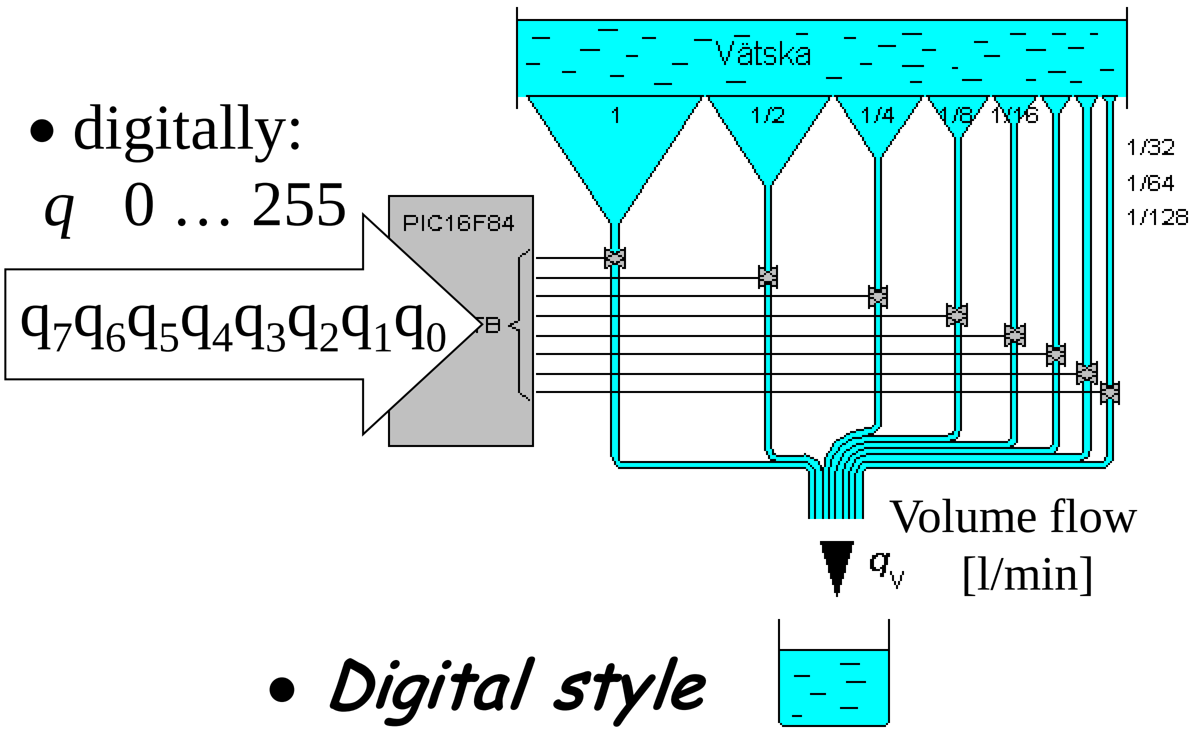
Digital or Analog

1 ½ ¼ 1/8 1/16 1/32 1/64 1/128

binary coded funnels

- digitally:

q 0 … 255



- ***Digital style***

- or analog?

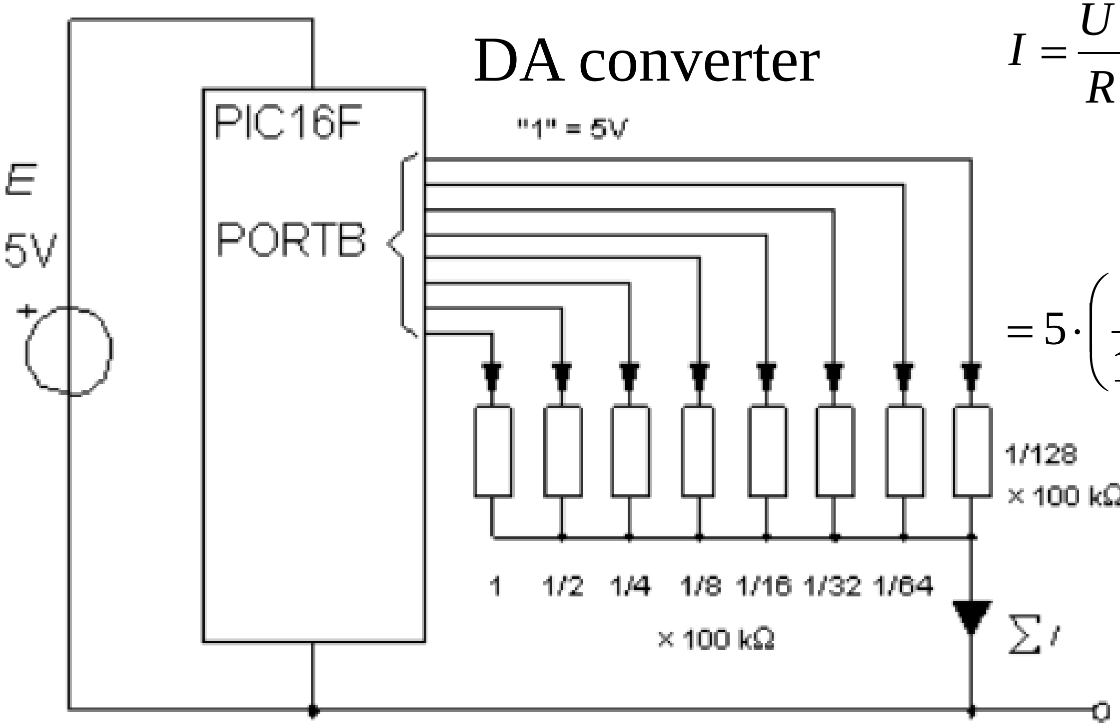
- ***Old school***

Digital→Analog converter?

$b_7b_6b_5b_4b_3b_2b_1b_0$

- Binary coded resistor values

DA converter



1 ½ ¼ 1/8 1/16 1/32 1/64 1/128 ×100 kΩ

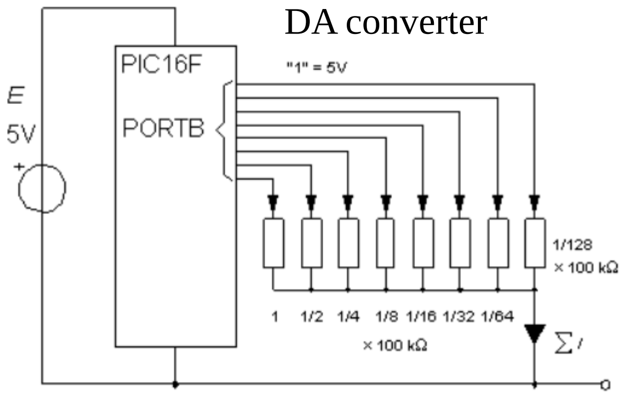
$$I = \frac{U}{R} = \frac{U}{\dfrac{1}{\left(\dfrac{1}{R_1} + \dfrac{1}{R_2} + \ldots + \dfrac{1}{R_n}\right)}}$$

$$= 5 \cdot \left(\frac{b_0}{100000} + \frac{b_1}{50000} + \frac{b_2}{25000} + \ldots + \frac{b_7}{781} \right)$$

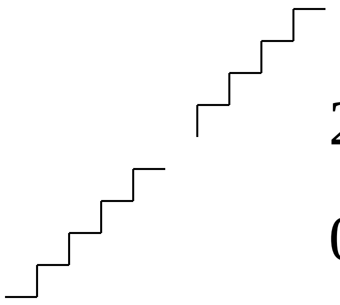
The current ***I*** is the **sum** of the currents from the ”binary coded” resistors.

Digital→Analog converter?

DA converter



$b_7 b_6 b_5 b_4 b_3 b_2 b_1 b_0$



256 steps

0,5 μA/step

$$I = \frac{U}{R} = 5 \cdot \left(\frac{b_0}{100000} + \frac{b_1}{50000} + \frac{b_2}{25000} + \frac{b_3}{12500} + \frac{b_4}{6250} + \frac{b_5}{3125} + \frac{b_6}{1563} + \frac{b_7}{781} \right)$$

$$I_{\max} = 5 \cdot \left(\frac{1}{100000} + \frac{1}{50000} + \frac{1}{25000} + \frac{1}{12500} + \frac{1}{6250} + \frac{1}{3125} + \frac{1}{1563} + \frac{1}{781} \right) = 128 \mu A$$

Problems with tolerances

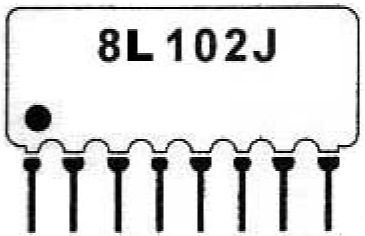
Binary coded resistors for 8 bit.

Biggest resistor *exactly* **100000 Ω** and smallest resistor *exactly* **781 Ω** (preferably 781,25)?

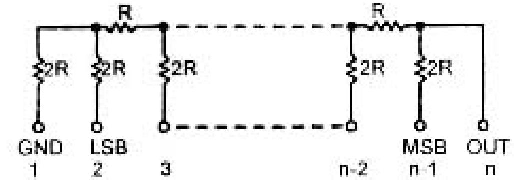
It is difficult to manufacture such various resistors with tight tolerances.

- There is a better solution!

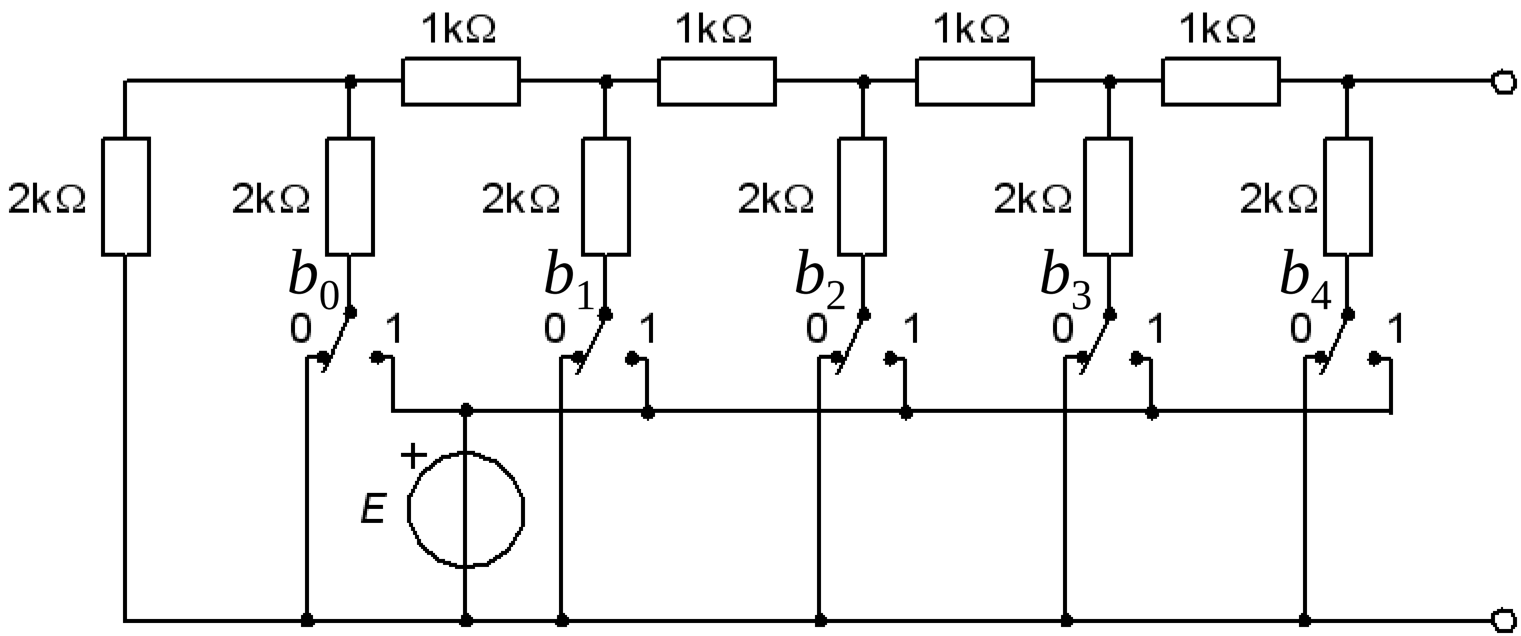
R2R- method.



R-2R-ladder



$b_4 b_3 b_2 b_1 b_0$



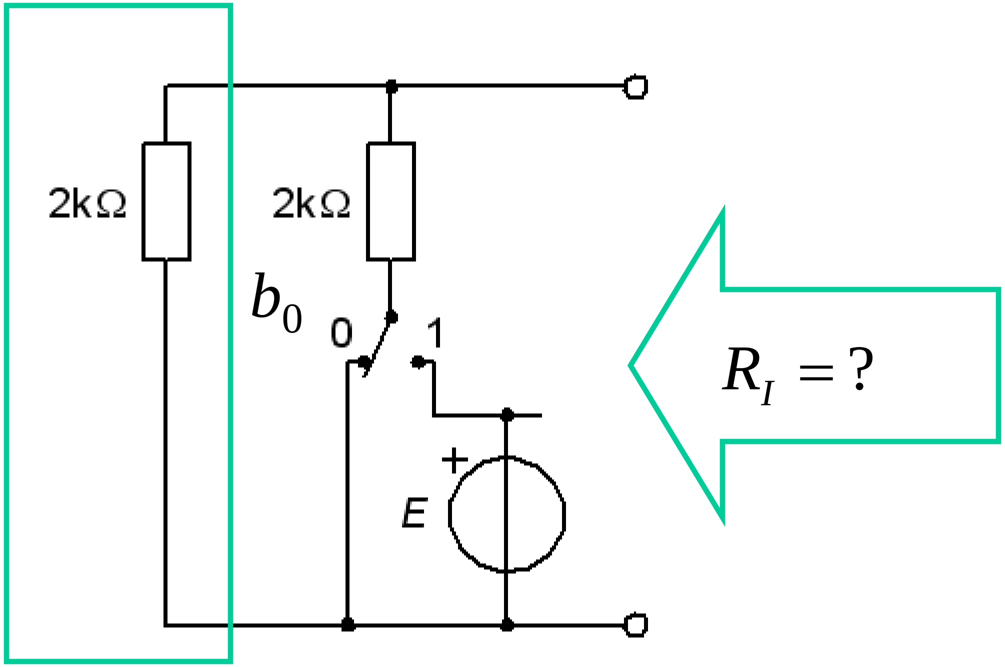
Just one resistance value needs to be manufactured, *R*, and then *R*+*R* =2*R*. One must be able to produce many "equal" resistors - the exact value is no longer important.

Two-terminal equivalent R_I

The R2R-ladder is not that easy to understand …

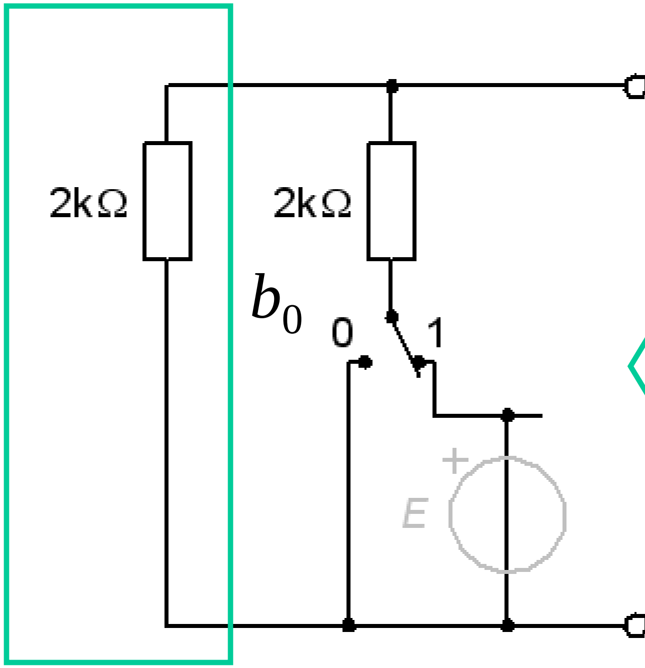
Repeated use of two-terminal equivalents and the superposition rule is what is required.

R-2R b_0=0 R_I =?



$$R_I = \frac{2 \cdot 2}{2+2} = 1\,\mathrm{k}\Omega$$

R-2R b_0=1 R_I =?

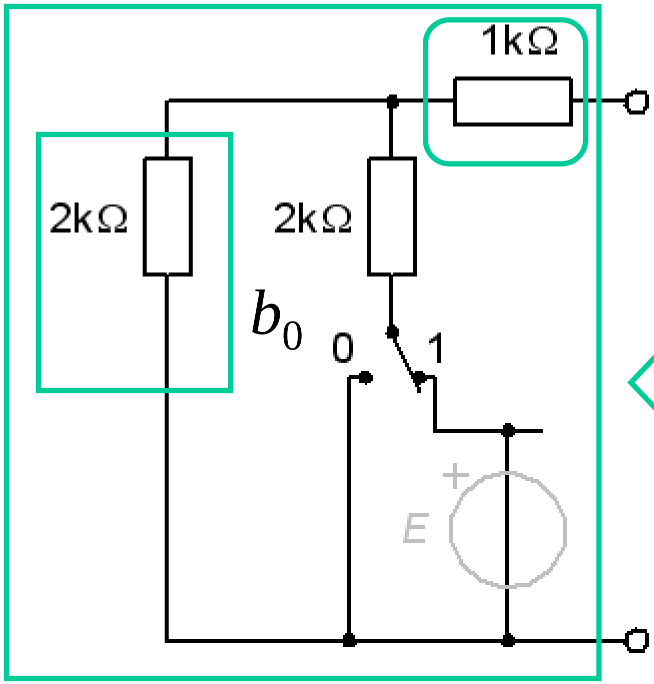


$R_I = ?$

$$R_I = \frac{2 \cdot 2}{2+2} = 1\,\mathrm{k\Omega}$$

b_0 1 or 0, same internal resistance!

R-2R b_0 $R_\text{I} = ?$

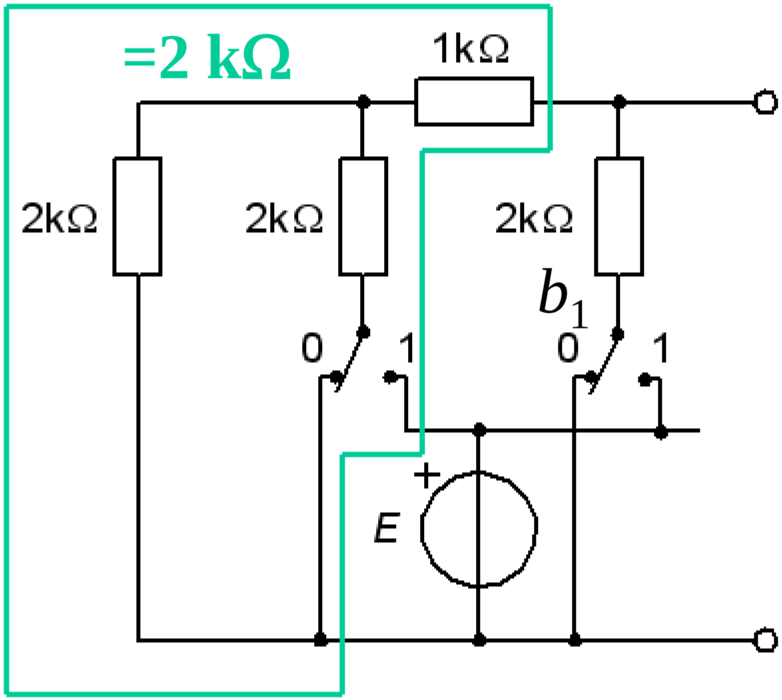


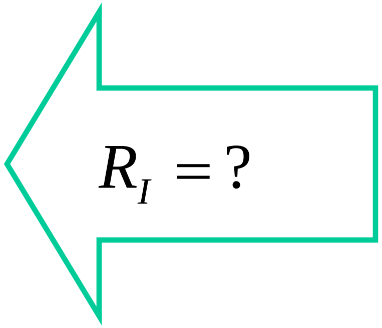
b_0

$R_I = 1 + 1 = 2\ \text{k}\Omega$

The total resistance of one stage becomes 2 kΩ.

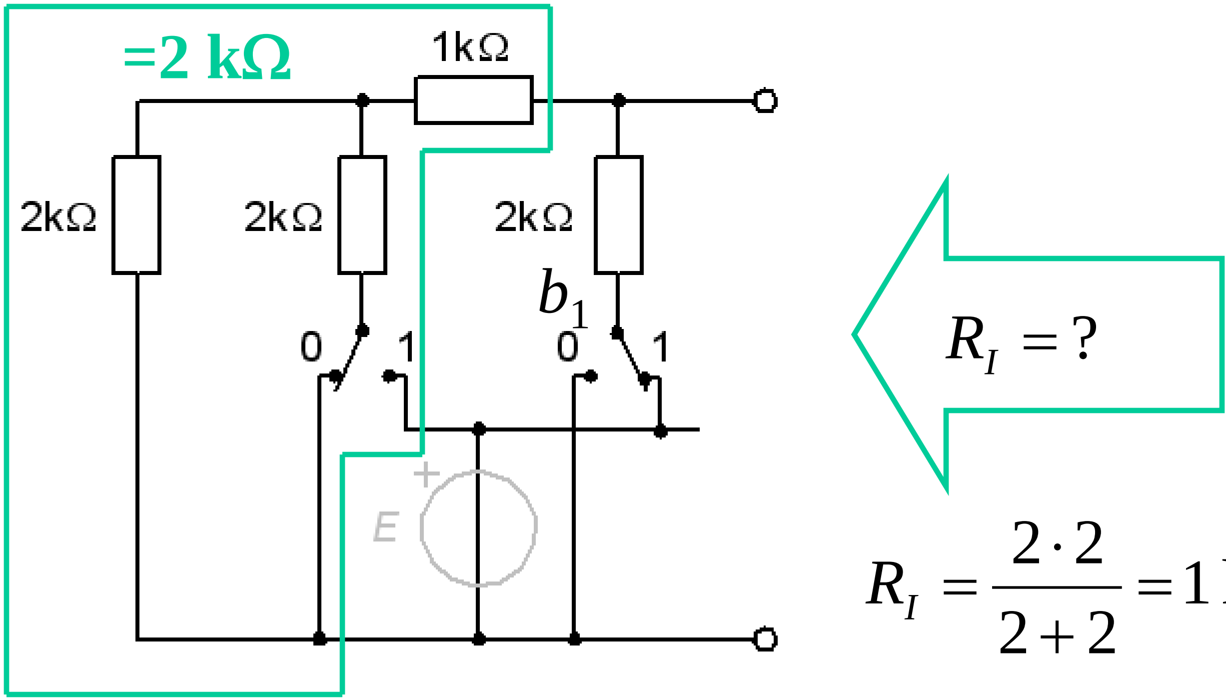
R-2R b_1=0 R_I =?





$$R_I = \frac{2 \cdot 2}{2+2} = 1\,\mathrm{k}\Omega$$

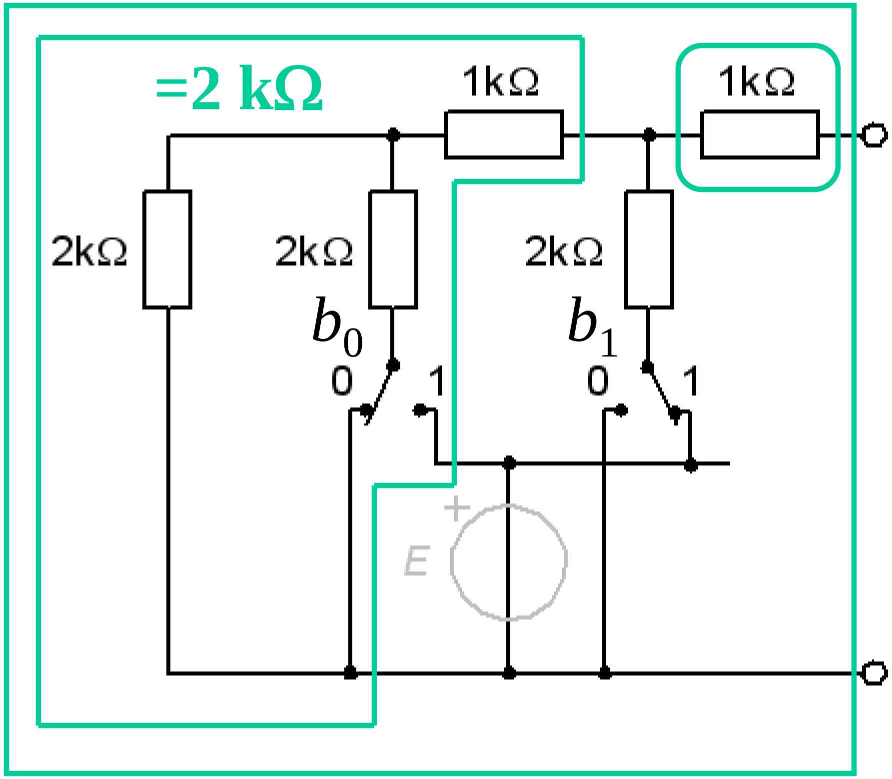
R-2R b_1=1 R_I =?



$$R_I = \frac{2 \cdot 2}{2+2} = 1\,\text{k}\Omega$$

b_1 1 or 0, same internal resistance!

R-2R b_1 R_I =?



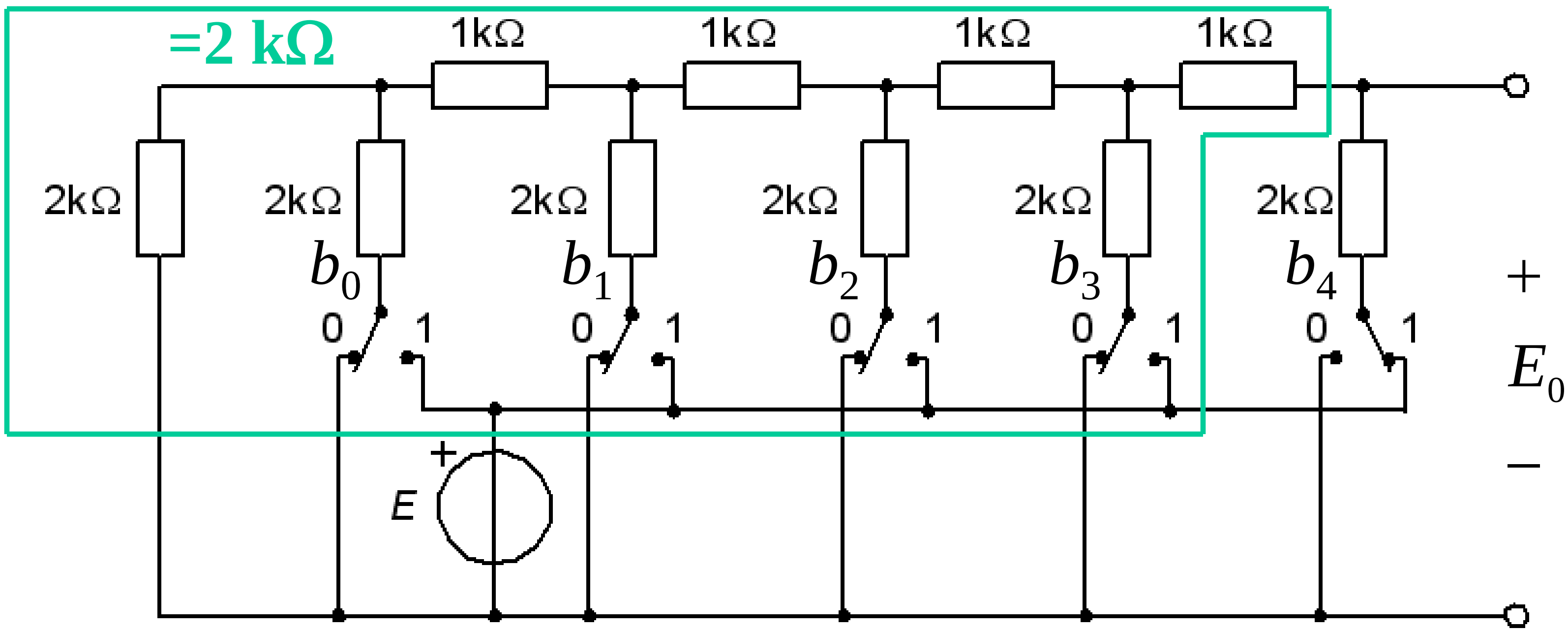
- Conclusion:

$R_I = 1 + 1 = 2$ kΩ

Regardless 1's or 0's is the total input resistance from the previous stages always 2 kΩ

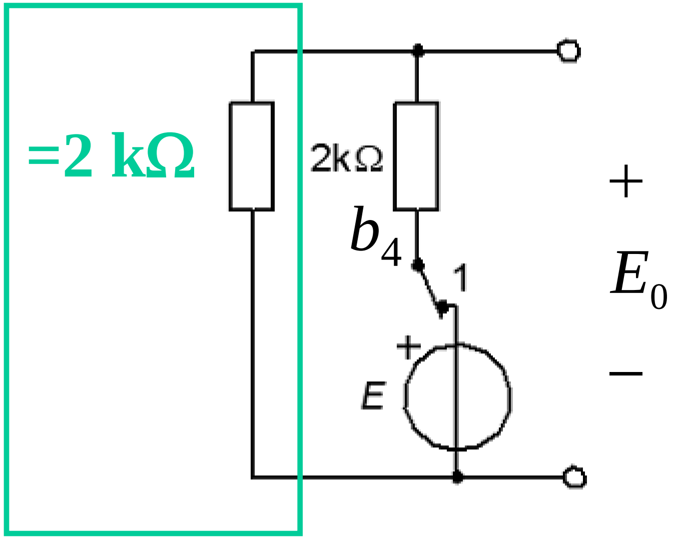
Two-terminal equivalent E_0

R-2R b_4=1 E_0=?



=2 kΩ
1kΩ
1kΩ
1kΩ
1kΩ
2kΩ
2kΩ
2kΩ
2kΩ
2kΩ
2kΩ
b_0
b_1
b_2
b_3
b_4
0
1
0
1
0
1
0
1
0
1
+
E_0
–
+
E

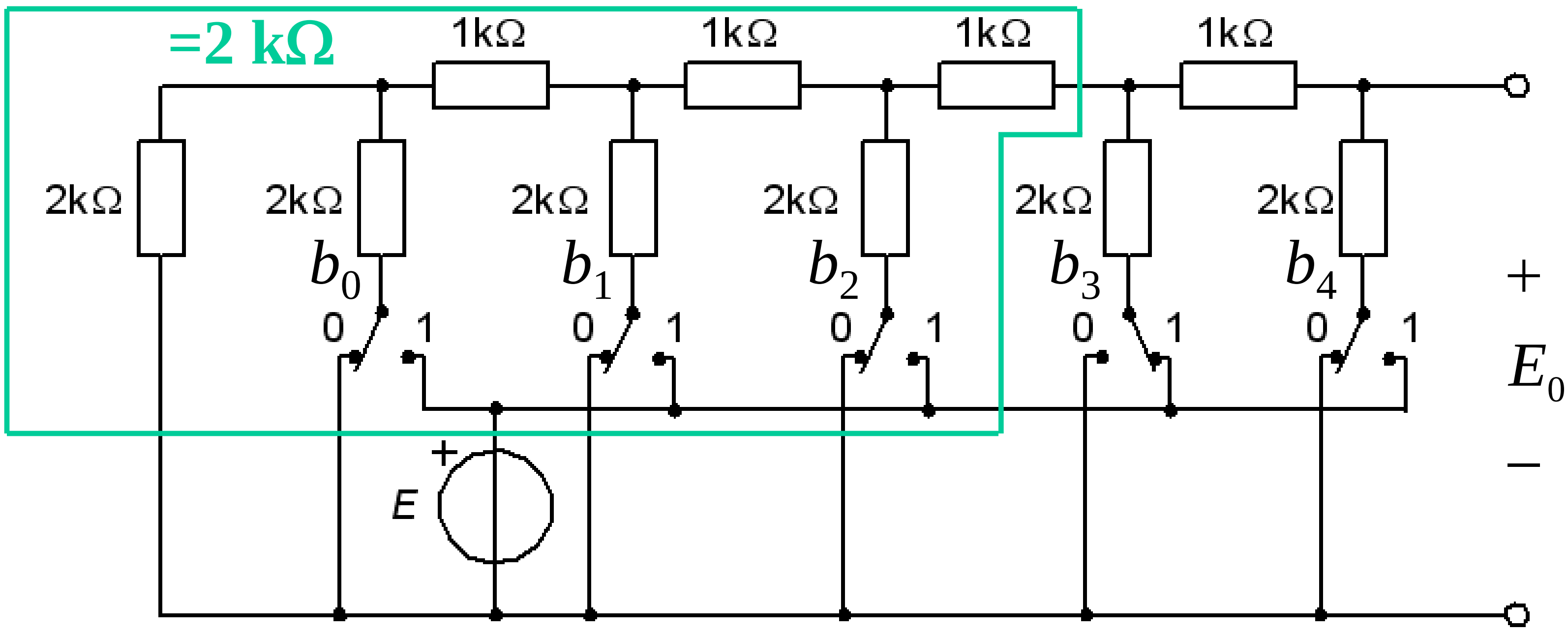
R-2R b_4=1 E_0=?



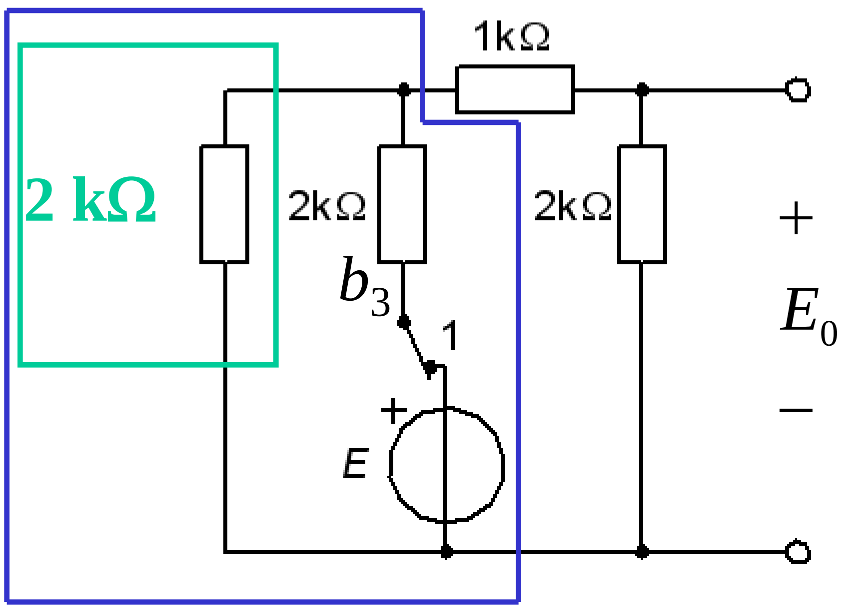
Volage divider:

$$E_0 = E\frac{2}{2+2} = \frac{E}{2}$$

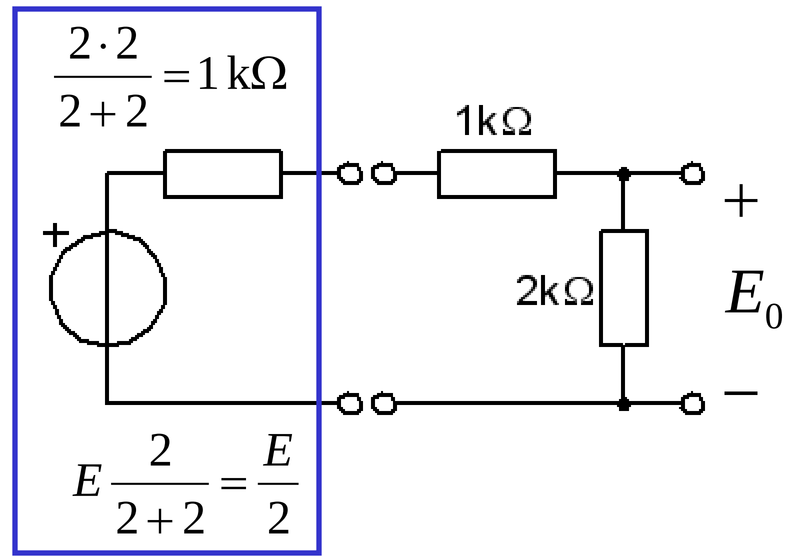
R-2R b_3=1 E_0=?

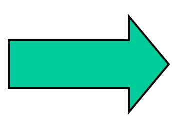

=2 kΩ
1kΩ
1kΩ
1kΩ
1kΩ
2kΩ
2kΩ
2kΩ
2kΩ
2kΩ
2kΩ
b_0
b_1
b_2
b_3
b_4
0 1
0 1
0 1
0 1
0 1
E
+
E_0
+
–

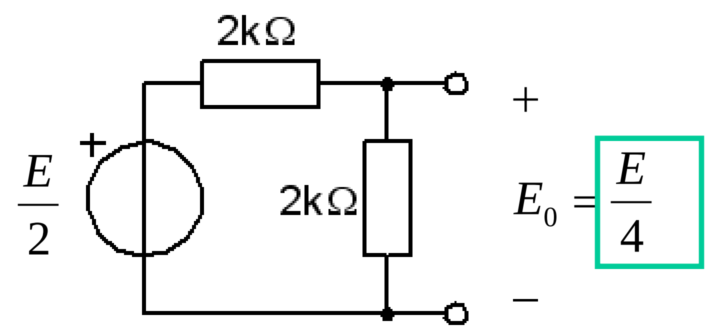
R-2R $b_3=1$ $E_0=?$



≡







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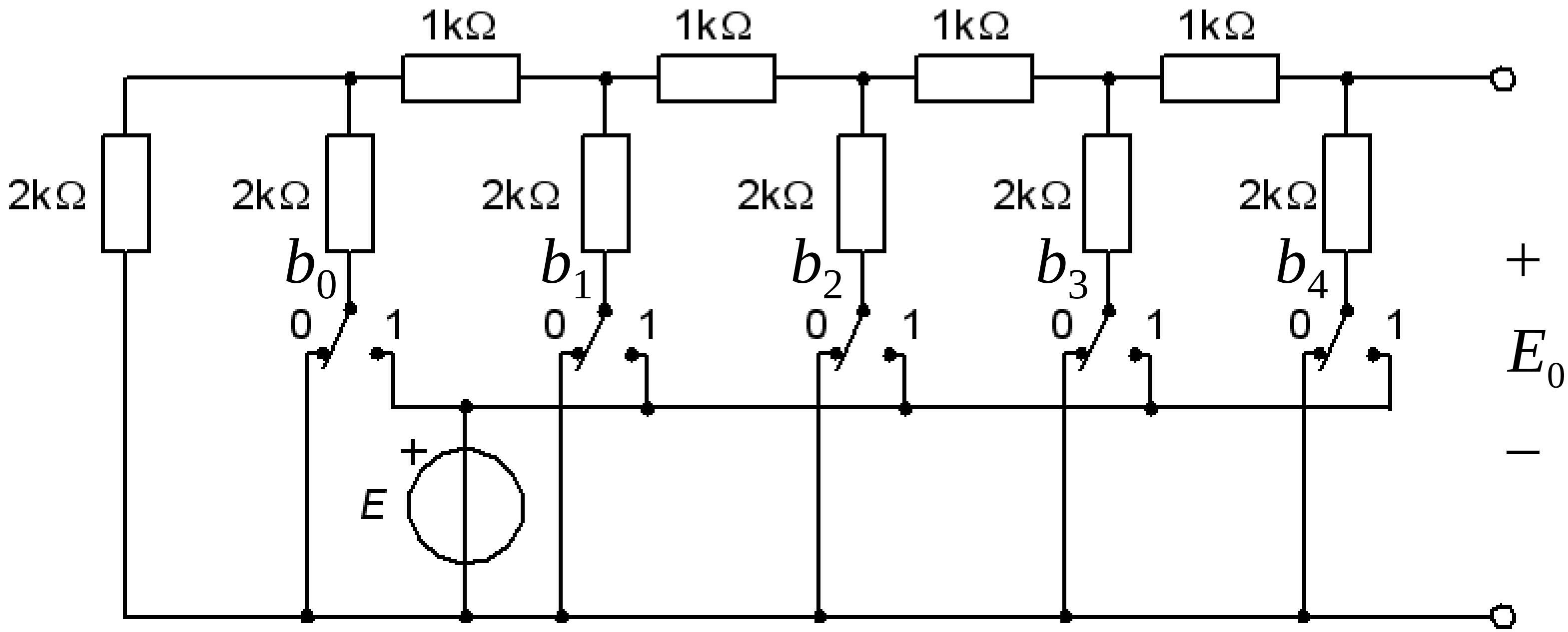
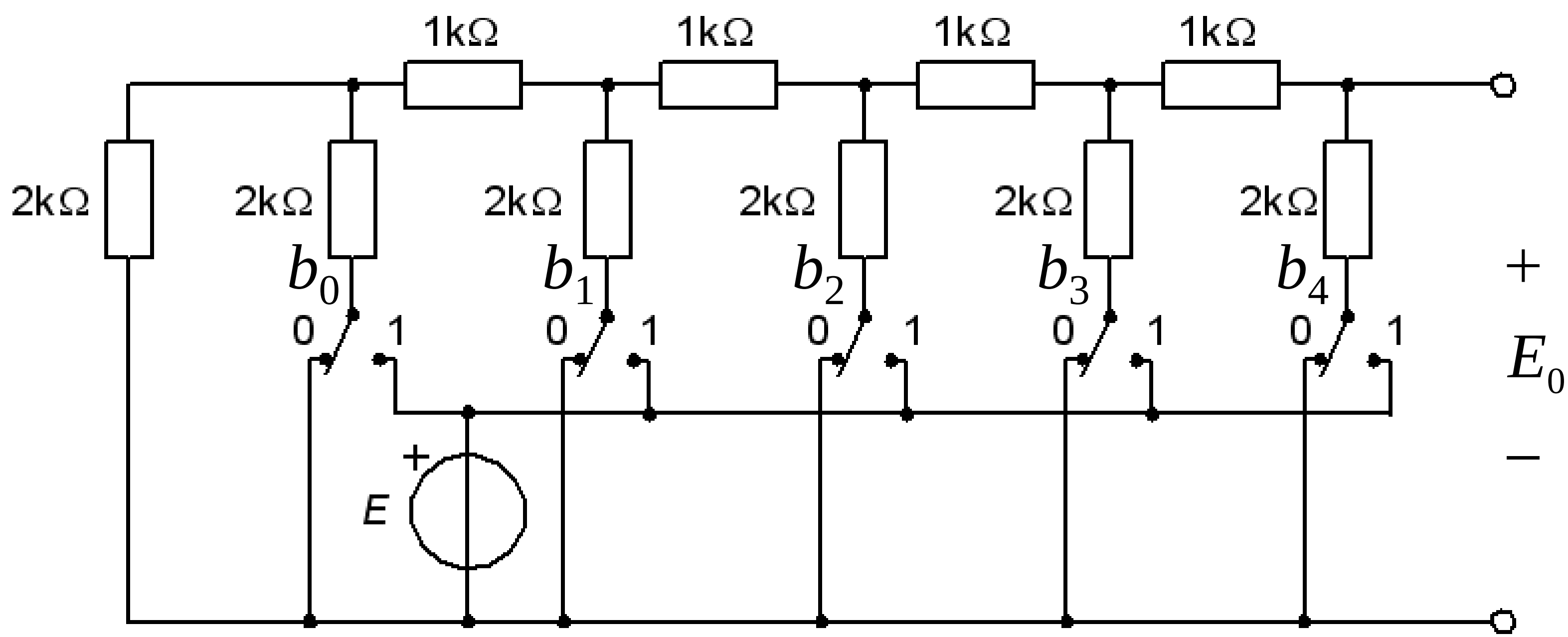
R-2R conclusion $E_0 \ldots$



$$b_4 = 1 \Rightarrow \boxed{\frac{E}{2}} \quad b_3 = 1 \Rightarrow \boxed{\frac{E}{4}} \quad b_2 = 1 \Rightarrow \boxed{\frac{E}{8}} \quad \ldots$$

- Reasonable guess – is it not?

R-2R superposition

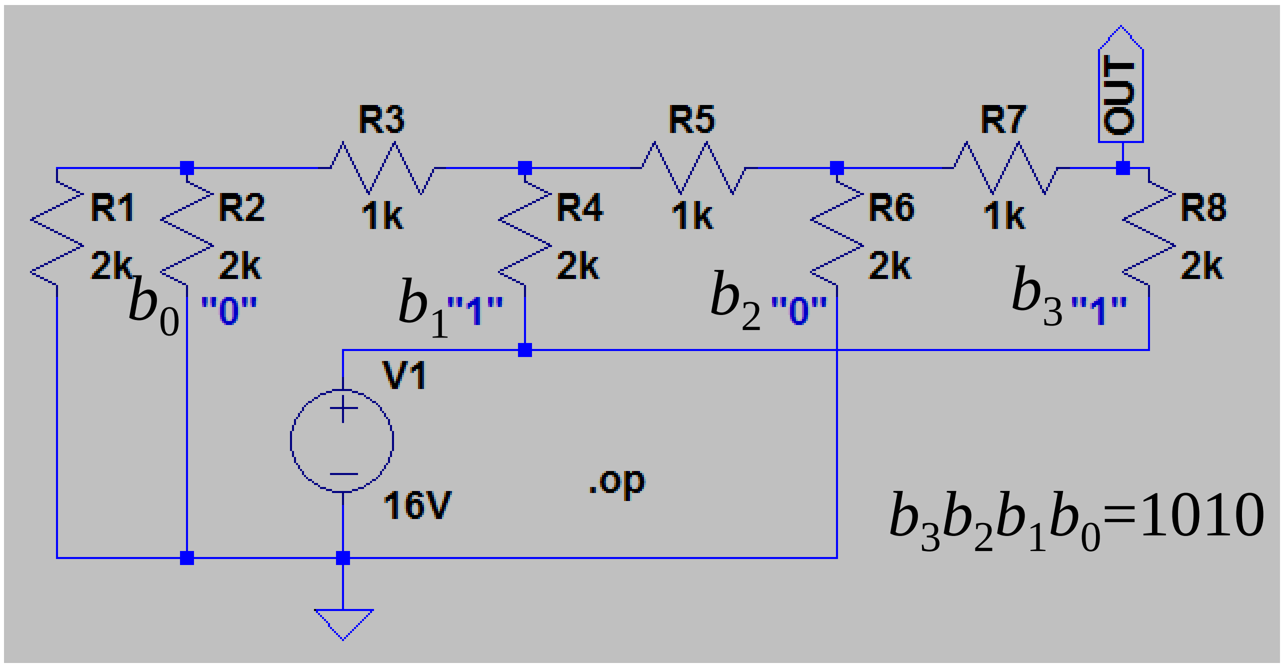


- According to the **superposition** principle, the contributions of $b_4\ b_3\ b_2\ \ldots\ b_0$ can be added individually:

$$b_4 b_3 b_2 b_1 b_0 \Rightarrow E_0 = E \cdot \left(\frac{b_4}{2} + \frac{b_3}{4} + \frac{b_2}{8} + \frac{b_1}{16} + \frac{b_0}{32} \right)$$

We have a DA-converter!

R-2R simulation



Guess value of voltage OUT?

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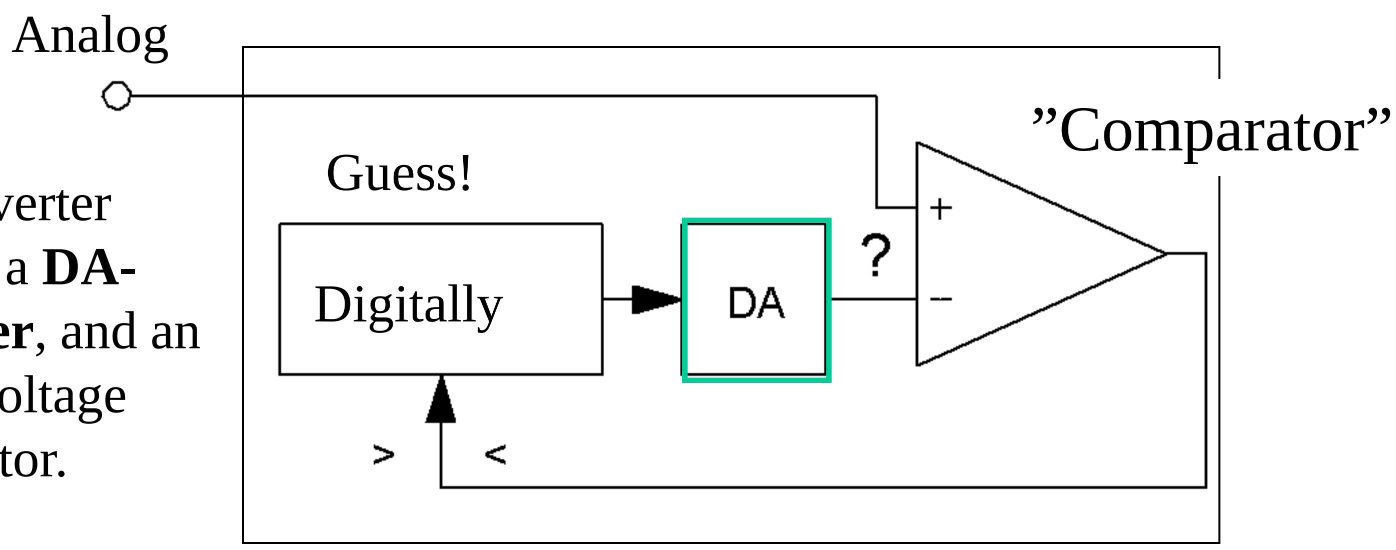
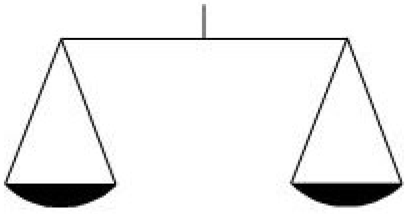
AD-converter?

Successive approximations

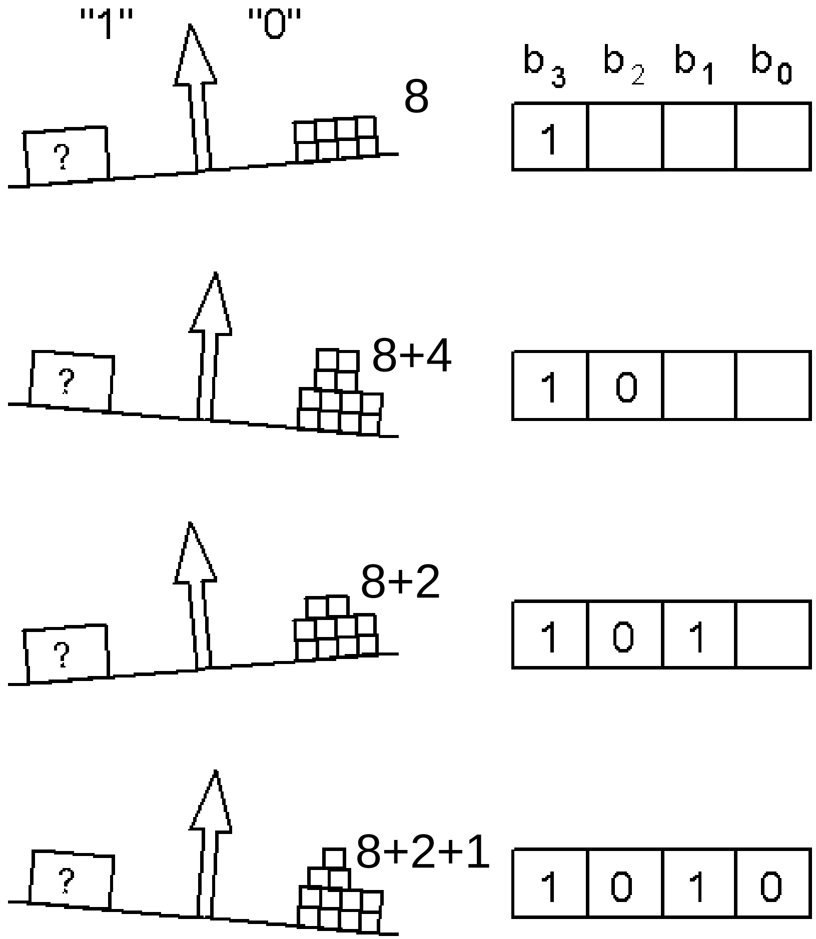
AD-converter contains a **DA-converter**, and an analog voltage comparator.

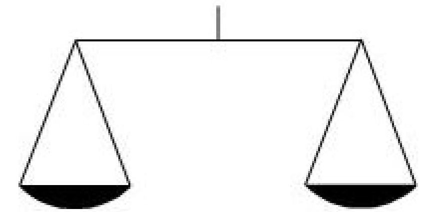


AD conversion according to the method of successive approximations is comparable to weigh an unknown mass with binary weights on a balance. We try step by step to adding binary "weight" if "<" or remove " weight" if ">".



Binary weights 8 4 2 1 …





AD conversion takes time. For each bit higher resolution a comparison one step further is required.

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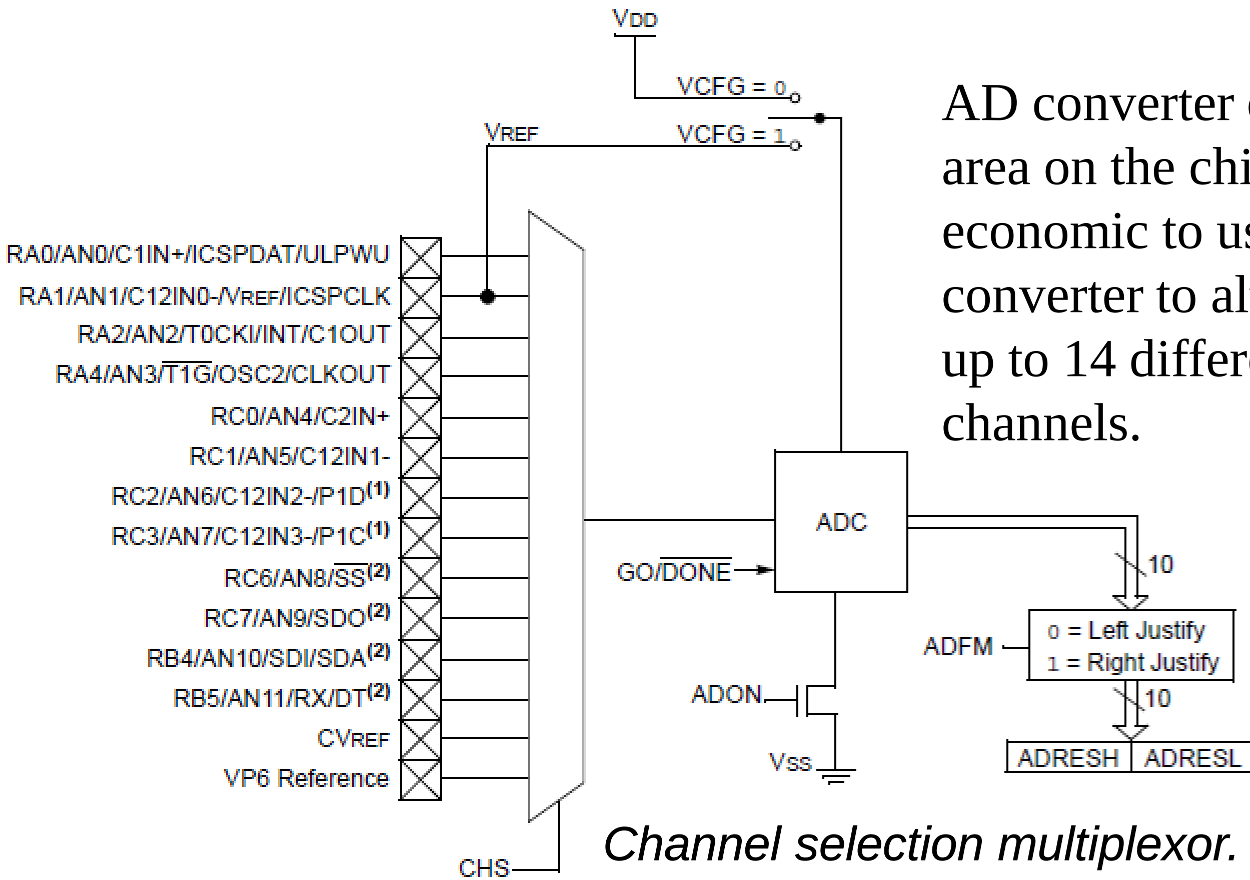
An AD-converter, 14 channels

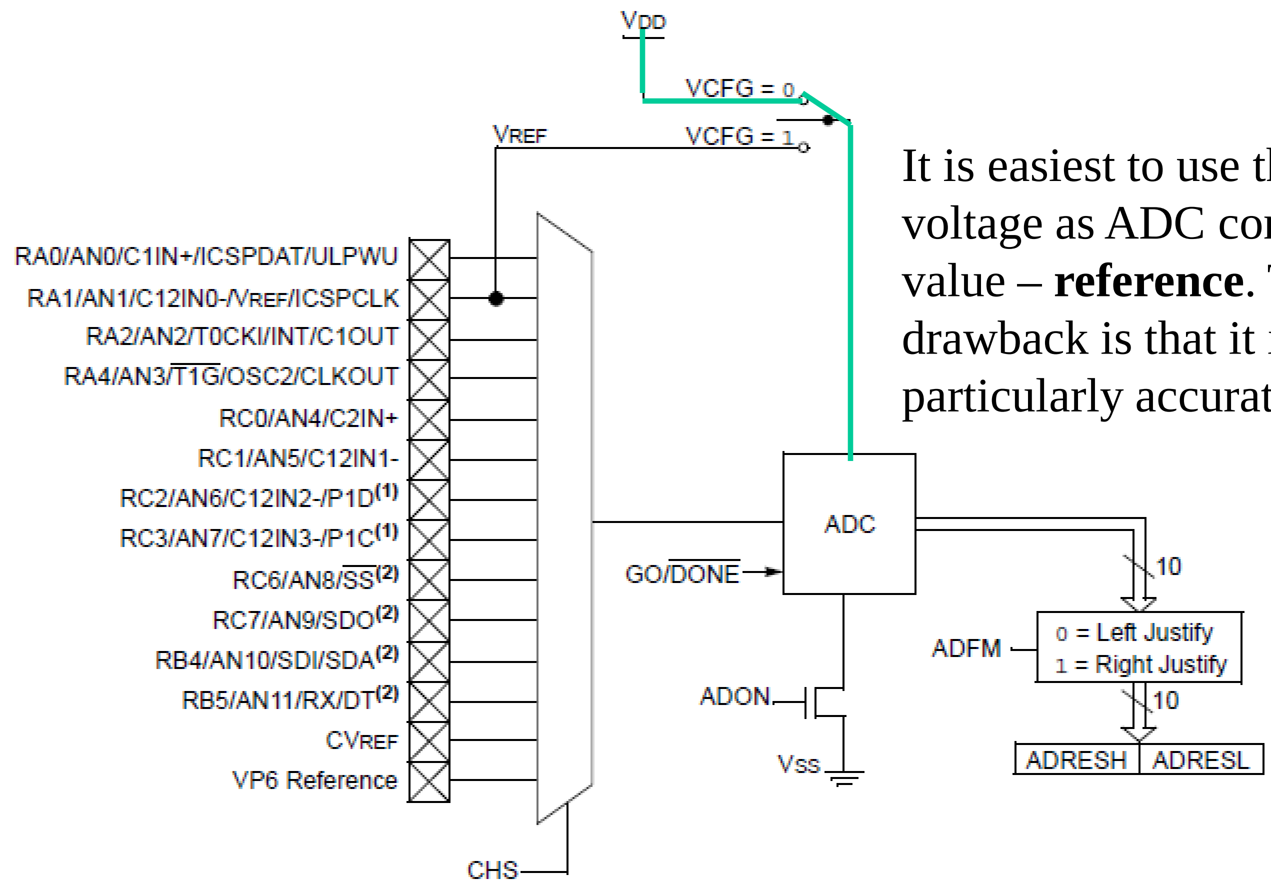


Channel selection multiplexor.

AD converter occupies a large area on the chip - so it is economic to use the same converter to alternately measure up to 14 different sources, channels.

The PIC-processor has a 10-bits AD-converter

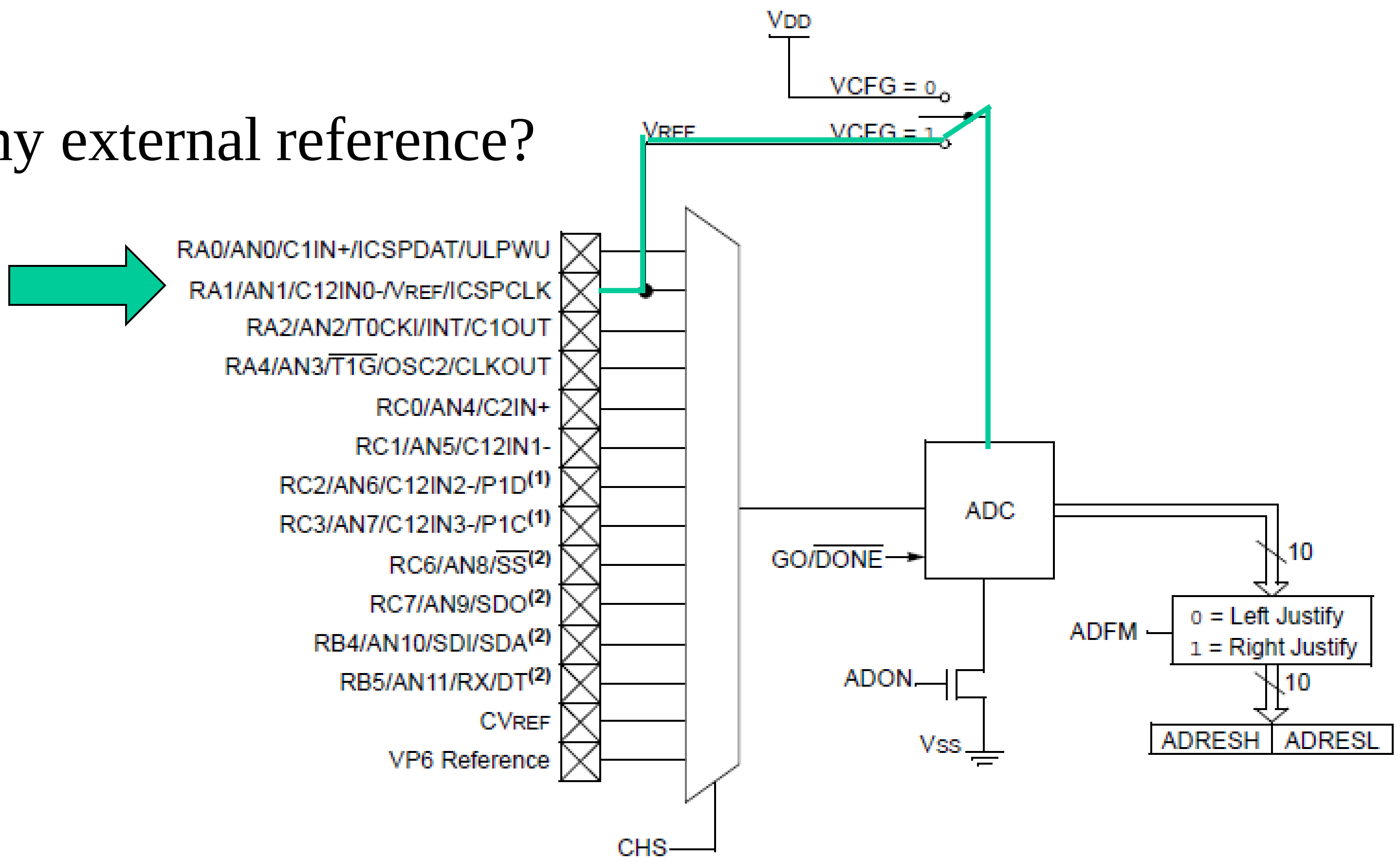
Supply voltage as reference



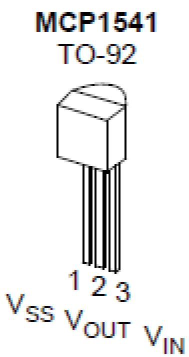
It is easiest to use the supply voltage as ADC comparison value – **reference**. The drawback is that it is not particularly accurate.

Internal or external reference?

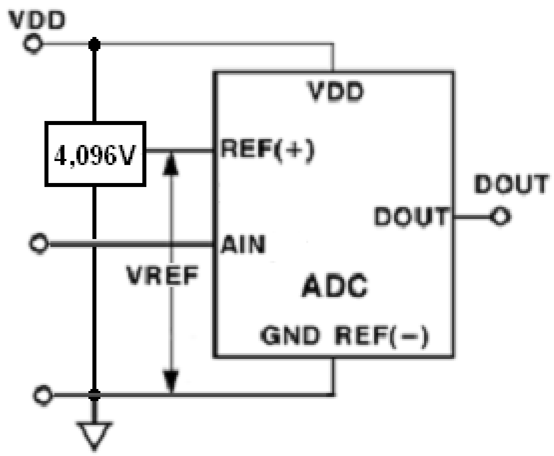
Why external reference?

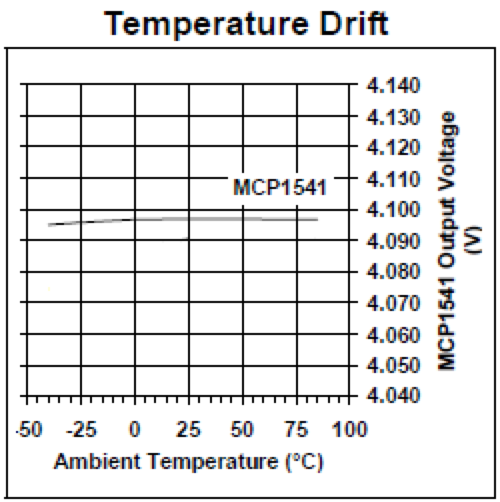


Stabilized reference 4,096 V



MCP1541





If you buy a stabilized reference circuit you can perhaps choose the value 4,096 V ($4096=2^{12}$) which gives a 10-bit AD-converter exact 4 mV-steps, *without* the need to scale the measured result with multiplications and divisions.

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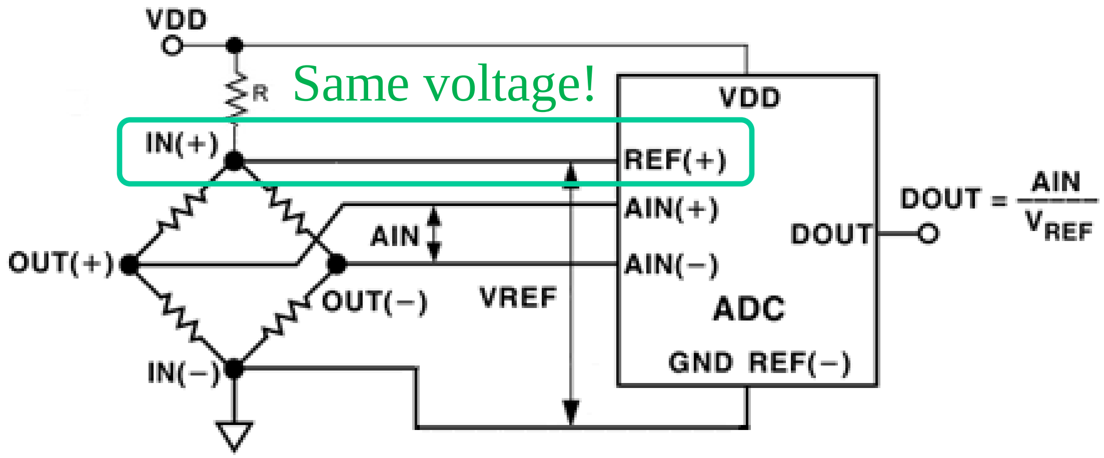
Ratiometric connection

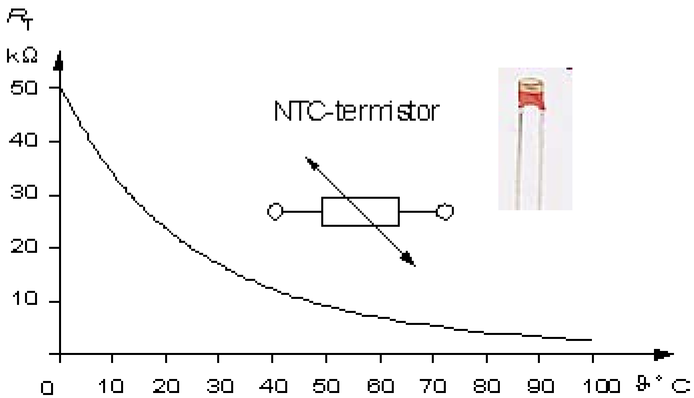
sensor

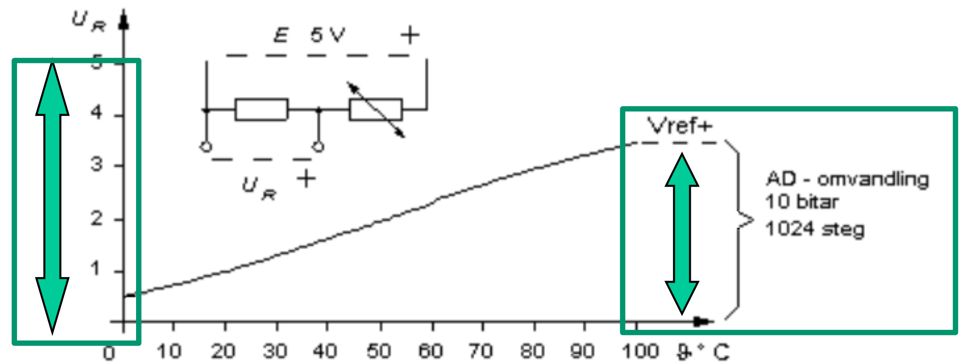


If a sensor measurement value depends on it’s supply voltage, you can either have stabilized supply (expensive) – or easier, use so-called ratiometric connection. If the sensor supply voltage and AD converter reference voltage **are the same**, then changes in this voltage will be the same for both, and the AD converted measured value will remain intact!

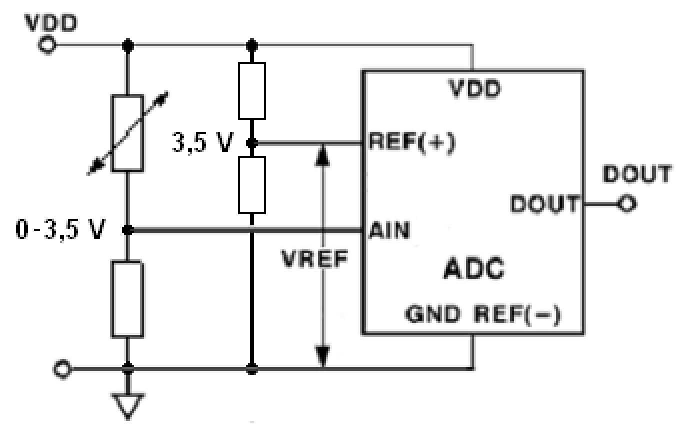
Adapt measuring range

An NTC thermistor has a high sensitivity but a non-linear temperature relationship.



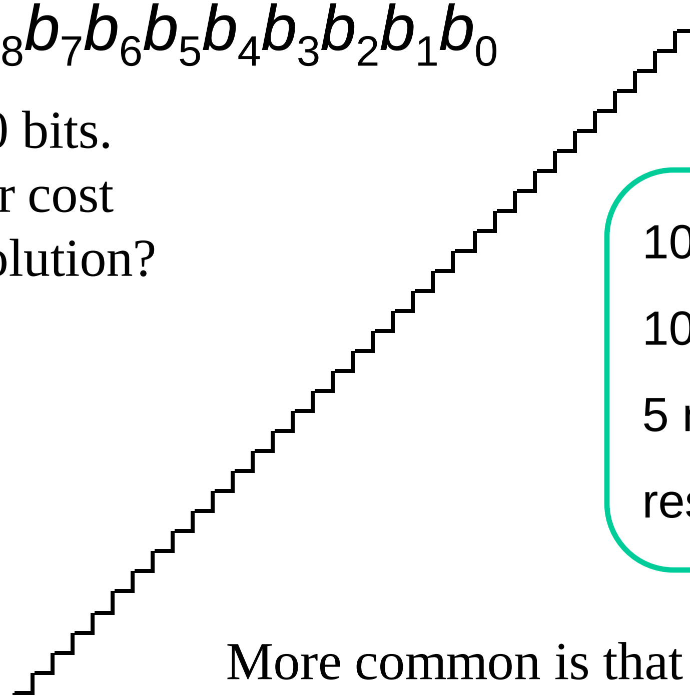


One linearize with a resistor – and then get the measuring range 0 …3,5 V. If the reference is 3,5 V instead of 5 V then one utilizes the entire ADC range for the measurement.



Are 10-bit resolution required?

$b_9 b_8 b_7 b_6 b_5 b_4 b_3 b_2 b_1 b_0$



AD converter is 10 bits.
What does a sensor cost
that has 10-bit resolution?

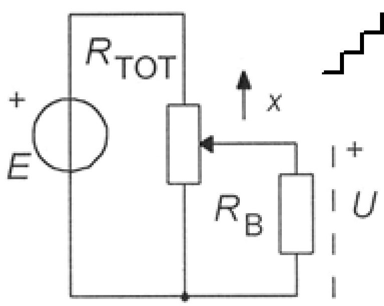
100 $?

10 bits

1024 steps

5 mV/step

resolution ≈ 0,1%

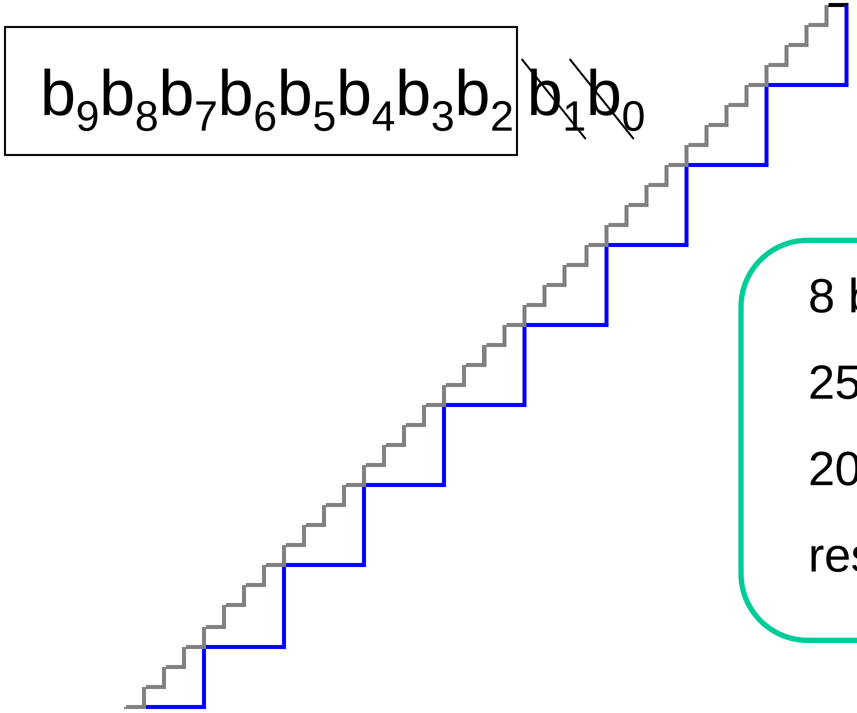


More common is that you can afford an 8-bit sensor. (PIC processor itself costs 2 $).

The picture shows a resistive position sensor that can take advantage of 10-bit resolution.

8-bit program

If one need only 8 bit resolution one can ignore the two least significant bits and handle the result as a byte.



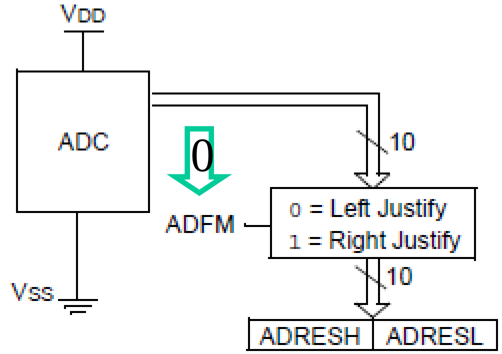
8 bit

256 steps

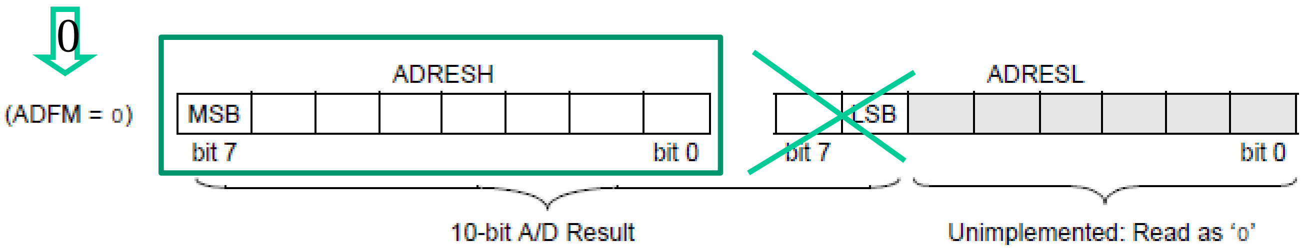
20 mV/step

resolution ≈1%

8-bit program



*One can care only about the 8 **most significant** bits!*



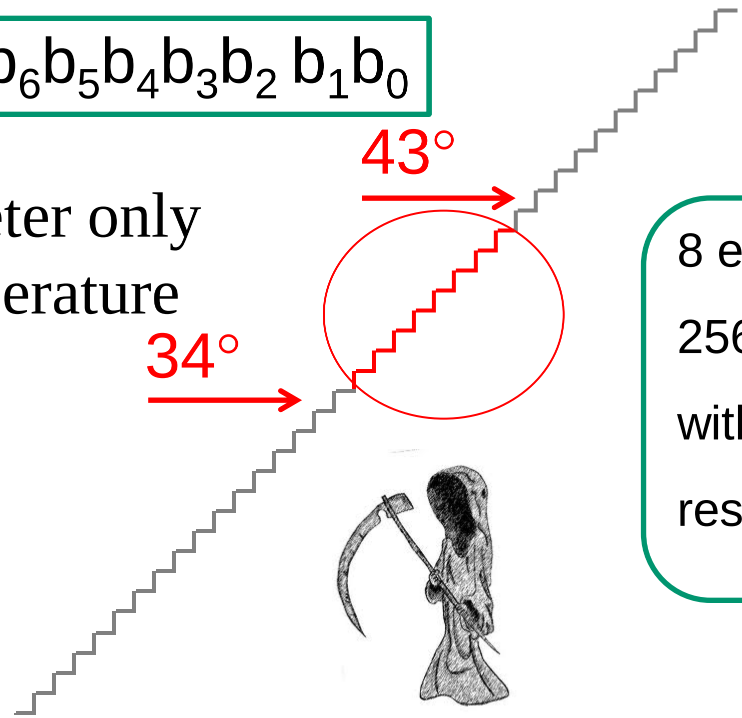

```
ADFM=0;
char value;
value = ADRESH;  /* 8-bit measurement */
```

Avoid amplifier

If one only need 8 bit resolution one can still use the 10-bit resolution to avoid the need to amplify the sensor signal, the two most significant bits becomes constant. One can therefore ignore to read them.

~~1~~ ~~0~~ $b_7b_6b_5b_4b_3b_2\,b_1b_0$

A fever thermometer only need a small temperature range 34°…43° (right?)



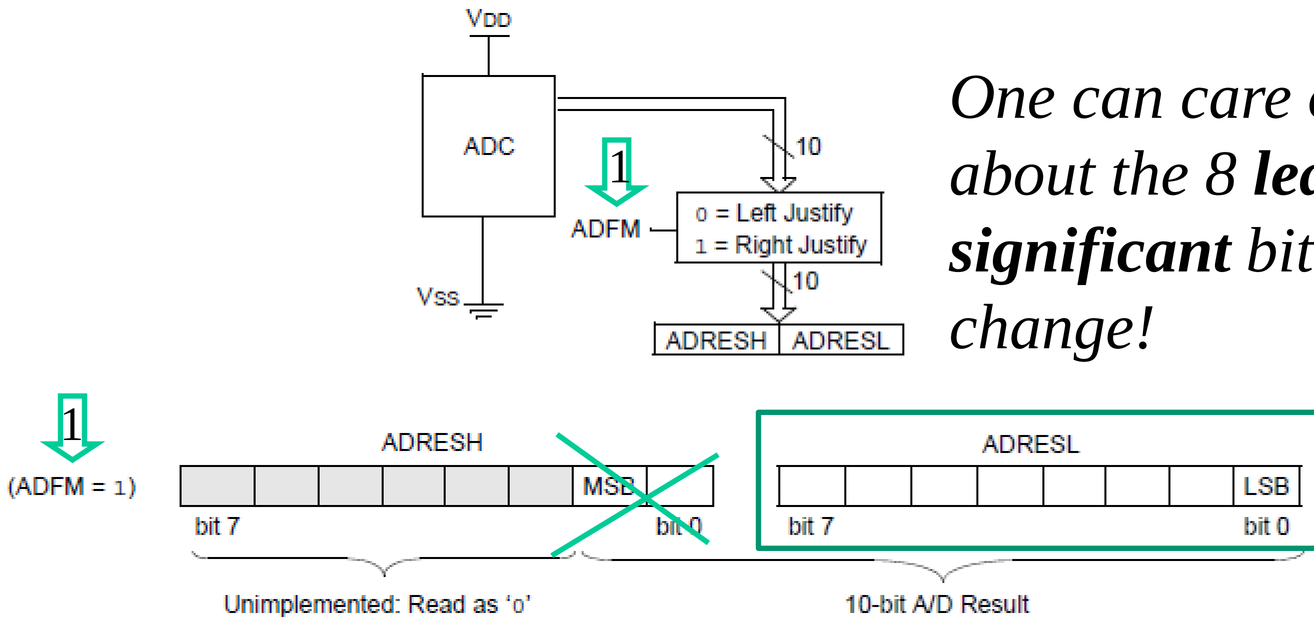
8 effective bits,

256 effective steps

with 5 mV/step

resolution ≈1%

8-bit program (10 bit)

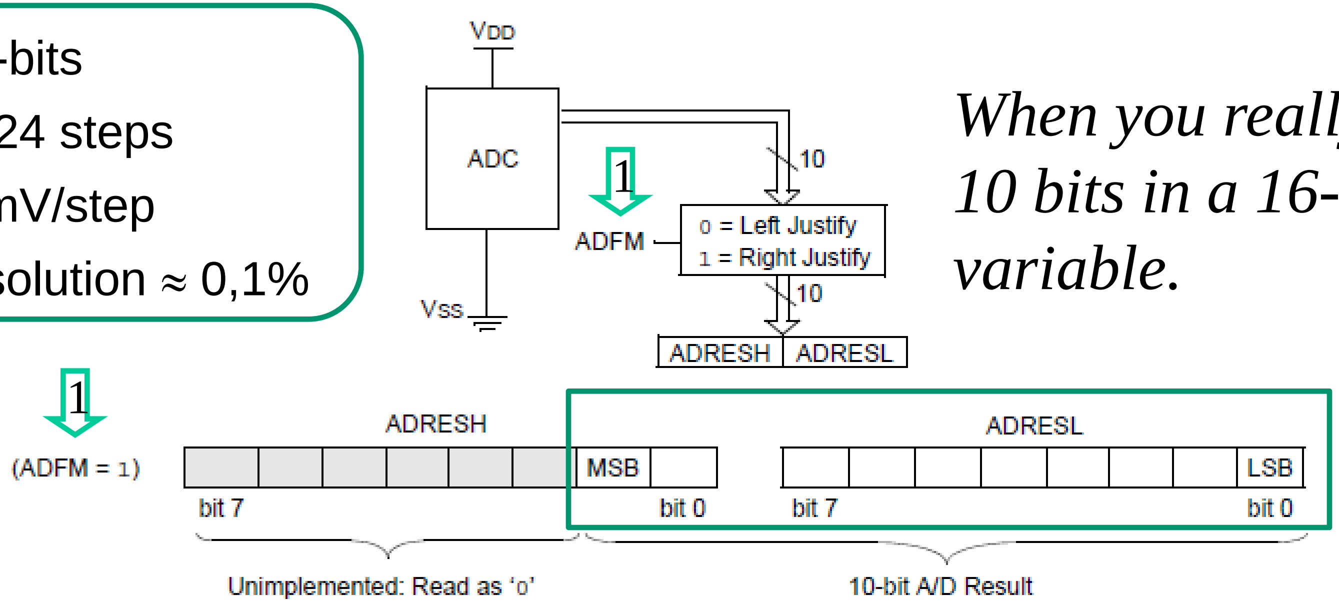


One can care only about the 8 ***least significant*** *bits that change!*

```
ADFM=0;
char value;
value = ADRESL;  /* 8-bit measurement */
```

16-bit program

10-bits
1024 steps
5 mV/step
resolution ≈ 0,1%

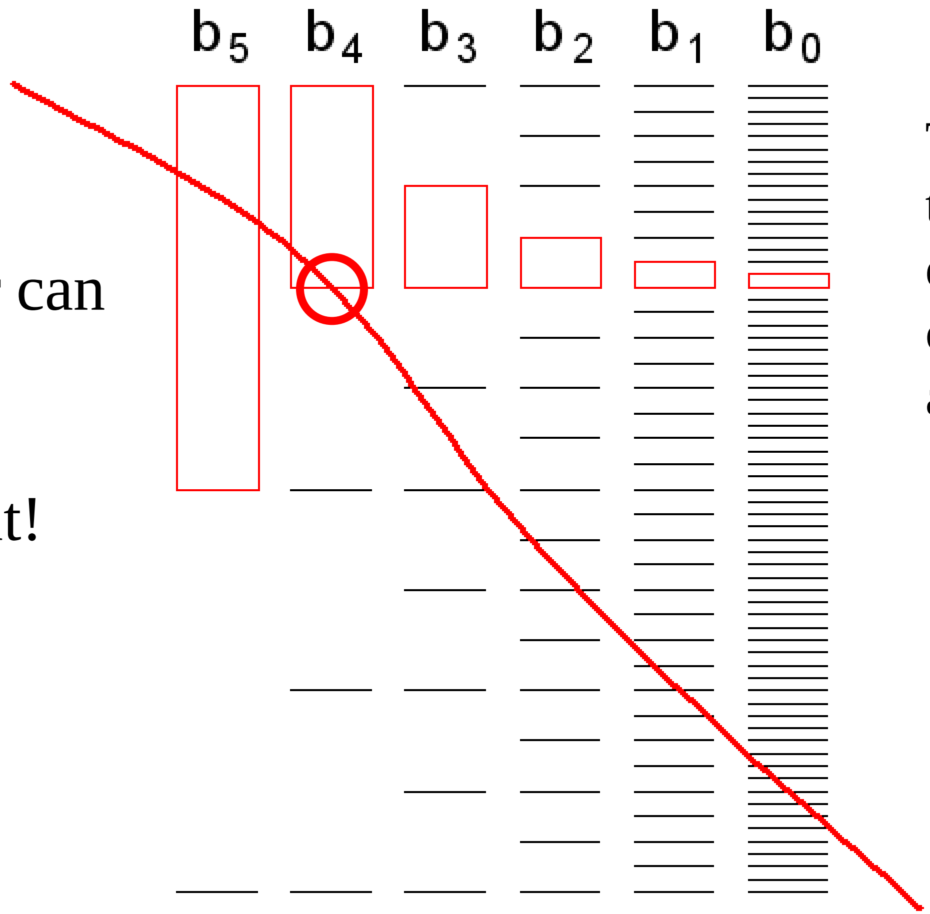


When you really need 10 bits in a 16-bit variable.

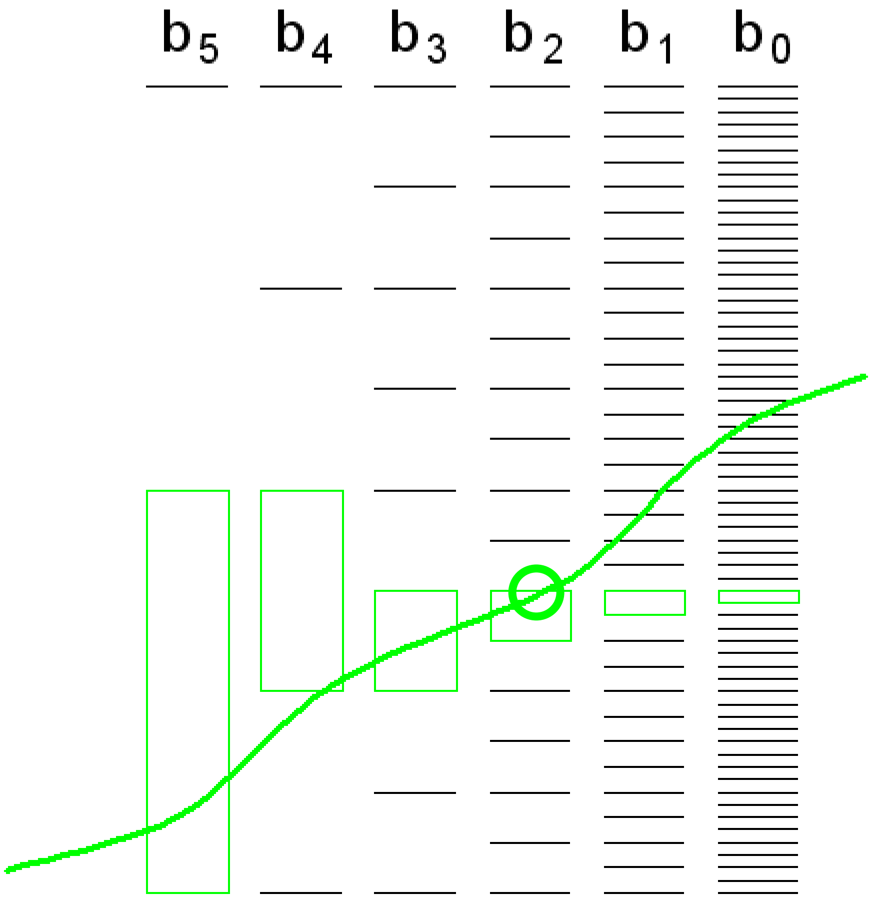
```
ADFM=1;
unsigned long value;
value =  ADRESH * 256;
value += ADRESL; /* 10-bit measurement */
```

What happens if the signal changes during conversion?

AD converter can not "undo" a previously determined bit!



The result is a value that has occurred during the conversion, but at an unspecified time!



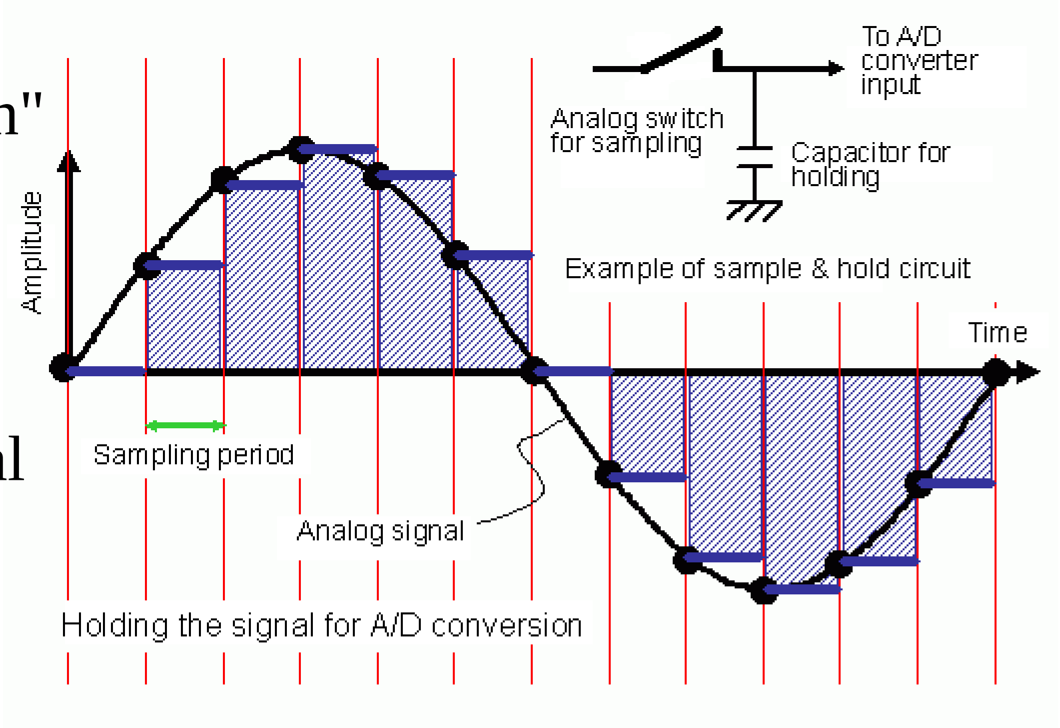
The problem

The time for the sampling is indeterminate!

Sample & Hold - circuit

The solution is that the analog signal is "frozen" during the conversion.

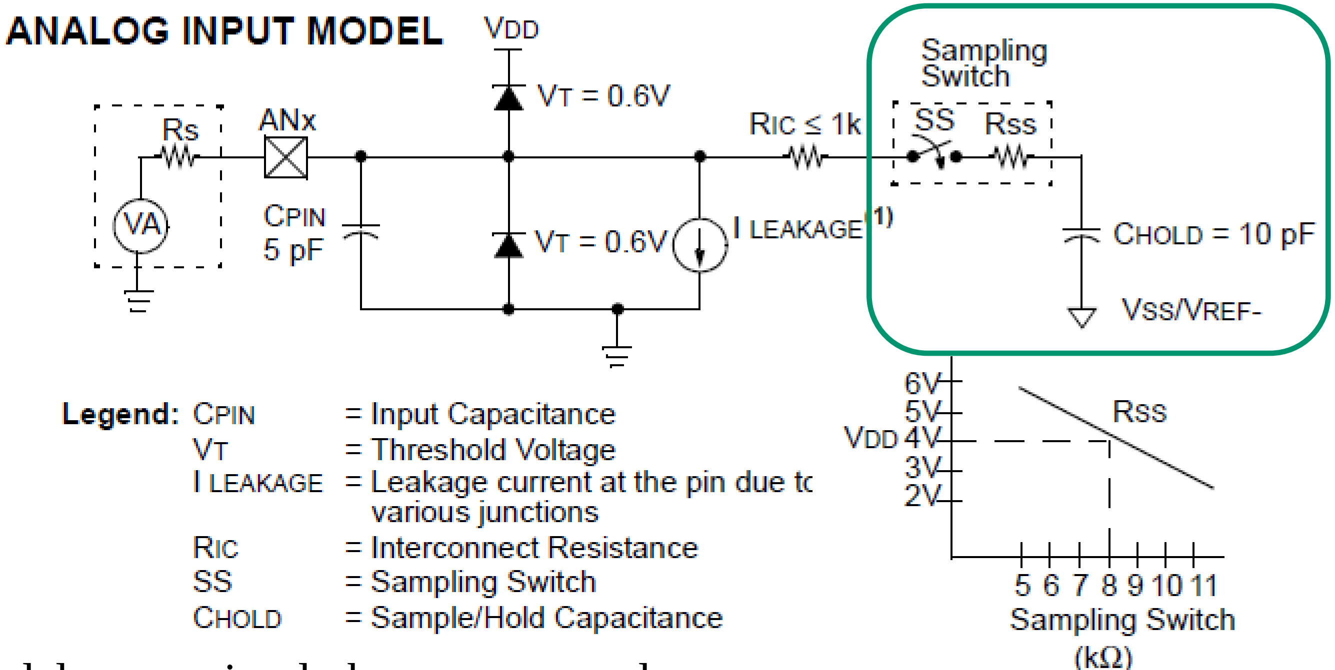
At the AD conversion start a switch is taking a "sample" of the signal and stores it in a capacitor.



The course PIC processor, the sampling capacitor has capacitance ≈10pF.

Acquisition time t_{ACQ}

Every time one has **chosen/changed channel** the **sampling capacitor** C_{HOLD} must have time to recharge to the analog voltage. This will take about 5 µs.



A 5 µs delay can simply be programmed as:

```
nop2(); nop2(); nop(); /* 5 us 4 MHz clock */;
```

AD-clock pulses

AD-converter can use a maximum clock frequency of 250 kHz. If the PIC processorn clock is **4 MHz** this must firs be divided 16 times before it can be used as AD-clock. This frequency divider is provided.

REGISTER 9-2: ADCON1: A/D CONTROL REGISTER 1

U-0	R/W-0	R/W-0	R/W-0	U-0	U-0	U-0	U-0
—	ADCS2	ADCS1	ADCS0	—	—	—	—
bit 7							bit 0

ADCS<2:0>: A/D Conversion Clock Select bits

000 = FOSC/2
001 = FOSC/8
010 = FOSC/32
x11 = FRC (clock derived from a dedicated internal oscillator = 500 kHz max)
100 = FOSC/4
101 = FOSC/16
110 = FOSC/64

```
ADCON1=0b0.101.0000;
```

$$1010000_2 = 80_{10} \qquad T_{AD} = 4\mu s \qquad f_{AD} = 500\text{kHz}$$

Start AD and wait for done

REGISTER 9-1: ADCON0: A/D CONTROL REGISTER 0

R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0	R/W-0
ADFM	VCFG	CHS3	CHS2	CHS1	CHS0	GO/$\overline{\text{DONE}}$	ADON
bit 7							bit 0

Start AD-conversion:

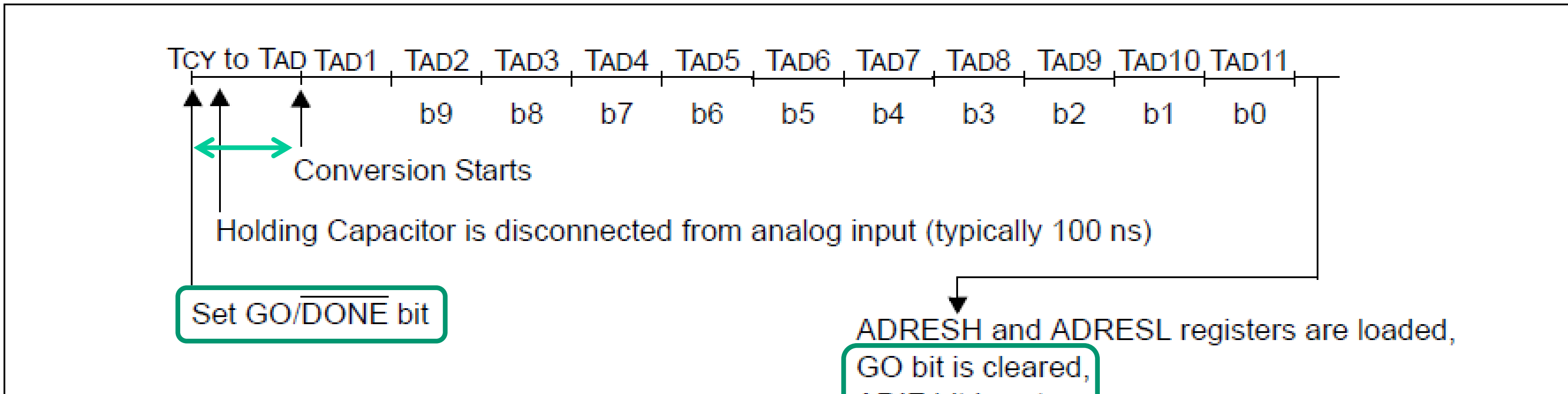
```
GO = 1;
```

Wait for AD-conversion done:

```
while(GO) ;
```

AD-conversion takes time

FIGURE 9-2: ANALOG-TO-DIGITAL CONVERSION TAD CYCLES



$$T_{AD} = 4 \mu s \quad (2+11) \cdot 4 = 52\,\mu s$$

The conversion takes approximately 2 + 11 AD clock pulses. If one ignores the fact that the PIC processor must do something (?) With the AD-converted value (which also takes time), then the theoretically maximum sampling rate becomes:

$$f_{S\,\max} = \frac{1}{52\,\mu s} = 19{,}2\,\text{kHz}$$

AD-conversion takes time

If one converts alternating two channels (stereo?) then there will also be the setting time of sampling capacitor $T_{\text{ACQ}} = 5$ μs.

$$f_{S\,\max} = \frac{1}{52+5+52+5\,[\,\mu\text{s}]} = 8{,}8\,\text{kHz}$$

The PIC processor can handle most industrial control processes - but it is of course totally inadequate as a "signal processor" for sound effects!

Many setup possibilities

TABLE 9-2: SUMMARY OF ASSOCIATED ADC REGISTERS

Name	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0	Value on POR, BOR	Value on all other Resets
ADCON0	ADFM	VCFG	CHS3	CHS2	CHS1	CHS0	GO/$\overline{DONE}$	ADON	0000 0000	0000 0000
ADCON1	—	ADCS2	ADCS1	ADCS0	—	—	—	—	-000 ----	-000 ----
ANSEL	ANS7	ANS6	ANS5	ANS4	ANS3	ANS2	ANS1	ANS0	1111 1111	1111 1111
ANSELH	—	—	—	—	ANS11	ANS10	ANS9	ANS8	---- 1111	---- 1111
ADRESH	A/D Result Register High Byte								xxxx xxxx	uuuu uuuu
ADRESL	A/D Result Register Low Byte								xxxx xxxx	uuuu uuuu
INTCON	GIE	PEIE	T0IE	INTE	RABIE	T0IF	INTF	RABIF	0000 000x	0000 000x
PIE1	—	ADIE	RCIE	TXIE	SSPIE	CCP1IE	TMR2IE	TMR1IE	-000 0000	-000 0000
PIR1	—	ADIF	RCIF	TXIF	SSPIF	CCP1IF	TMR2IF	TMR1IF	-000 0000	-000 0000
PORTA	—	—	RA5	RA4	RA3	RA2	RA1	RA0	--xx xxxx	--uu uuuu
PORTB	RB7	RB6	RB5	RB4	—	—	—	—	xxxx ----	uuuu ----
PORTC	RC7	RC6	RC5	RC4	RC3	RC2	RC1	RC0	xxxx xxxx	uuuu uuuu
TRISA	—	—	TRISA5	TRISA4	TRISA3	TRISA2	TRISA1	TRISA0	--11 1111	--11 1111
TRISB	TRISB7	TRISB6	TRISB5	TRISB4	—	—	—	—	1111 ----	1111 ----
TRISC	TRISC7	TRISC6	TRISC5	TRISC4	TRISC3	TRISC2	TRISC1	TRISC0	1111 1111	1111 1111

Legend: x = unknown, u = unchanged, – = unimplemented read as '0'. Shaded cells are not used for ADC module.

AD-conversion – step by step

1. Configure Port:
   - Disable pin output driver (See TRIS register)
   - Configure pin as analog (See ANSEL register).
2. Configure the ADC module:
   - Select ADC conversion clock (ADCON1, ADCS<2:0>).
   - Configure voltage reference (ADCON0, VCFG).
   - Select ADC input channel (ADCON0, CHS<3:0>).
   - Select result format (ADCON0, ADFM).
   - Turn on ADC module (ADCON0, ADON)
3. Start conversion set the GO/DONE bit. (ADCON0, GO)
4. Wait for ADC conversion to complete, polling the GO/DONE bit. (ADCON0, GO)
5. Read ADC Result (ADRESH, ADRESL)