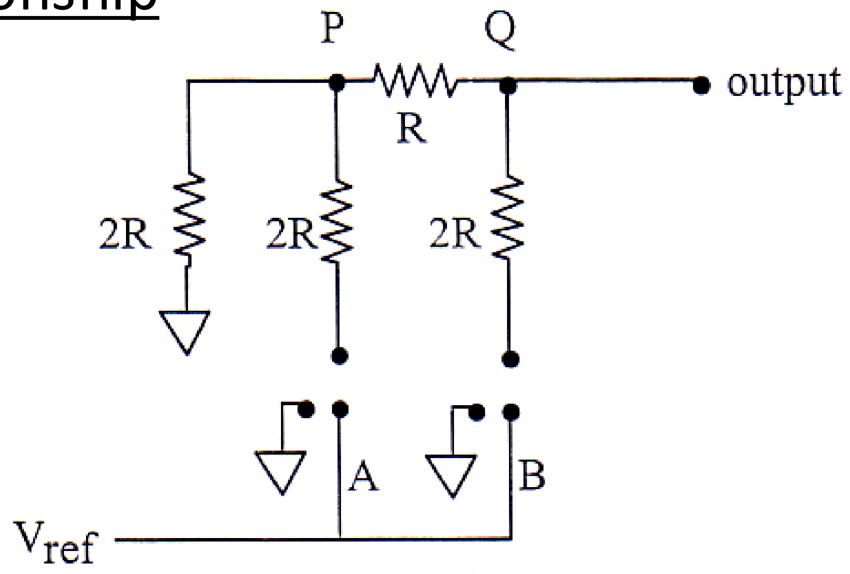
B=1, A=0

B=0, A=1

B=1, A =1

$$V_{out} = \frac{V_{ref}}{2^2}\left(2^1 B + 2^0 A\right)$$

and <u>prove that the relationship holds for all.</u>



2-bit converter

For a 2-bit DAC with bits **B** (MSB) and **A** (LSB), the output is:

$V_{out} = -V_{REF}\left(\frac{B}{2} + \frac{A}{4}\right)$ or $V_{out} = \frac{V_{ref}}{2^2}\left(2^1 B + 2^0 A\right)$

where:

- B = Most Significant Bit (MSB)
- A = Least Significant Bit (LSB)
- V_{REF} = Reference voltage

2-bit converter

Case 1: B = 0, A = 0

Binary input:

$$BA = 00$$

Substitute into the equation:

$$V_{out} = -V_{REF}\left(\frac{0}{2} + \frac{0}{4}\right)$$

$$V_{out} = 0$$

Output = 0 V

Resistance between Ground and P:

$$\frac{2R \times 2R}{2R + 2R} = R$$

Resistance between P and Q = R

Pull down resistance at the output Q

$$\frac{(R+R) \times 2R}{(R+R) + 2R} = R$$

2-bit converter

Case 2: B = 1, A = 0

Binary input:

$$BA = 10$$

Substitute:

$$V_{out} = -V_{REF}\left(\frac{1}{2} + \frac{0}{4}\right)$$

$$V_{out} = -\frac{V_{REF}}{2}$$

Output = -0.5 V_{REF}

Resistance between Ground and P:

$$\frac{2R \times 2R}{2R + 2R} = R$$

Resistance between P and Q = R

Voltage at the output Q

$$\frac{(R+R)}{(R+R)+2R} V_{ref} = \frac{1}{2} V_{ref}$$

2-bit converter

Case 3: B = 0, A = 1

Binary input:

$$BA = 01$$

Substitute:

$$V_{out} = -V_{REF}\left(\frac{0}{2} + \frac{1}{4}\right)$$

$$V_{out} = -\frac{V_{REF}}{4}$$

Output = -0.25 V_{REF}

2-bit converter

Case 4: B = 1, A = 1

Binary input:

$$BA = 11$$

Substitute:

$$V_{out} = -V_{REF}\left(\frac{1}{2} + \frac{1}{4}\right)$$

$$V_{out} = -\frac{3V_{REF}}{4}$$

Output = -0.75 V_{REF}

$$V_p = \frac{2R}{2R + 2R} V_{ref}$$

$$R_p = \frac{2R \times 2R}{2R + 2R} = R$$

$$R_Q = R_p + R$$

$$V_Q = \frac{2R}{2R + 2R}\left(V_{ref} + \frac{V_{ref}}{2}\right)$$

2-bit converter

If $V_{REF} = 10V$

B	A	Output
0	0	0 V
0	1	-2.5 V
1	0	-5.0 V
1	1	-7.5 V

After checking all four possible input combinations proves that the equation

$$V_{out} = -V_{REF}\left(\frac{B}{2} + \frac{A}{4}\right)$$

correctly describes the output of the 2-bit DAC.

N-bit converter

So for an n-bit R-2R ladder ADC we have the output given by:

$$V_{out} = \frac{V_{ref}}{2^n}\left(2^{n-1}S_{n-1} + 2^{n-2}S_{n-1} + \ldots\ldots\ldots\ldots 2^0 S_0\right)$$

where S_n represents the state (0 or 1) of the n^{th} bit in the system.

For an arbitrary n-bit R-2R ladder DAC we have the output:

$$V_{out} = \frac{V_{ref}}{2^n}(2^{n-1}S_{n-1} + 2^{n-2}S_{n-2} + \cdots + 2^0 S_0)$$

Symbol	**Meaning**
Vout	Output analog voltage
Vref	Reference voltage
n	Number of bits
S(n-1)	MSB (Most Significant Bit)
S_0	LSB (Least Significant Bit)
$2^{(n-1)}$, $2^{(n-2)}$...	Binary weights

Example: 4 bit DAC

$$V_{out} = \frac{V_{ref}}{2^n}(2^{n-1}S_{n-1} + 2^{n-2}S_{n-2} + \cdots + 2^0 S_0)$$

- Suppose: n = 4
- Then the formula becomes:

$$V_{out} = \frac{V_{ref}}{16}(2^3 S_3 + 2^2 S_2 + 2^1 S_1 + 2^0 S_0)$$

- Since:

$2^3 = 8$

$2^2 = 4$

$2^1 = 2$

$2^0 = 1$

Example: 4 bit DAC

$$V_{out} = \frac{V_{ref}}{16}(2^3 S_3 + 2^2 S_2 + 2^1 S_1 + 2^0 S_0)$$

- Suppose Binary input = 1010_2

Bit	Value
S3	1
S2	0
S1	1
S0	0

$$V_{out} = \frac{V_{ref}}{16}(8(1) + 4(0) + 2(1) + 0)$$

$$V_{out} = \frac{10V_{ref}}{16}$$

So:

```
Output = 10/16 of VREF
```

Problem: Assume that VREF = 10 V for the 4 bit DAC. What are the resolution and full-scale output of this converter?

Problem: Assume that VREF = 10 V for the 4 bit DAC. What are the resolution and full-scale output of this converter?

For a **4-bit DAC**, the digital input can represent values from:

$$0000_2 = 0 \quad \textit{to} \quad 1111_2 = 15$$

There are: $2^4 = 16$ possible output levels.

DAC Output Formula

For an ideal 4-bit DAC:

$$V_{out} = -V_{REF}\left(\frac{B}{2^4}\right)$$

where:

- $V_{REF} = 10\ V$
- B = decimal value of the binary input
- $2^4 = 16$

Problem: Assume that VREF = 10 V for the 4 bit DAC. What are the resolution and full-scale output of this converter?

1. Resolution

Resolution is the smallest change in output voltage caused by a 1-bit change in the input (the weight of the LSB).

Set only the LSB to 1:

$$B = 0001_2 = 1$$

Substitute into the formula:

$$V_{out} = -10\left(\frac{1}{16}\right)$$

$$V_{out} = -0.625\ V$$

Therefore,

$$\boxed{\text{Resolution} = 0.625\ V/step}$$

(The negative sign simply indicates the DAC is an inverting DAC. Resolution is usually quoted as the magnitude.)

Problem: Assume that VREF = 10 V for the 4 bit DAC. What are the resolution and full-scale output of this converter?

2. Full-Scale Output

Full-scale output occurs when all bits are 1:

$$B = 1111_2 = 15$$

Substitute into the formula:

$$V_{out} = -10\left(\frac{15}{16}\right)$$

$$V_{out} = -9.375\ V$$

Therefore,

$$\boxed{\text{Full−scale output} = -9.375\ V}$$

Problem: Assume that VREF = 10 V for the 4 bit DAC. What are the resolution and full-scale output of this converter?

Answer:

The resolution is equal to the weight of the LSB, which we can determine by setting B = 0001 = 1

resolution = -10 V * 1/16 = -0.625 V

The full-scale output occurs for B = 1111 = 15_{10}.

full scale = -10 V * 15/ 16 = -9.375 V

Questions ?

A.What is the advantage of R/2R ladder DACs over those that use binary weighted resistors?

B. A certain six-bit DAC uses binary-weighted resistors. If the MSB resistor is 20 k Ω what is the LSB resistor?

C. What will happen to both resolution and full-scale output when V_{REF} is increased by 20 percent?

Questions ?

A. What is the advantage of R/2R ladder DACs over those that use binary weighted resistors?

Ans: It uses only two different sizes of resistors.

B. A certain six-bit DAC uses binary-weighted resistors. If the MSB resistor is 20 k Ω what is the LSB resistor?

Ans: 640 k Ω.

C. What will happen to both resolution and full-scale output when VREF is increased by 20 percent?

Ans: Increases by 20 percent.

DAC Specification

- A wide variety of DACs are available as ICs or as self-contained, encapsulate packages.
- One should be familiar with the more important manufacturers' specifications in order to evaluate a DAC for a particular application.
  - Resolution: the percentage resolution of a DAC depends solely on the number of bits.
  - Accuracy: The two most common are called full-scale error and linearity error, which are normally expressed as a percentage of the converter's full-scale output (% F.S.). It is important to understand that accuracy and resolution of a DAC must be compatible.

Input Code	Ideal Output (mV)	Actual Output (mV)
0000	0	2
0001	100	102
1000	800	802
1111	1500	1502

A DAC IC – TI DAC0800LCN

Texas Instruments have an IC, the DAC0800 digital to analog converter.

- DAC0800
  - 8-bit resolution
  - Uses R-2R ladder network
  - Max settling time is 100 ns
  - Full range accuracy is ± 0.2% Full-Scale.
  - Reference voltage typically 10 V.
  - Power supply typically from ± 5 V to ± 15 V.

A DAC IC – TI DAC0800LCN

Typical Applications

DAC08 is used in:

- waveform generation
- audio systems
- motor control
- instrumentation
- embedded systems
- microcontroller interfacing

DAC Specification

- Offset error: Ideally, the output of a DAC will be zero volts when the binary input is all 0s. In practice, however, the output voltage will be very small in this situation; this is called **offset error.**

Output examples showing an offset of 2mv

- Settling Time: The operating speed of a DAC is usually specified by giving its settling time, which is the time required for the DAC output to go from zero to full scale as the binary input is changed from all 0s to all 1s.

Input Code	Ideal Output (mV)	Actual Output (mV)
0000	0	2
0001	100	102
1000	800	802
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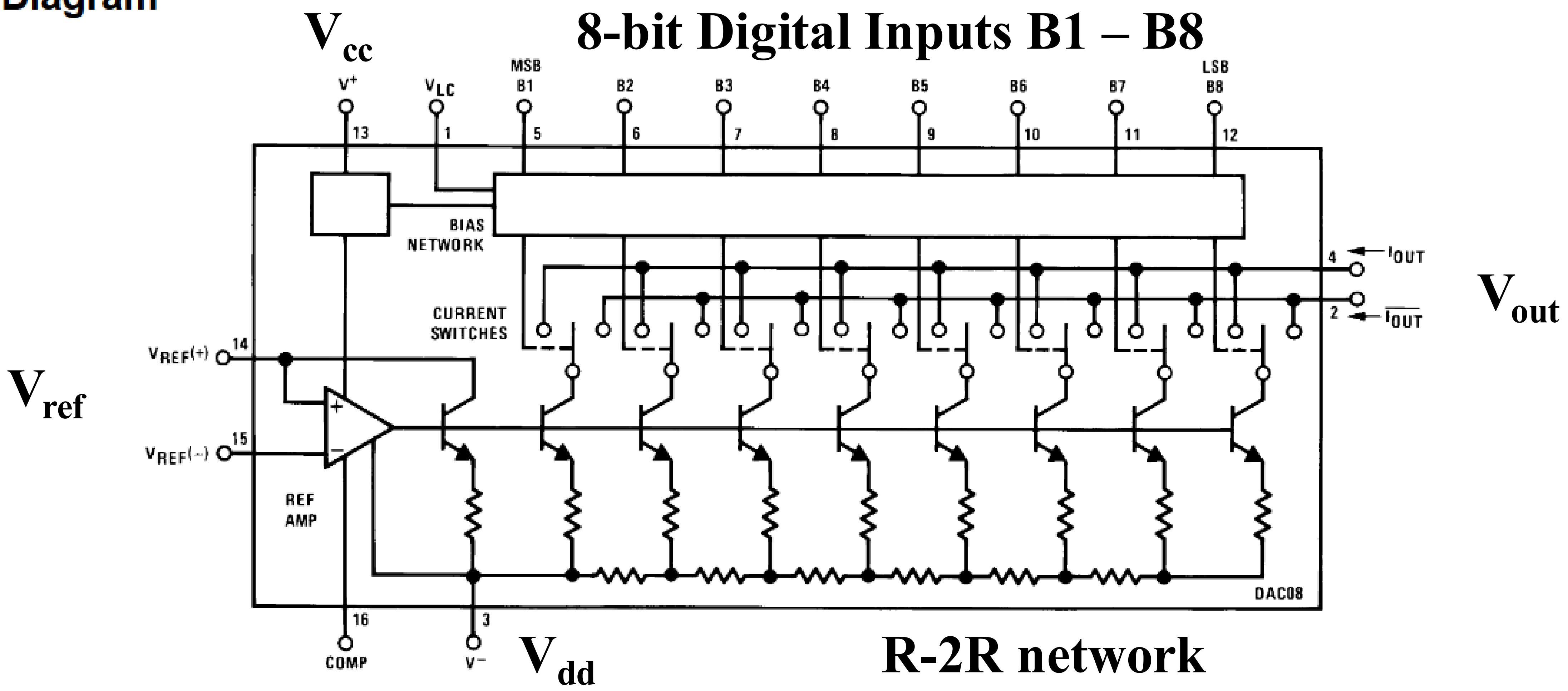
A DAC IC – TI DAC0800LCN

Block Diagram



Pin numbers represent the PDIP package. The SOIC package pin numbers differ from that of the PDIP package.

Figure 4.

DAC - Main parts

1. Digital Inputs (B1–B8)
2. Bias Network
3. Current Switches
4. Weighted Current Sources
5. Reference Amplifier (REF AMP)
6. Output Pins

DAC - Main parts

1. Digital Inputs (B1–B8)

At the top:

- B1 = MSB (Most Significant Bit)
- B8 = LSB (Least Significant Bit)

These pins receive binary data.

Each bit controls a current switch inside the DAC.

Binary Input	Meaning
10000000	Half-scale output
11111111	Full-scale output
00000001	Smallest output

DAC - Main parts

2. Bias Network

This section generates stable internal operating currents.

It ensures:

- accurate conversion
- stable operation
- proper weighting of each bit

Think of it as the “control center” for current distribution.

DAC - Main parts

3. Current Switches

Each input bit controls a switch.

If the bit = 1:

•the switch turns ON

•current contributes to output

If the bit = 0:

•the switch turns OFF

•no contribution

Higher bits contribute more current.

DAC - Main parts

4. Weighted Current Sources

The transistor-resistor network at the bottom creates binary-weighted currents.

Each bit has a different weight.
So the MSB contributes the largest current.

Bit	Weight
B1 (MSB)	128
B2	64
B3	32
B4	16
B5	8
B6	4
B7	2
B8 (LSB)	1

DAC - Main parts

5. Reference Amplifier (REF AMP)

Pins:

- VREF(+)
- VREF(-)

This section determines the reference current.

The reference voltage controls:

- full-scale output current
- DAC range

Higher reference voltage → larger analog output.

DAC - Main parts

6. Output Pins

Two outputs:

•IOUT

•\overline{IOUT} (complementary output)

These are current outputs.

Usually an op-amp is connected to convert current into voltage.

DAC - Main parts

Pin	Function
V+	Positive power supply
V−	Negative power supply
VREF(+)	Positive reference voltage
VREF(−)	Negative reference
B1–B8	Digital inputs
IOUT	Analog current output
COMP	Compensation pin

DAC - **How It Works**

Suppose input is: 10110010

The DAC turns ON the corresponding switches.
Currents are added according to bit weights:
128 + 32 + 16 + 2 = 178
So output current becomes:
178 / 255 of full-scale current

larger binary number → larger analog output
smaller binary number → smaller analog output

That means:

- B1 = 1
- B2 = 0
- B3 = 1
- B4 = 1
- B5 = 0
- B6 = 0
- B7 = 1
- B8 = 0

DAC Applications

Used when a digital circuit output must provide an analog voltage or current

- Control
  Use a digital computer output to adjust motor speed or furnace temperature
- Automatic testing
  Computer generated signals to test analog circuitry
- Signal reconstruction
  Restoring an analog signal after it has been converted to digital. Audio CD systems, and audio/video recording
- Analog to digital conversion
- Direct Digital Synthesis

Problem: A certain eight-bit DAC has a full-scale output of 2 mA and a full-scale error of $\pm$0.5% F.S. What is the range of possible outputs for an input of 10000000?

Problem: A certain eight-bit DAC has a full-scale output of 2 mA and a full-scale error of $\pm$0.5% F.S. What is the range of possible outputs for an input of 10000000?

Answer:

The step size is 2 mA/255 = 7.84 μ A.

Since 10000000 = 128_{10}, the ideal output should be

128 * 7.84 μA = 1004 μ A.

The error can be as much as

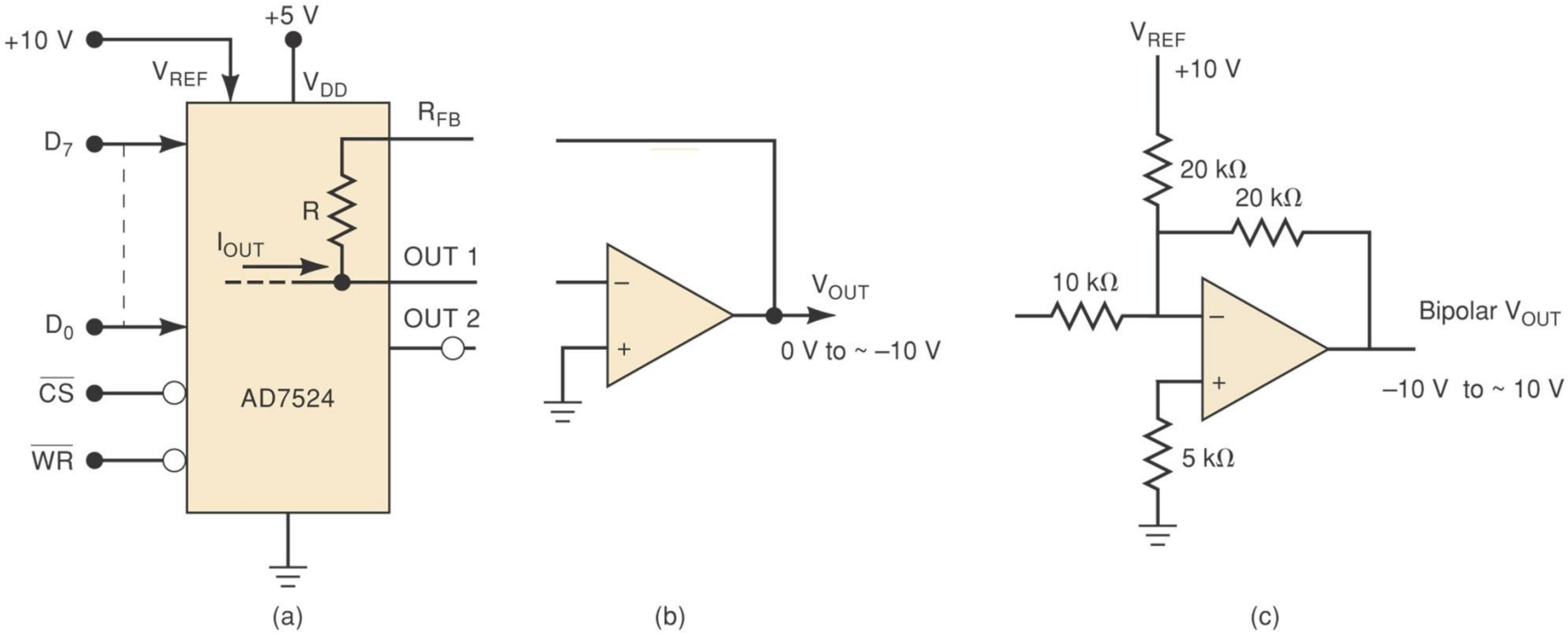
$\pm$ 0.5% * 2 mA = $\pm$ 10 μ A

Thus, the actual output can deviate by this amount from the ideal 1004 μ A, so the actual output can be anywhere from 994 to 1014 μ A.

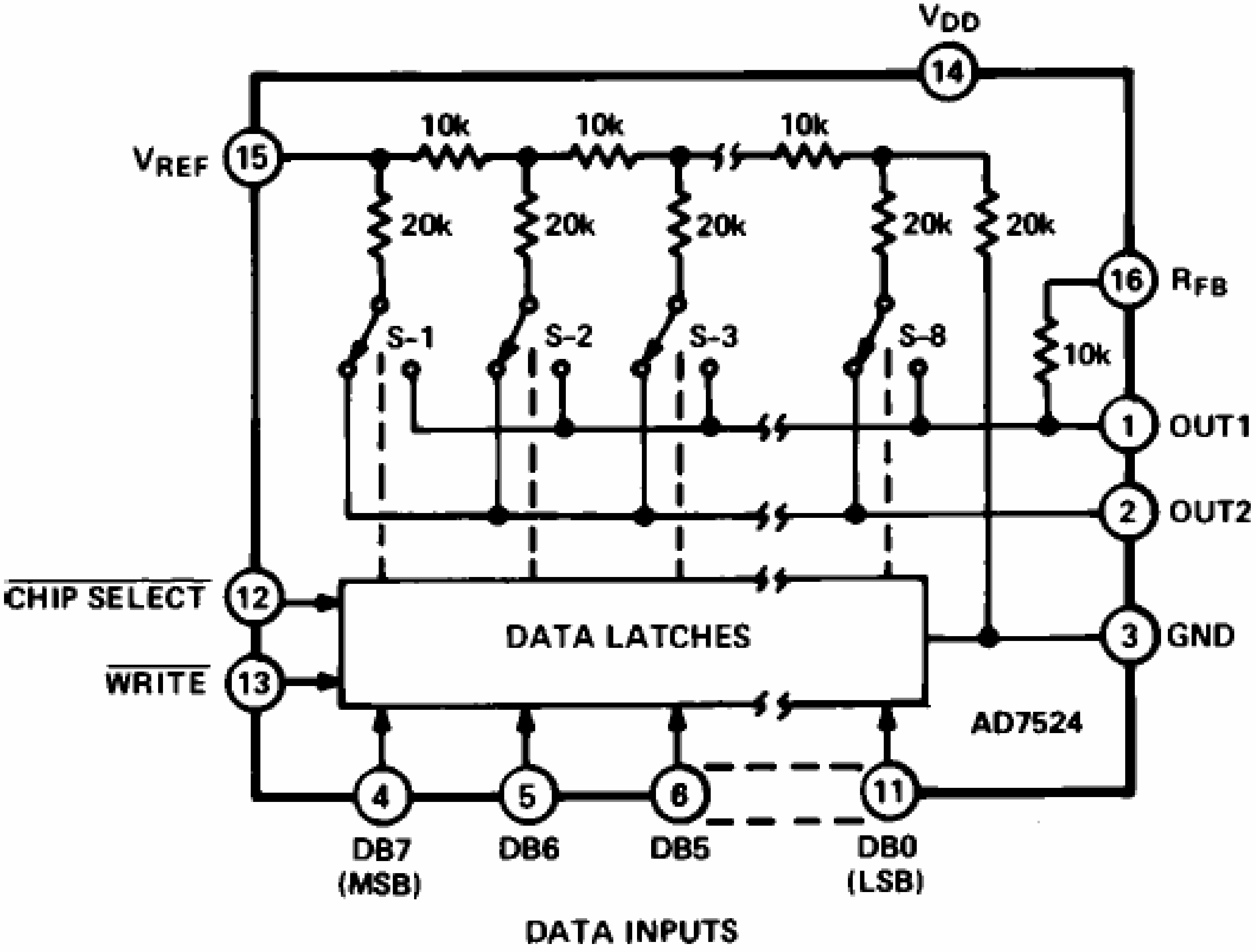
An IC DAC

- AD7524
  - CMOS IC
  - 8 bit D/A
  - Uses R/2R ladder network
  - Max settling time is 100 ns
  - Full range accuracy is +/- 0.2% F.S.
  - Reference voltage can be negative and positive from 0 to 25 V.

(a) AD7524 8-bit DAC with latched inputs;
(b) op-amp current-to-voltage converter provides 0 to approximately -10 V out;
(c) op-amp circuit to produce bipolar output from -10 V to approximately +10 V.



FUNCTIONAL BLOCK DIAGRAM



DAC Applications

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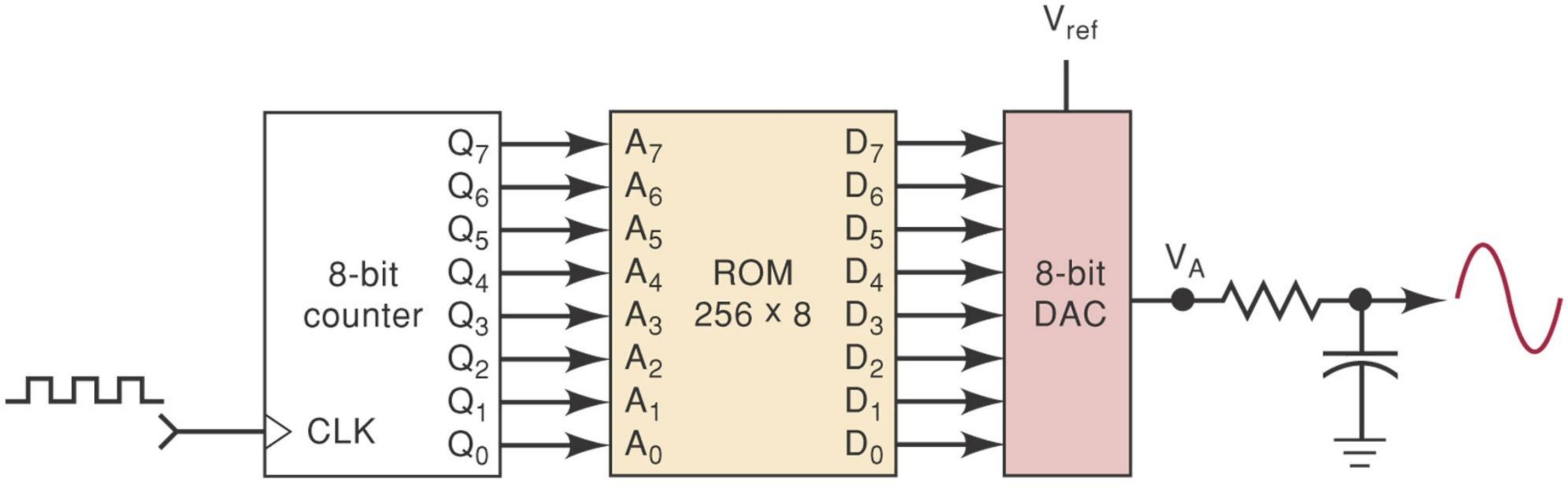
  - Direct Digital Synthesis

Generating a sinusoidal waveform.

Generating a sinusoidal waveform is a common D/A application. This will typically use the following parts:

- A clock for pulse generation
- A counter driven by the clock
- A sine (or waveform coded) ROM
- An DAC driven by the ROM O/P
- A low pass filter to reduce distortion or other signal shaping circuitry

Creating a waveform by using a ROM and a DAC

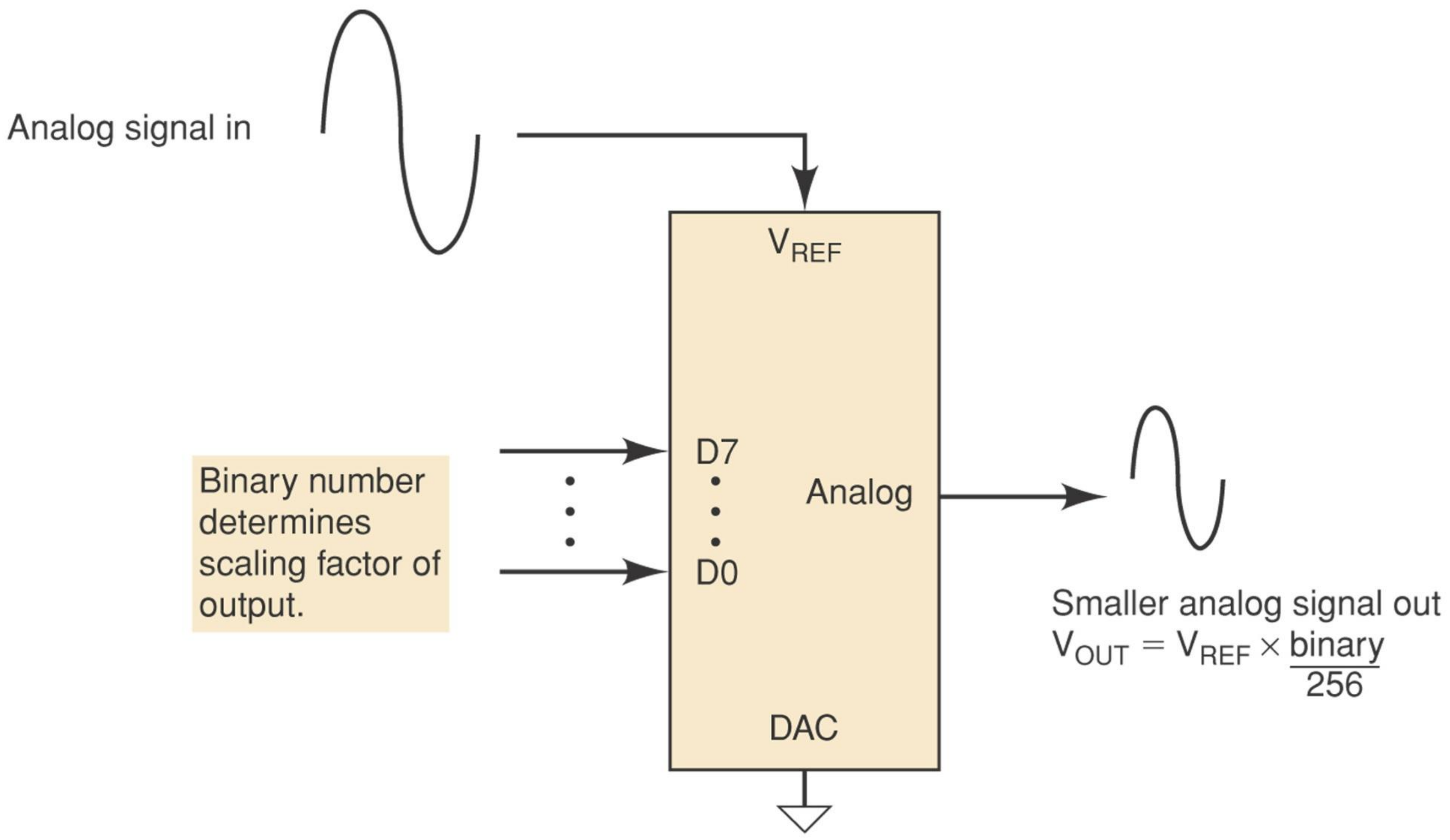


A common way to generate waveforms digitally is by using a **ROM (Read-Only Memory)** and a **DAC (Digital-to-Analog Converter)**.

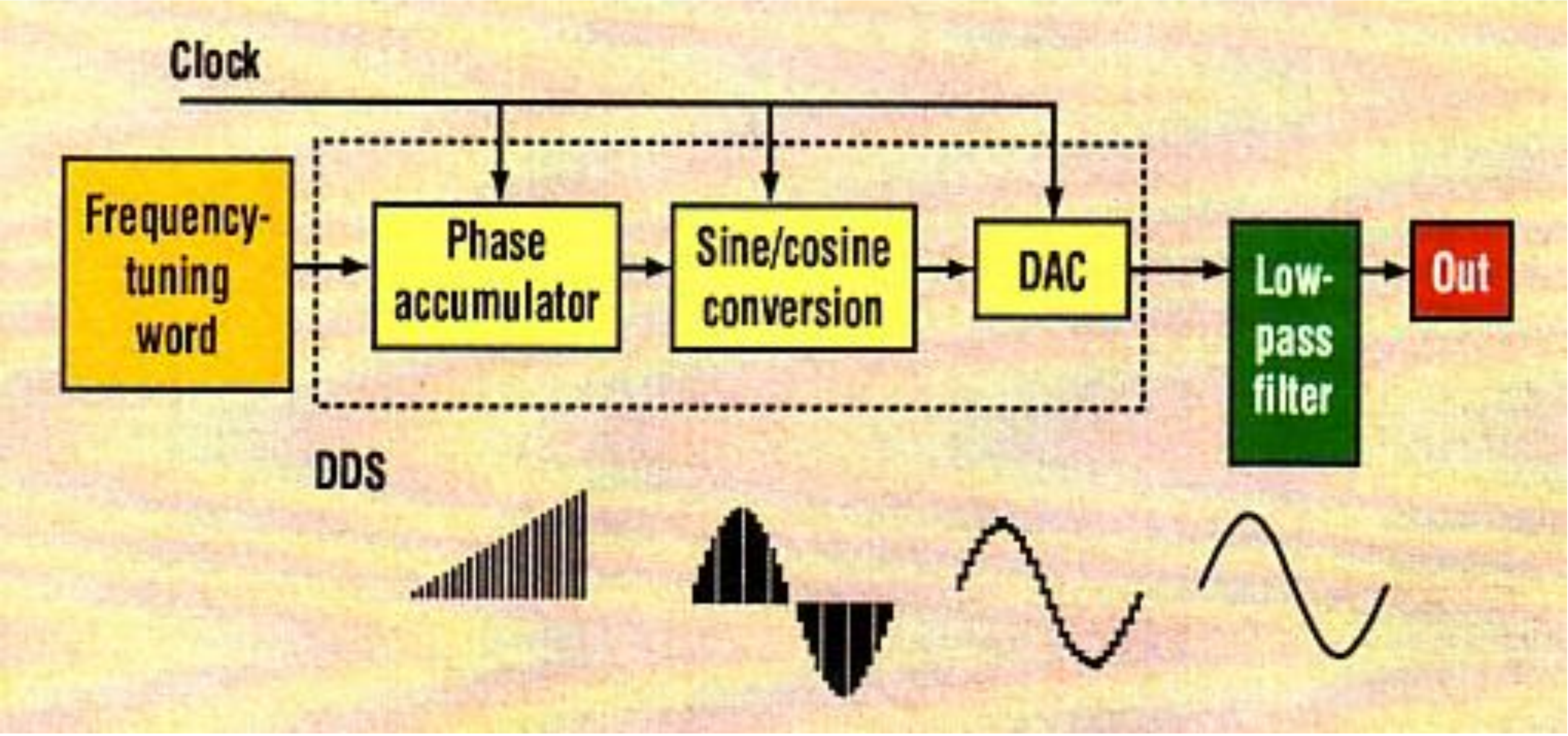
Basic Idea

1. Store waveform samples in the ROM.
2. Read the samples one by one using a clock.
3. Send each sample to the DAC.
4. The DAC converts the digital samples into analog voltages.
5. A low-pass filter smooths the output into a continuous waveform.

A DAC used to control the amplitude of an analog signal.



DAC forms an integral part of DDS systems.



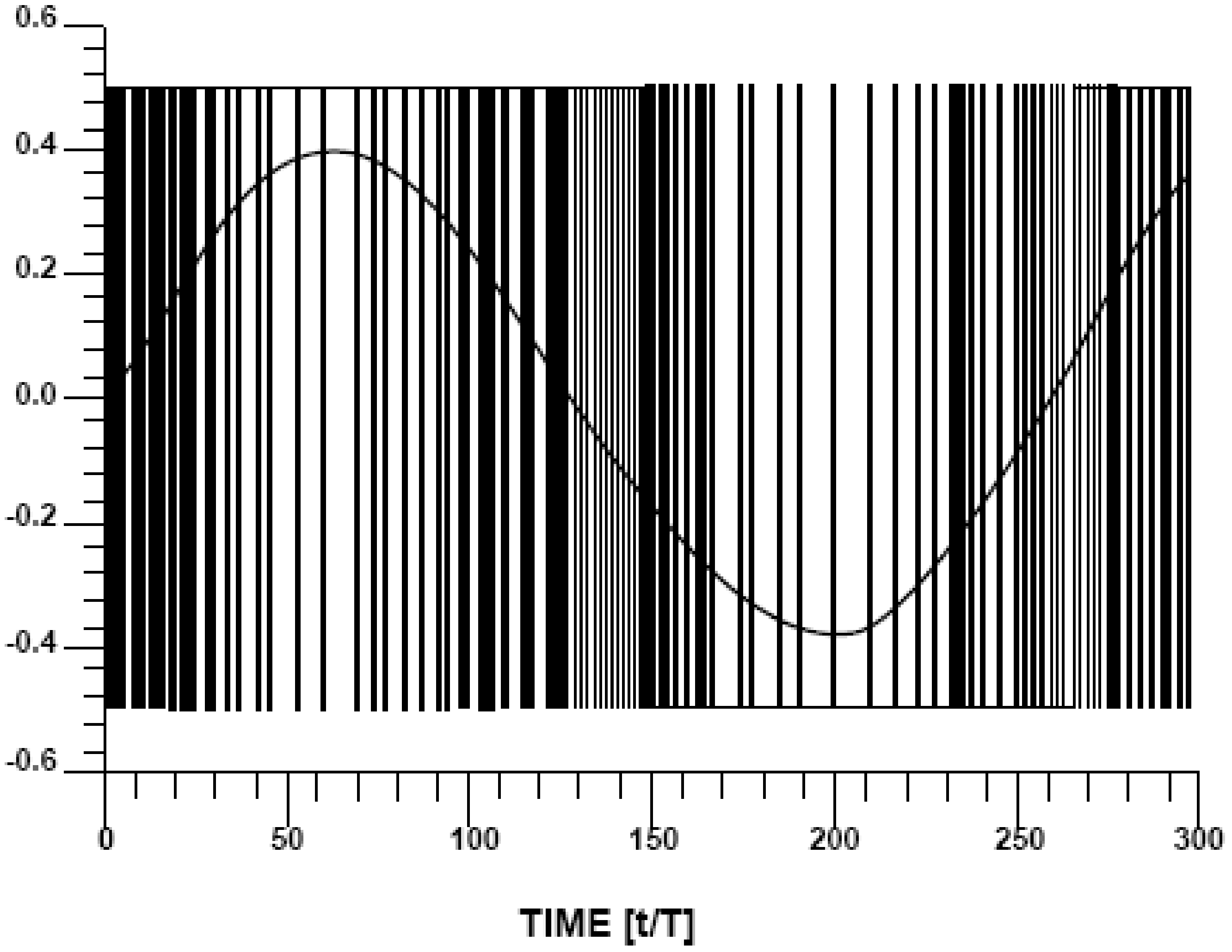
DAC forms an integral part of DDS systems.

DAC in a DDS System
DDS (Direct Digital Synthesis) is a method of generating analog waveforms (sine, square, triangle, etc.) using digital circuitry.

The **DAC (Digital-to-Analog Converter)** is a key component in a DDS system because it converts the digitally generated waveform samples into a continuous analog signal.

Pulse Width Modulation (PWM) DAC

A single digital output can be used to generate a waveform!
This is done by low pass filtering a PWM output.



This method is used in high power sub woofer amplifiers!!

Called "class D"