#### Practical Sample and Hold Circuit



Control input open and closes solid-state switch at sampling rate  $\mathbf{f}_{\mathbf{s}}$  .

Modes of operation - tracking (switch closed) hold (switch open)

Sample and Hold Parameters

<u>acquisition time</u> - time for instant switch closes until V<sub>i</sub> within defined % of input. Determined by input time constant  $\tau = Ri_nC$   $5\tau$  value = 99.3% of final value <u>aperture time</u> - time it takes switch to open <u>decay rate</u> - rate of discharge of C when circuit is in hold mode

#### Sampling Rate

To accurately reproduce the analog input data with samples the sampling rate,  $f_s$ , must be twice as high as the highest frequency expected in the input signal. This is known as the Nyquist criterion.

$$f_{s(min)} = 2f_h$$

Where  $f_h$  = the highest discernible f component in input signal  $f_{s(min)}$  = minimum sampling f

Nyquist rate is the <u>minimum</u> frequency and requires an ideal pulse to reconstruct the original signal into an analog value

Sampling a signal is a form of modulation that creates signals that have a fundmental frequency spectrum of the original signal and an infinite number of harmonic aliases.



Sampling at less than  $2f_h$  causes aliasing and folding of sampled signals. This means that the original information will not be reproduced at the same frequency as the original

Folding occurs when the lower frequencies of a harmonic envelope coincide with the higher frequencies of another envelope.



Aliasing occurs when a harmonic frequency is introduced into the original input frequency range.

For signals to be reconstructed correctly, the harmonic components must all occur in the range 0 to  $f_s/2$ .

Take a frequency spectrum view of the sampled signals to get a better understanding of the aliasing and folding.

Sampling at  $f_s = 1000$  Hz with an input frequency of fin of 100 Hz. Ten samples/period- above Nyquist rate



Lowpass filter extracts the range 0 to 500 Hz 0 to  $+f_s/2$ 

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Lower f_s: let f_s = 60 Hz
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$$f_s = 60 \text{ Hz}$$
  $f_{in} = 100 \text{ Hz}$   
 $f_1 = f_s - f_{in} = -40 \text{ Hz}$   $f_2 = f_s + f_{in} = 160 \text{ Hz}$   
 $f_{11} = -f_2 = -160 \text{ Hz}$ 



Increase sampling f to 80 Hz

$$f_s = 80 \text{ Hz}$$
  $f_{in} = 100 \text{ Hz}$   
 $f_1 = f_s - f_{in} = -20 \text{ Hz}$   $f_2 = f_s + f_{in} = 180 \text{ Hz}$   
 $f_{11} = -f_2 = -180 \text{ Hz}$ 

The range to reproduce will be 0 - 40 Hz et38b-2.ppt 5 Sampling Rate of 80 Hz with input of 100 Hz.



The 20 Hz signal is reproduced since it falls in the range of 0 -  $f_s/2$ .

The last two graphs are examples of undersampling with  $f_s < f_{in}$ 

Increase sampling f to 100 Hz

$$f_s = 100 \text{ Hz}$$
  $f_{in} = 100 \text{ Hz}$   
 $f_1 = f_s - f_{in} = 0 \text{ Hz}$   $f_2 = f_s + f_{in} = 200 \text{ Hz}$   
 $f_{11} = -f_2 = -200 \text{ Hz}$ 



With the sampling rate set equal to the input f, the reconstructed signal becomes dc. Other harmonics are generated at +- 200 Hz



Same point sampled on each cycle of sine wave

Folding occurs when  $f_s > f_{in}$  bus less than the Nyquist Rate.



A 25 Hz signal is reconstructed since it falls in the range 0 to  $f_s/2$ .

-50

0

frequency (Hz)

50

100

150

200

250

With a sample rate of 125 Hz we get the same points as though we had sampled a 25 Hz signal

The lower frequencies of f<sub>s</sub> appear in range 0- 62.5 Hz

-200

-150

-100



In on/off control error signal is binary in nature. Comparator is hardware of software that compares the sensor value to the desired value (setpoint) and then outputs a binary value.

Final control element is run at either 100% or 0%



When room temperature falls below a preset temperature, the thermostat contacts activate the furnace fan and fuel supply.

Furnace is on with 100% output or of with 0% output

#### Criteria For Application of On/off Control

- 1.) Precise control must not be required
- 2.) Process must have sufficient internal storage capacity to allow final control element to supply the load while measurement is taken.
- 3.) Energy entering the load must be small compared to the stored energy in the process

**Controller Time Plots** 



#### **Differential Gap Controller**

To improve the stability of an on/off controller a hysteresis is added to the comparator element This is called <u>differential gap control</u>



Logic - when measured variable goes above upper boundary final control element turns on. Remains on until variable falls below lower level Gap also known as <u>dead zone</u>. Typically 0.5-2.0% of full range.

Gap introduces a know control error but reduces cycling

Analog Signal Conversion

Two Problems

Input - analog-to-digital conversion continuous signals converted to discrete values (Analog -to-digital)

Output - digital-to-analog conversion discrete values converted to continuous signals (Digital-to-analog)

Number of bits in digital signal determines the resolution of the digital signals. Depends on voltage span also.

Resolution - smallest number that can be measured Accuracy - is the number measured correct

#### **Review of Binary Numbers**

Only two symbols in system { 1, 0 } called bits Logic 1 and Logic 0 represent on/off states in circuits

System is positional using powers of 2

2 <sup>0</sup> = 1	2 <sup>4</sup> = 16	2 <sup>8</sup> = 256
2 <sup>1</sup> = 2	2 <sup>5</sup> = 32	2 <sup>9</sup> = 512
$2^2 = 4$	$2^6 = 64$	$2^{10} = 1024$
2 <sup>3</sup> = 8	2 <sup>7</sup> = 128	211 = 2048
		$2^{12} = 4096$

Group of 8 bits called byte Two bytes,16 bits, called word

Left-most bit is usually the most significant bit (MSB) The right most is usually the least significant bit (LSB)

> MSB (2<sup>7</sup>) LSB (2<sup>0</sup>) 10111010

A n bit binary number can represent 2<sup>n</sup> different decimal numbers. This includes a zero.

**Review of Binary Numbers** 

Converting binary to decimal - use the power of 2 associated with the position and multiply it by the bit value.

Example: convert the number above

$$10111010 = 1x2^{7}+0x2^{6}+1x2^{5}+1x2^{4}+1x2^{3}+0x2^{2}+1x2^{1}+$$
$$....0x2^{0}$$
$$10111010 = 128 + 0 + 32 + 16 + 8 + 0 + 2 + 0$$
$$10111010 = 186_{10}$$

To convert a decimal number into a binary value, use repeated division by 2 of decimal value record remainder (1, 0) and continue until division is no longer possible.

Example: convert 19 to binary use table

Example: Decimal-to-binary conversion (cont.)

9/2 = 4 remainder 1

4	9	19	decimal
1	1	biı	nary

4/2 = 2 remainder 0

 2	4	9	19	decimal
0	1	1	binary	

2/2 = 1 remainder 0

1	2	4	9	19	decimal
0	0	1	1		binary

 $\frac{1}{2} = 0 \text{ remainder 1}$   $\frac{0 | 1 | 2 | 4 | 9 | 19 \text{ decimal}}{1 | 0 | 0 | 1 | 1 | \text{ binary}}$  19 = 10011 binary

# Resolution and Accuracy of Digital Signals

Resolution determined by the number of bits

Analog input vs Digital Output (3 bit system)



The output is a discretized version of the continuous input

Error determined by the step size of the digital signal

### **Resolution Formulas**

Resolution in terms of full scale voltage is equal to value of Least Significant bit

$$V_{\text{LSB}} = \frac{V_{\text{fs}}}{2^n}$$

Where

V<sub>fs</sub> = full scale voltage n = number of bits V<sub>LSB</sub> = voltage value of LSB

Converting to digital value with a finite number of bits also introduces quantization errors

Quantization error ranges from +  $V_{LSB}$  to - $V_{LSB}$ Numerically, maximum quantization error is equal to:

$$Q.E. = \frac{V_{LSB}}{2}$$

Where

Q.E. = quantization error  $V_{LSB}$  = voltage value of LSB

Percent resolution

%resolution = 
$$\frac{1}{2^n - 1} \cdot 100\%$$

Wheren = number of bits in digital representationet38b-2.ppt18

## **Digital Resolution and Error**



Error in natural binary coding is +- 1/2 LSB

**Resolution 3-bit system** 

LSB = 
$$\frac{V_{fs}}{2^n}$$
  $V_{LSB} = \frac{10V}{2^3} = \frac{10}{8} = 1.25$ 

Max. digital value less analog value by value of LSB

Example: An 8-bit digital system is used to convert an analog signal to digital signal for a data acquisition system. The voltage range for the conversion is 0-10 V. Find the resolution of the system and the value of the least significant bit

signal converted to 256 different levels  $LSB = \frac{V_{fs}}{2^{n}}$ n=8 %resolution =  $\frac{1}{2^{n}-1} \cdot 100\%$ %resolution =  $\frac{1}{2^{8}-1} \cdot 100\%$ %resolution = 0.392%

 $V_{fs} = 10 \text{ Vdc}$  n = 8 bits

$$LSB = \frac{V_{fs}}{2^{n}} = \frac{10 \text{ V}}{2^{8}} = \frac{10}{256} = 0.0390625 \text{ V}$$

The digital convert above is replaced with a 12 bit system. Compute the resolution and the value of the least significant bit.

signal converted to 4096 different levels n = 12

$$LSB = \frac{V_{fs}}{2^{n}}$$
n = 12 bits
%resolution =  $\frac{1}{2^{12} - 1} \cdot 100\%$ 
%resolution = 0.0244%

$$V_{fs}$$
 = 10 Vdc  $V_{LSB} = \frac{V_{fs}}{2^n} = \frac{10 \text{ V}}{2^{12}} = \frac{10}{4096} = 0.002441 \text{ V}$ 

### Effects of Resolution





# Difference between analog value and digital reconstruction is quantizing error

# Binary-weighted Resistor Digital-to-Analog Converter (DAC)



B0, B(n-3), B(n-2), ....B(n-1) take on values of 1 or 0 depending of the digital output

$$\begin{split} V_{0} &= -I_{F} \cdot R_{F} \\ V_{0} &= -R_{F} \sum_{i=1}^{n} \frac{B(n-i) \cdot V}{2^{i-1}R} \end{split} \qquad \text{Formula for output} \end{split}$$

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 $l2 = \frac{V}{2R}$ 

 $11 = \frac{V}{P}$ 

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



$$B = 1 + 0 + 2 = R$$

$$B = 1 + 0 + 2 = R$$

$$B = 1 + 0 + 2 = R$$

$$B = 1 + 0 + 2 = R$$

$$B = 1 + 2 = R$$

$$B = 1 + 2 = R$$

$$B = 1 + 2 = R$$

$$R = 1 + 2 =$$

# Limitations of Binary-weighted Resistor DACs

Typical Values of digital words 8-12 bits (max 20 bits)

Range of resistors  $2^{12}/1 = 4096/1$ 

If smallest resistor = 10k largest must be 4096\*10k or 40,960,000 ohms 40.96 Meg!!!

Limited to 6 - 8 words due to scale of resistors

Current Resolution of OP AMPs

Assuming V = 10 Vdc

For LSB  $I_{LSB} = V/R^*2^{(n-1)}$ 

For value of R=10k

 $I_{LSB} = 10/40.96 M\Omega = 2.44 \times 10^{-7} A$ 

Approaches range of bias currents needed to activate the OP AMP