PHYS2641 – Laboratory Skills and Electronics

Electronics

Lecture 3

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Last week

- PID control systems
- ‘Operational amplifiers’
- Some simple op-amp circuits

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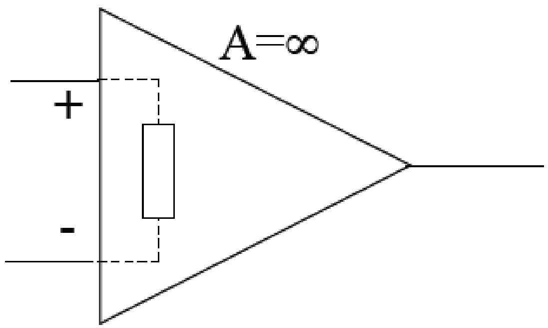
Last week –
Op-amps: General properties

For an *ideal* op-amp:

- The open-loop gain A is ***infinite***
- The input impedance is ***infinite***
- The output impedance is ***zero***



These give us '**Golden Rules**' for a ***negative-feedback*** system:

1. The output will always attempt to drive the inputs to the same voltage (the steady-state error is zero)
2. No current flows into the inputs
3. Loading does not affect the output

Using these rules we can figure out the behaviour of fairly complex op-amp circuits!

This is also a very useful property!

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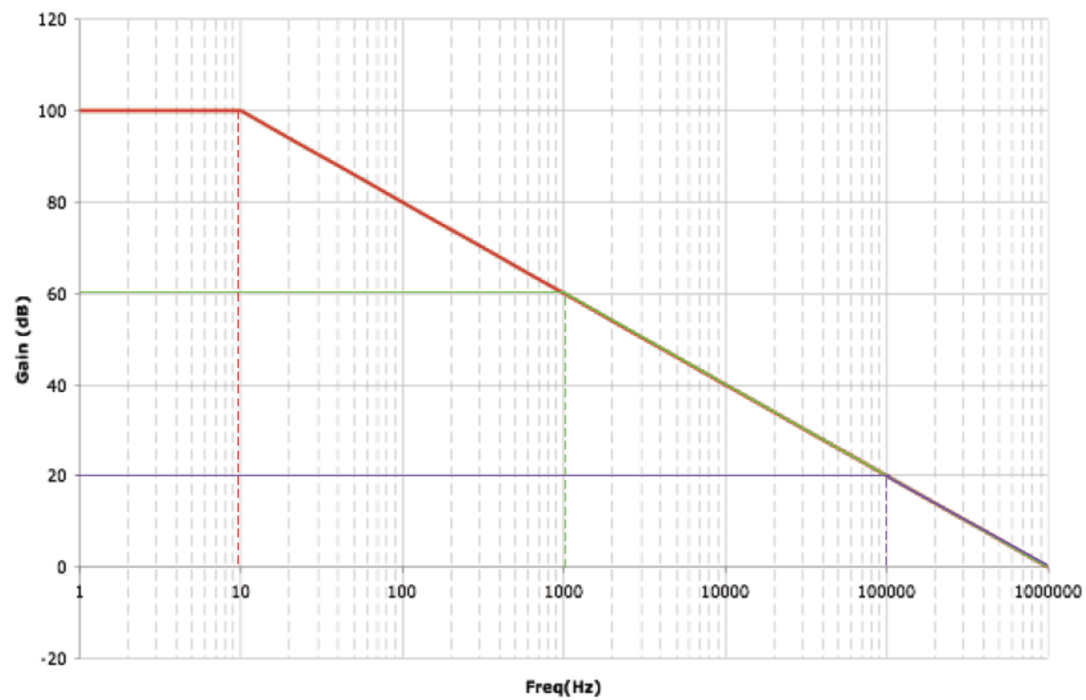
Last week – Frequency response

- Ideal op-amp has infinite gain
- Real op-amps have limited gain, which *drops off with increasing frequency*

This is described by the *'gain-bandwidth product'* (i.e. Gain x Frequency = const.)

There is a trade-off between Gain and Bandwidth

We can use ***feedback*** to *reduce the gain* and thereby *increase the bandwidth*



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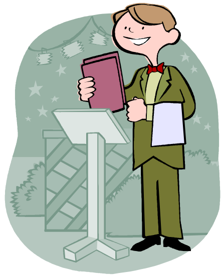
Today's menu



Aims:

1. Limitations of real op-amps, Comparators
2. Positive feedback
3. Stability and oscillations in control systems

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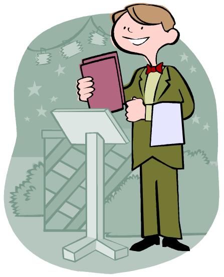
Today's menu



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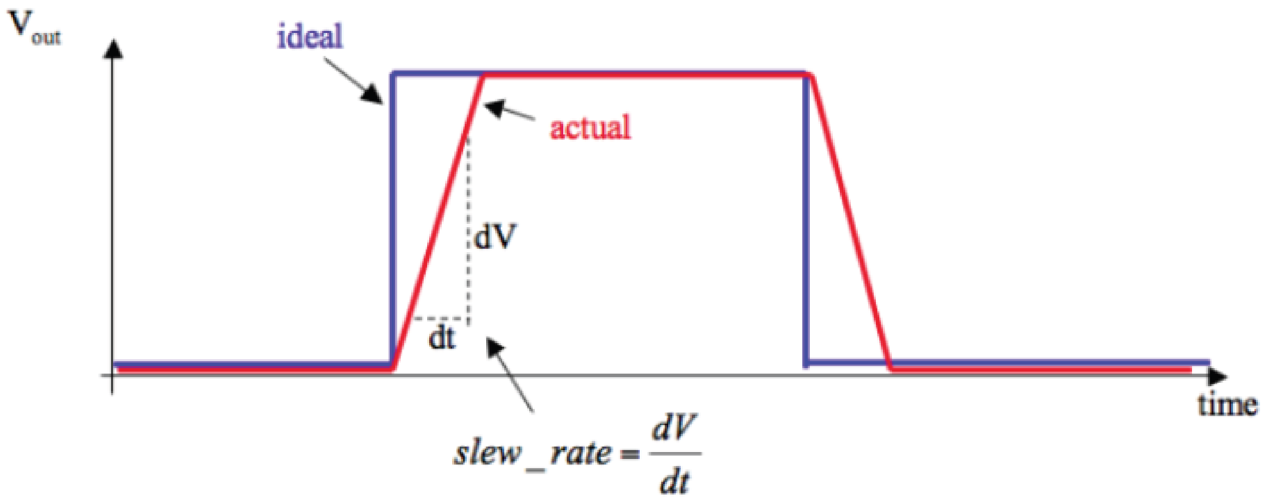
Slew-rate

- The output response of an ideal op-amp is instantaneous
- Real op-amps have limited rate-of-change of the output. This is known as the '***Slew-rate***', usually measured in V/μs



- Slew-rate limits suitability of some op-amps (e.g. 741) in high-frequency circuit applications

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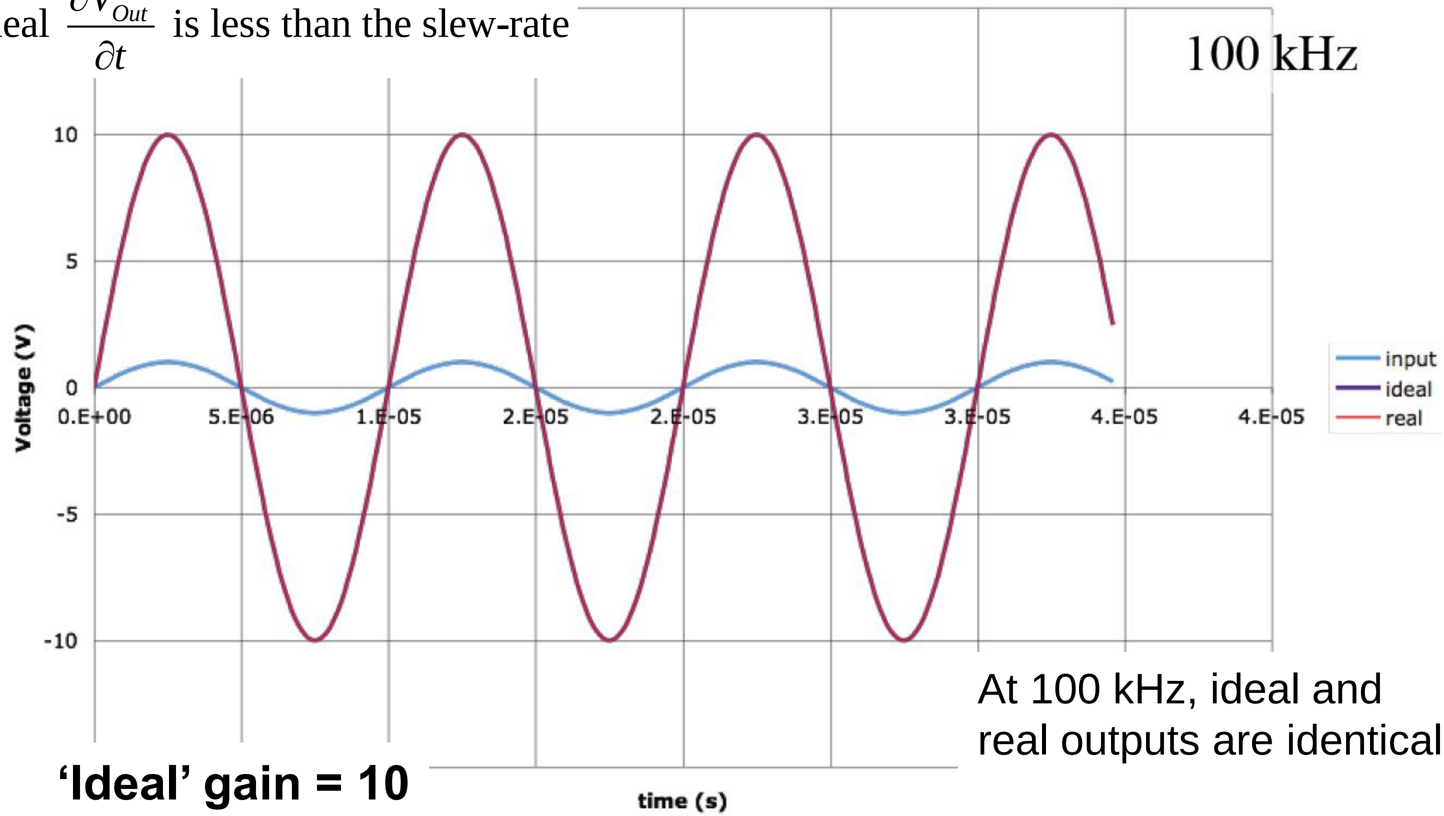
Slew-rate: example

Ideal $\frac{\partial V_{Out}}{\partial t}$ is less than the slew-rate



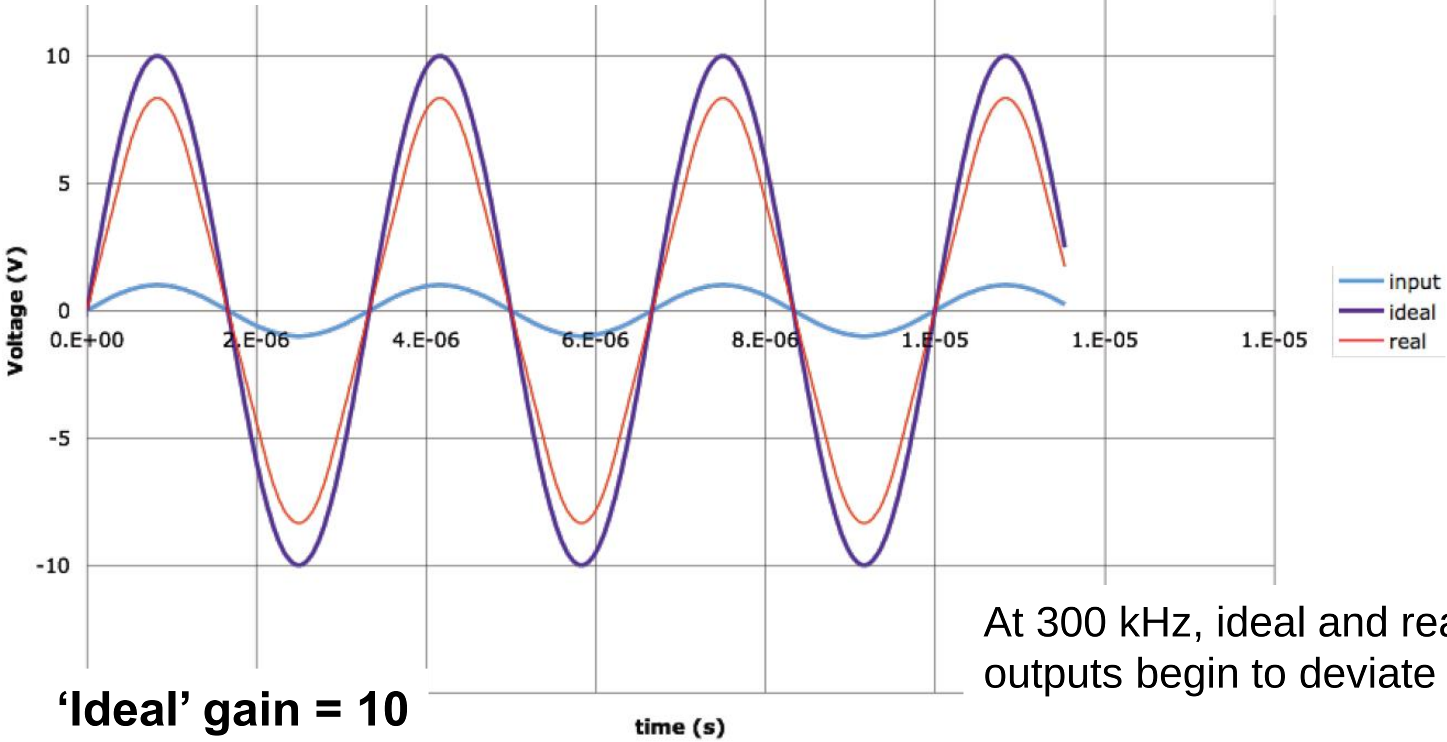
At 100 kHz, ideal and real outputs are identical

'Ideal' gain = 10

Slew-rate: example (2)

Ideal $\frac{\partial V_{Out}}{\partial t}$ is slightly greater than the slew-rate

300 kHz



At 300 kHz, ideal and real outputs begin to deviate

'Ideal' gain = 10

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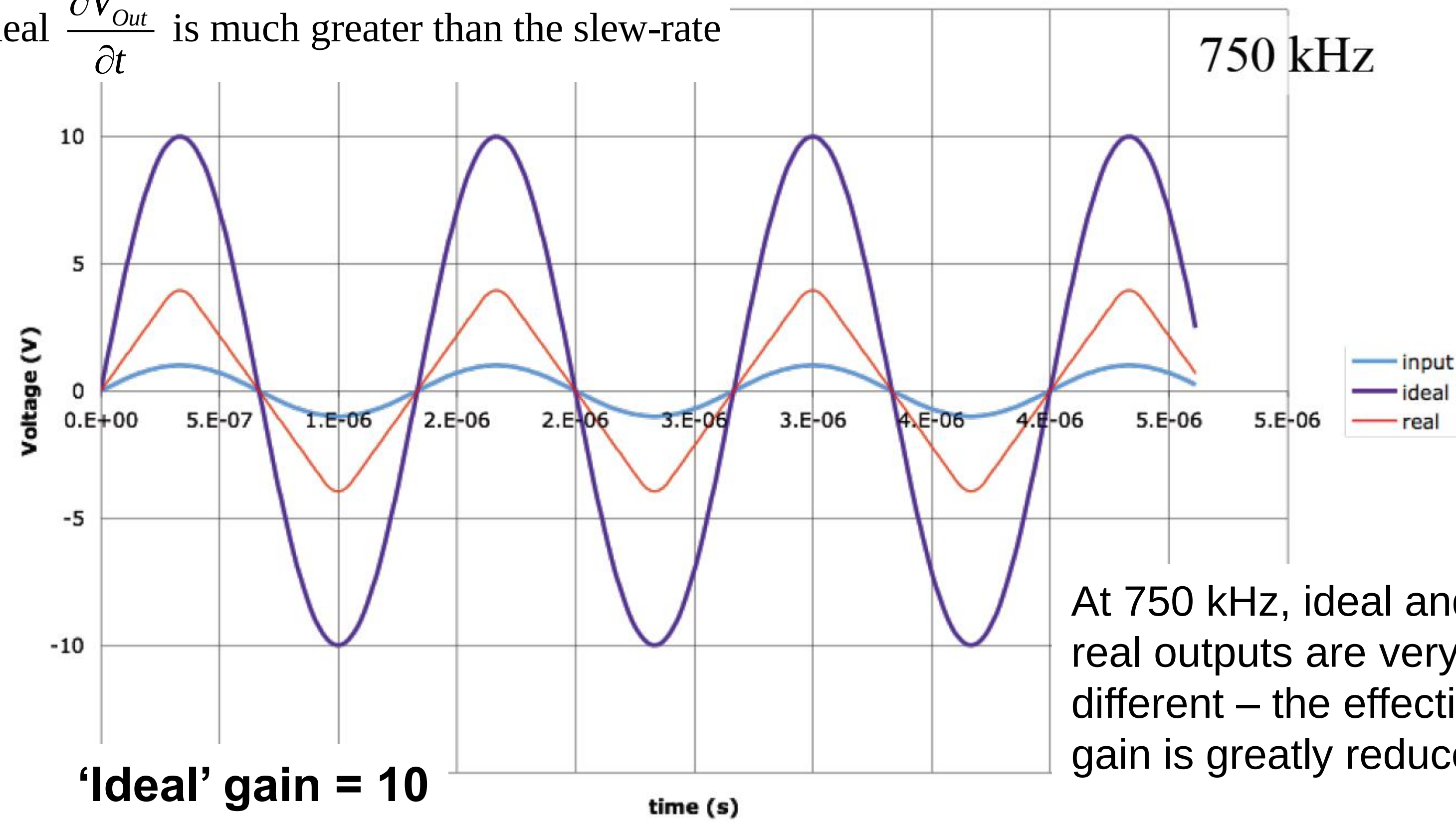
Slew-rate: example (3)

Ideal $\frac{\partial V_{Out}}{\partial t}$ is much greater than the slew-rate



‘Ideal’ gain = 10

At 750 kHz, ideal and real outputs are very different – the effective gain is greatly reduced

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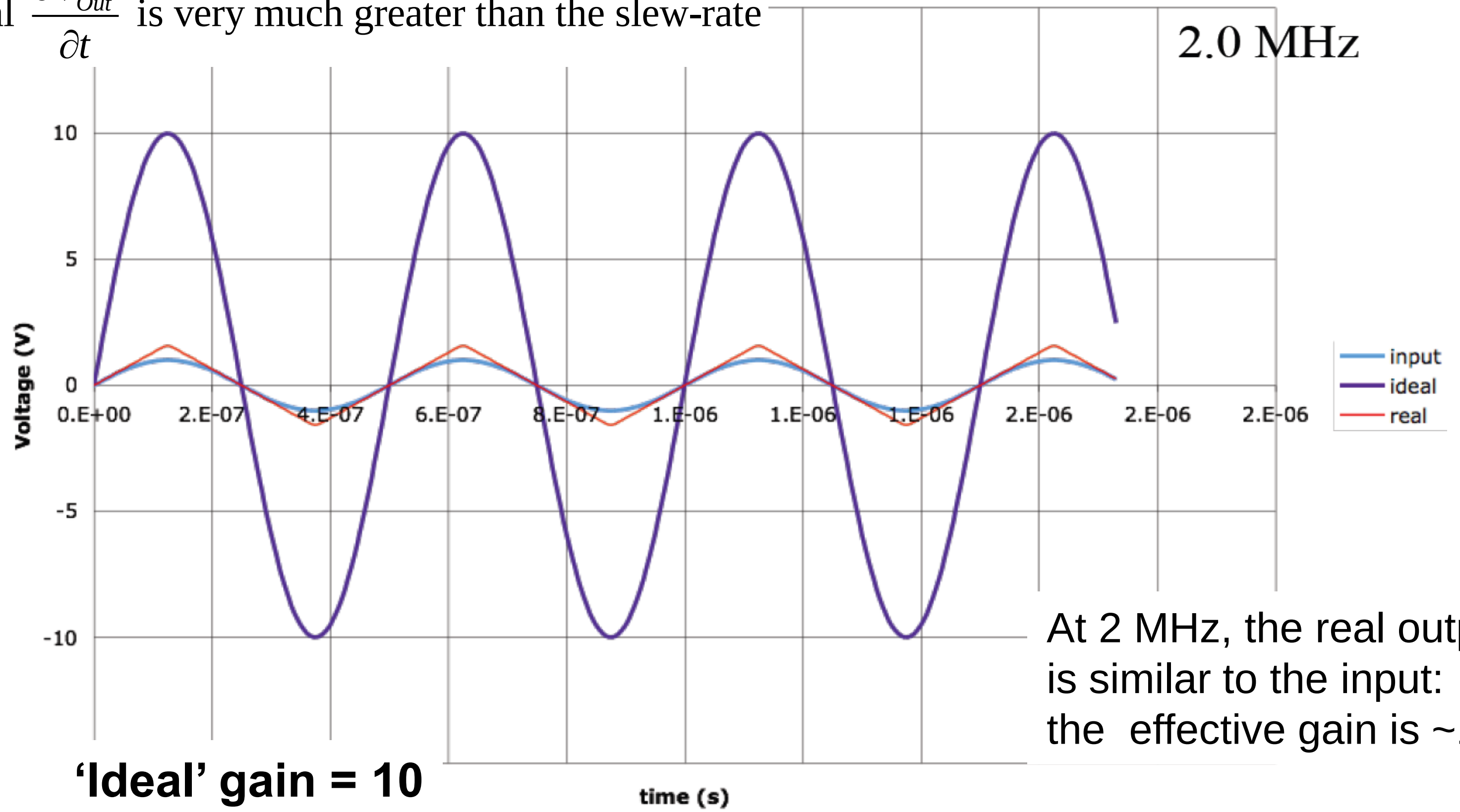
Slew-rate: example (4)

Ideal $\frac{\partial V_{Out}}{\partial t}$ is very much greater than the slew-rate



At 2 MHz, the real output is similar to the input: the effective gain is ~1

'Ideal' gain = 10

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Slew-rate-limited gain

- At high frequencies the slew-rate tends to decrease the amplitude of the output, and limits the effective voltage gain
- This is a different effect to ***and completely separate from*** the intrinsic drop-off in gain as frequency increases (which is due to gain-bandwidth product)

- If an amplifier is slew-rate-limited, the effective gain depends on the amplitude of the input signal – as V_{out} is limited [bandwidth-limited gain does not depend on input amplitude]

- Slew-rate-limiting is non-linear and gives rise to additional frequency-components in the output – i.e. a sinusoidal input does not result in a sinusoidal output [bandwidth-limited gain remains linear]

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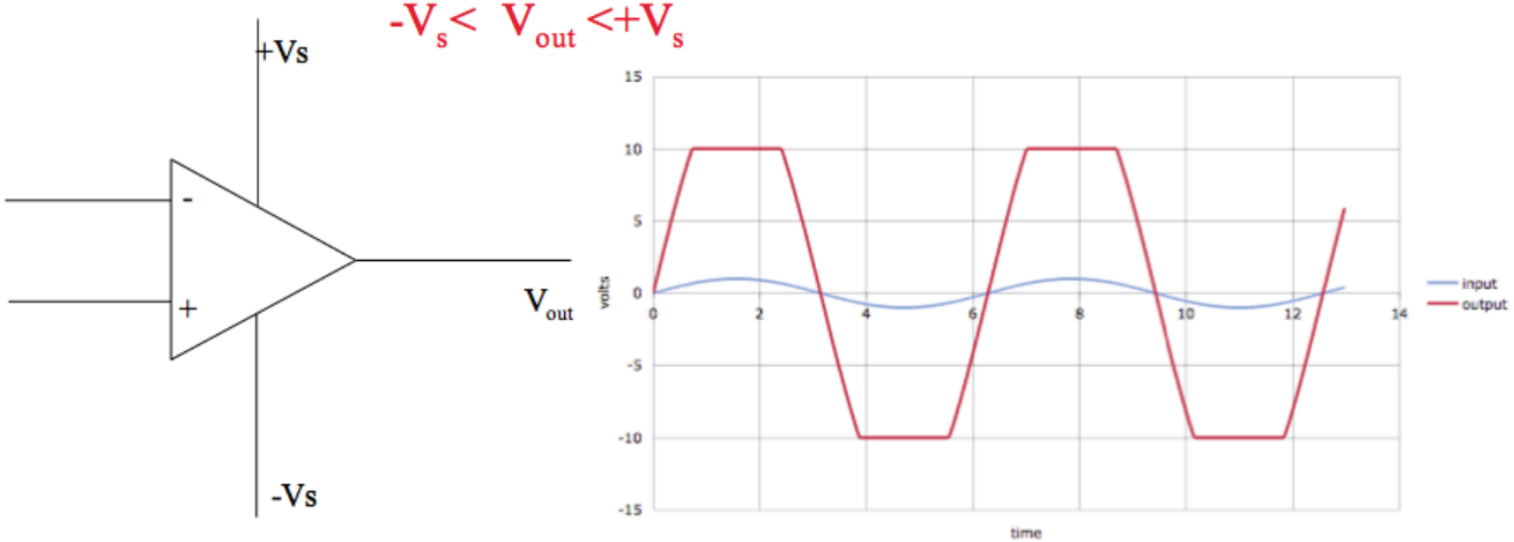
Saturation

- Output voltage of an ideal op-amp is unlimited (recall infinite gain)
- Max output of a real op-amp output is **limited** by the ***Power-supply rail voltages***!

$-V_s < V_{out} < +V_s$



Gain = 15, Vs=+/-10V

Saturation: design example

When the output saturates, information is lost: you know that the input is above a certain level, but cannot know details of the waveform it takes

Example: You have a small, noisy, signal that you want to amplify. Signal amplitude V_{signal}=10mV, V_{noise}=5mV. Your power supply is such that your amplifier output can range from -10V to +10V.

What is the maximum gain we can sensibly use?

The 'obvious answer' is that we use a gain of 1000, so 10mV $\rightarrow$ 10V

However, including noise the total input $V_{in} = V_{signal}+V_{noise}$ =15mV, so we must set

$$\text{Gain} \leq \frac{10\ \text{V}}{15\ \text{mV}} \approx 667$$

Despite having a potential +/- 10 V amplifier output, to avoid saturation our maximum signal output amplitude is < 7 V

Saturation: uses

Saturation limits the output voltage (gain) which can be obtained from a given op-amp circuit

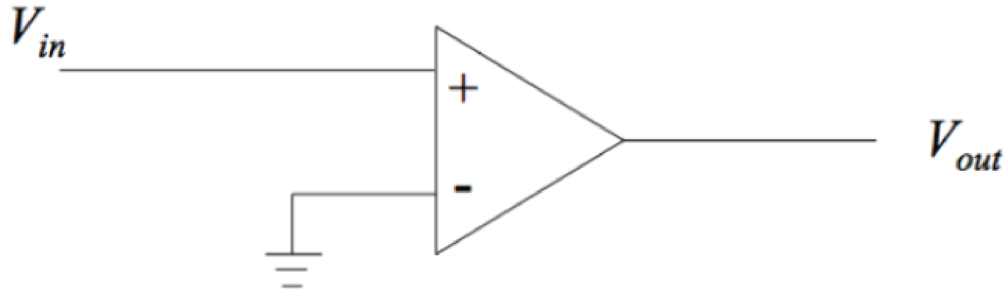
The output voltage is limited to the supply rail voltage which is used to power the op-amp

The output current is also limited by the current which can be drawn from the supply rails: this can limit the output current of a ‘buffer’ (last lecture)

However, saturation can also be employed in circuit design to create digital waveforms, perform logic operations etc.

Comparator

A simple comparator circuit consists of an op-amp ***without*** feedback

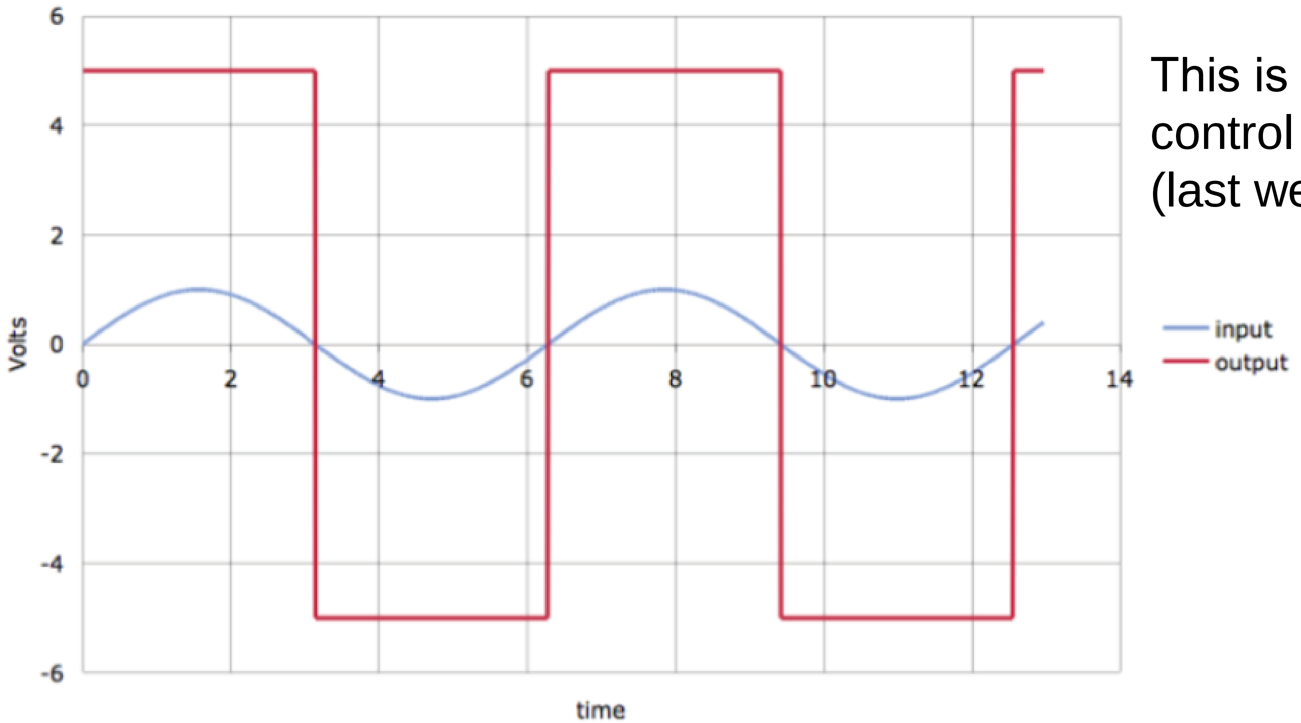


If V_{in} is sinusoidal, what form do we expect for V_{out}?

Remember – V_{out} is the product of the op-amp *'open-loop gain'* (*$A>10^5$*) and the *error signal* ($V_+ - V_- = V_{in}$)

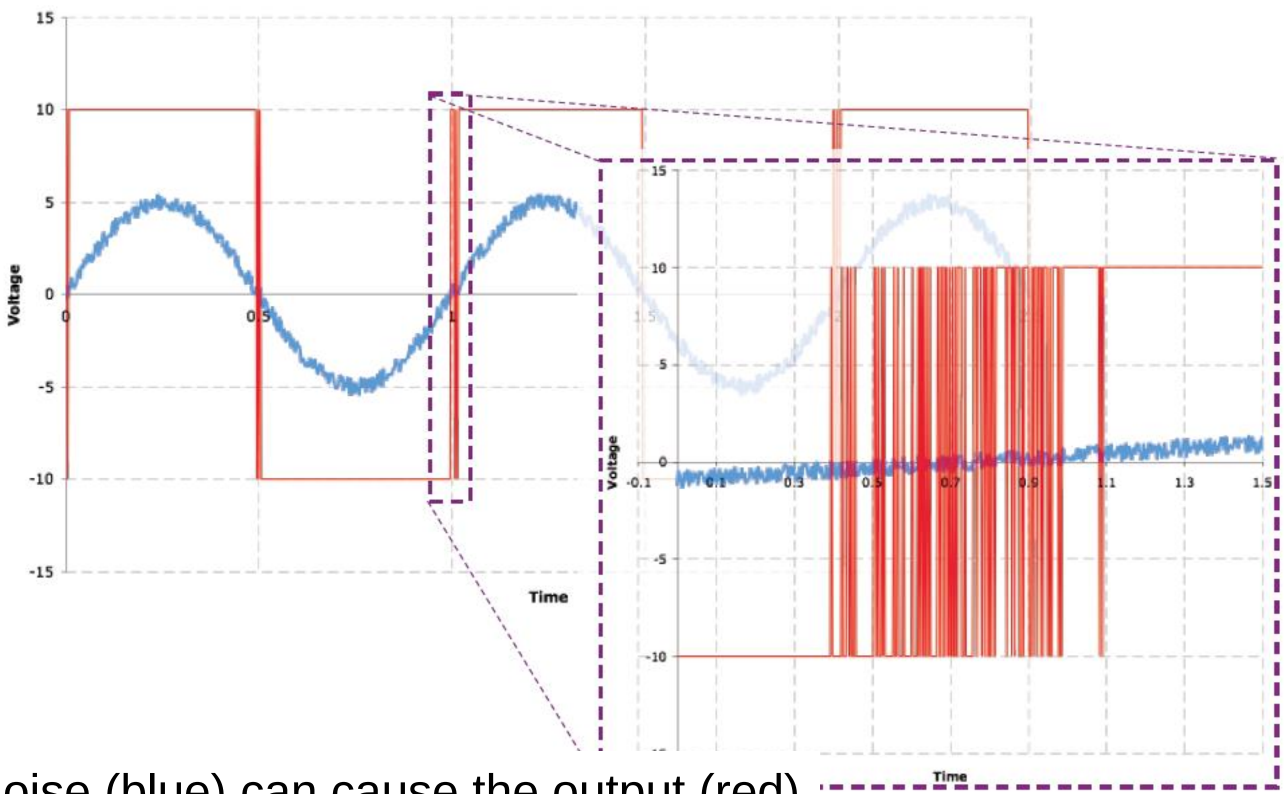
Comparator (2)

V_{out} will saturate at either positive or negative supply-rail voltage, depending on the sign of V_{in} (equivalent to sign of $V_+ - V_-$): a ‘comparison’ between voltages V_+ and V_-



This is an ‘on-off’ control system (last week)

Comparator (3)



Input noise (blue) can cause the output (red) to oscillate when the input signal is ~ zero

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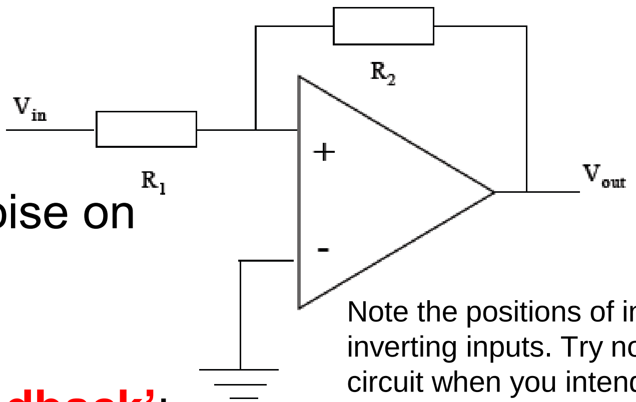
Schmidt trigger

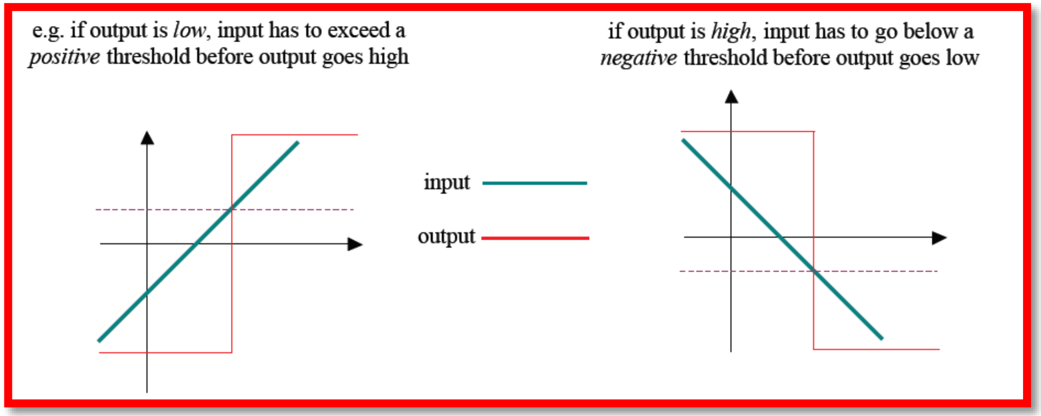


A ‘hysteretic’ comparator which ignores noise on the input below a ‘threshold’ value.

Note the positions of inverting/non-inverting inputs. Try not to make this circuit when you intend to make a (non-)inverting amplifier!

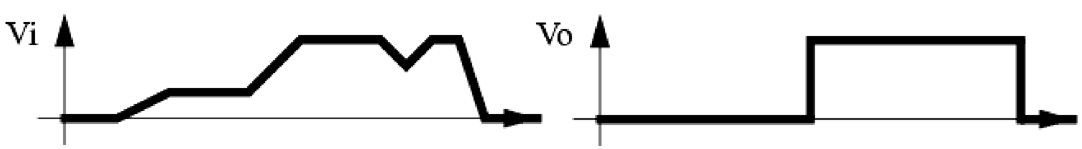
The circuit is configured with **‘positive-feedback’**; (V_{out} feeds back into non-inverting input) so the output ***saturates***, i.e.

$$V_{out} = \pm V_{\text{supply}}$$

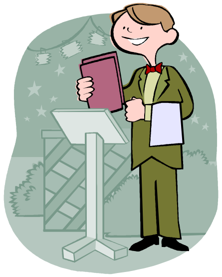


Threshold voltage at which the output reverses is:

$$\boxed{V_{\text{threshold}} = \mp V_{\text{supply}}\left(\frac{R_1}{R_2}\right)}$$



Today's menu



Aims:

1. Limitations of real op-amps, Comparators
2. Positive feedback
3. Stability and oscillations in control systems

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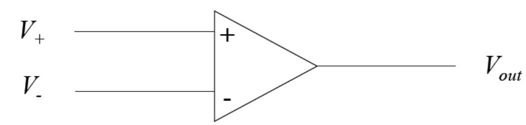
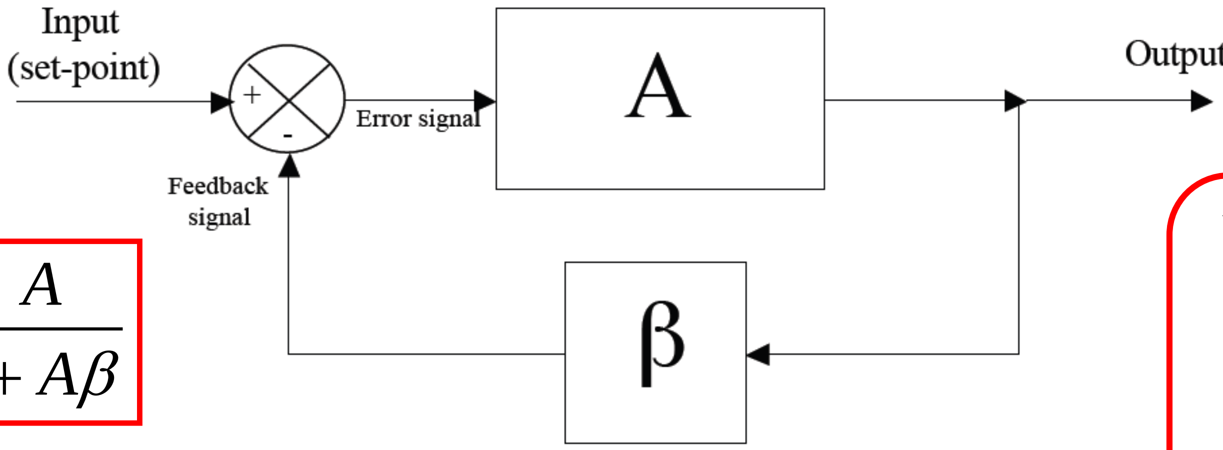
Control systems

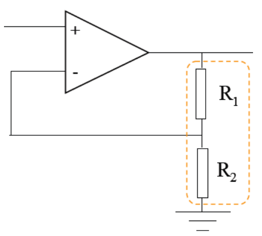


$$V_{out} = A(V_+ - V_-)$$

Recall – Closed loop control system:



$$\text{Gain} = \frac{A}{1 + A\beta}$$



$$V_- = \beta V_{out}$$

Aβ is sometimes referred to as the **'loop gain'**

Aβ > 0 results in *Negative feedback*, when *Aβ* >> 0 the gain is determined solely by *β*

Negative feedback provides a **stable output** and **control of gain**

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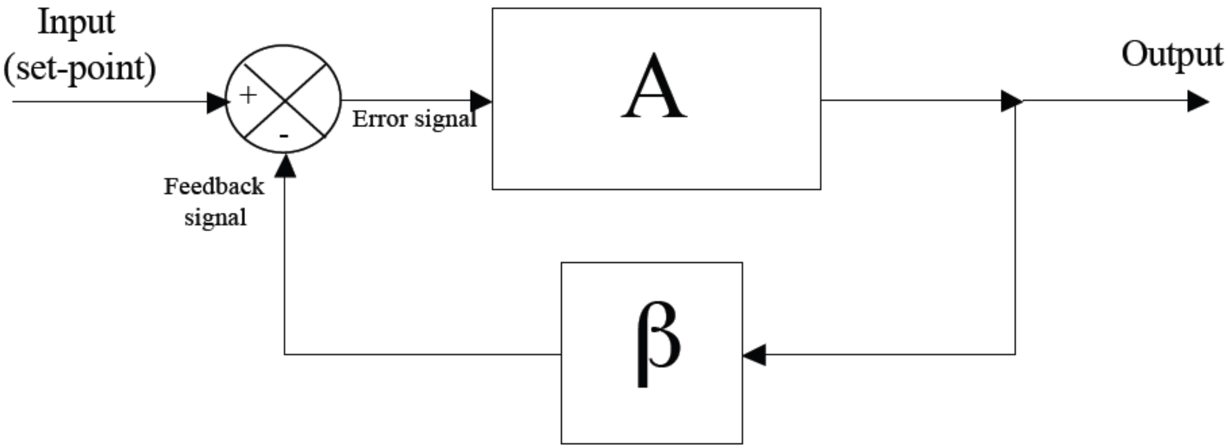
Control systems

Recall – Closed loop control system:



$$\boxed{\text{Gain} = \frac{A}{1 + A\beta}}$$

But, what happens when Aβ < 0 ??

Answer: **‘Positive feedback’!**

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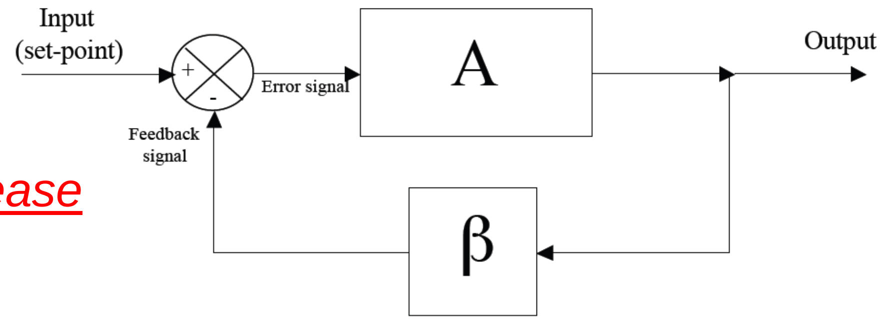
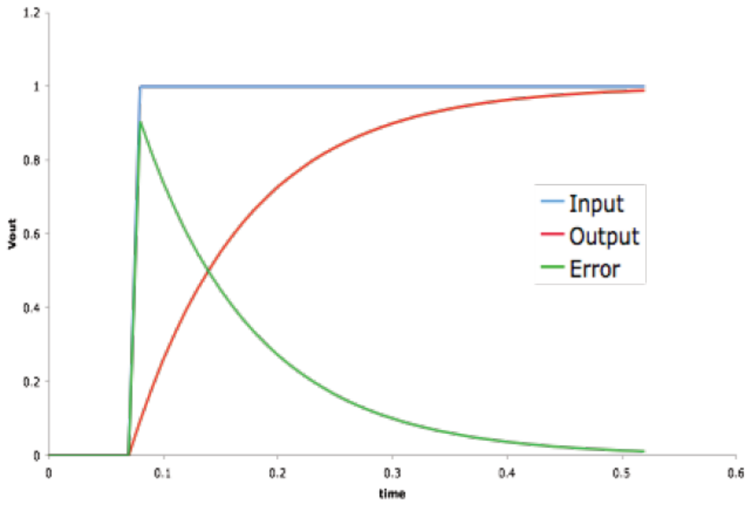
Positive feedback

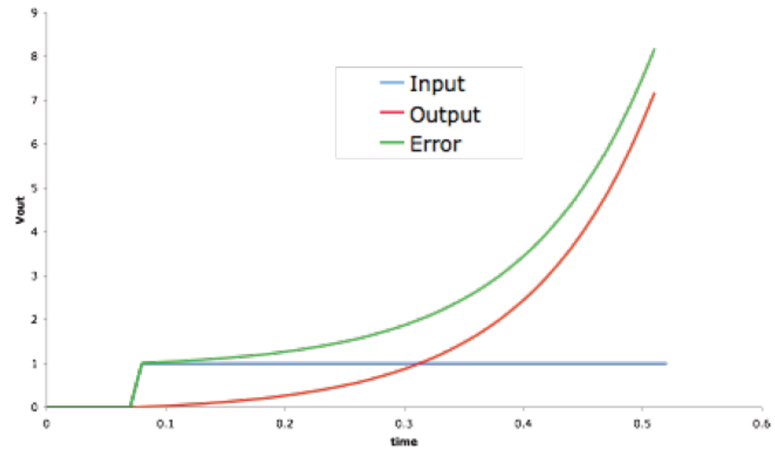
Negative feedback tends to *reduce* the error signal – stable output

Positive feedback causes V_{err} to *increase*





Negative feedback



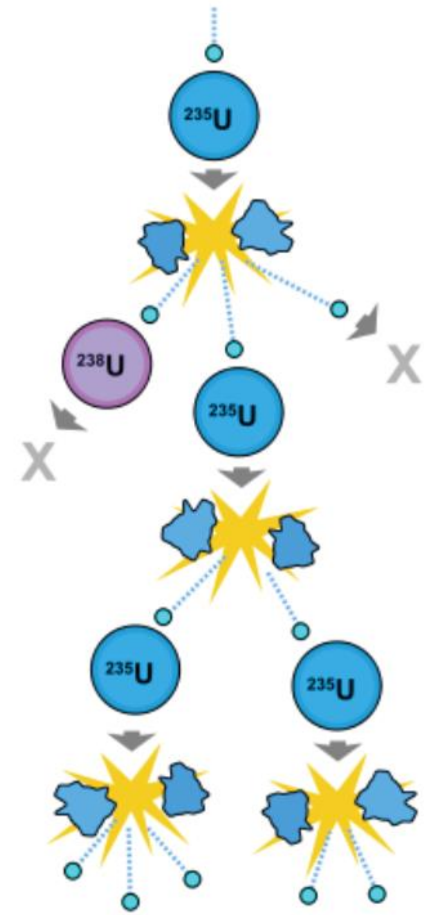
Positive feedback

Example of positive feedback

Nuclear fission chain-reaction:

- Neutron with sufficient KE is absorbed by U_{235} atom
- U_{235} atom spits into fission fragments, releasing further energetic neutrons
- More U_{235} atoms absorb neutrons $\rightarrow$ fission $\rightarrow$ release more neutrons

Each cycle more atoms undergo fission, and more neutrons are released: a cascade reaction occurs



Example of positive feedback (2)

‘Bank-run’:

- A bank appears to be on the verge of insolvency
- People rush to withdraw their cash
- Bank moves closer to insolvency
- More people rush to withdraw cash...

High-gain positive feedback tends to lead to exponential growth, until limited by environmental or systemic factors:

Bank becomes insolvent – no more cash to give out

All U_{235} atoms have fissioned – no further reaction

Amplifier output limited by supply-rail voltage – **Saturation**!

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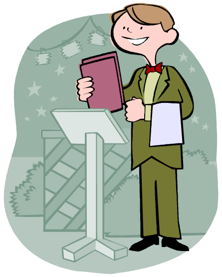
Today's menu



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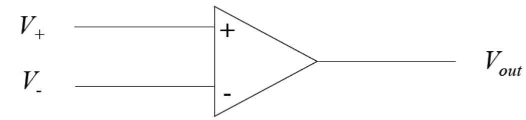
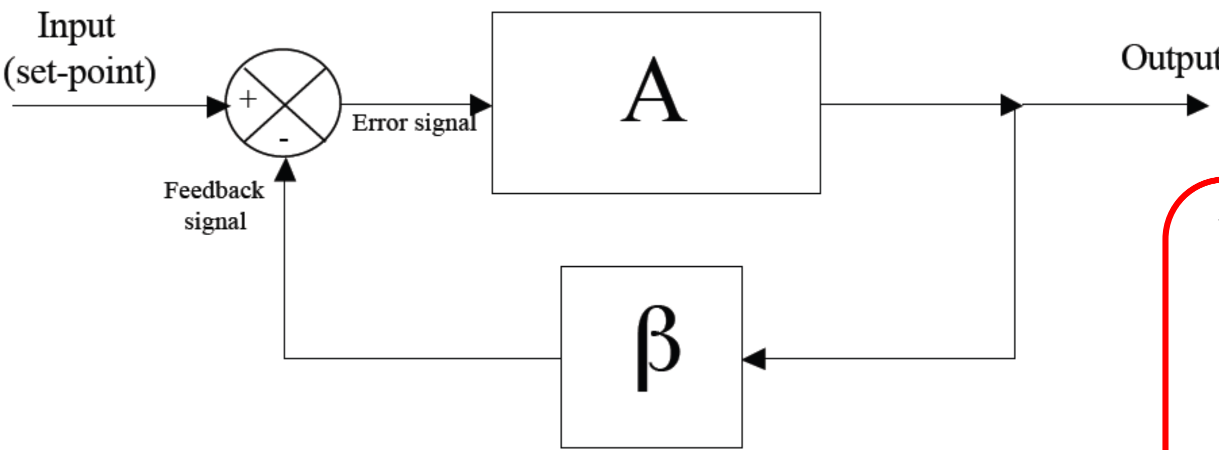
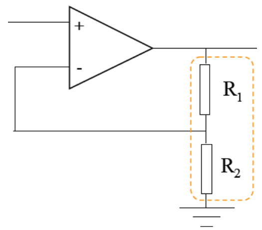
Control systems



$$V_{out} = A\left(V_+ - V_-\right)$$





$$V_- = \beta V_{out}$$

$$\boxed{\text{Gain} = \frac{A}{1 + A\beta}}$$

$A\beta > 0$ results in *Negative feedback*: guaranteed stable

$A\beta < 0$ results in *Positive feedback*

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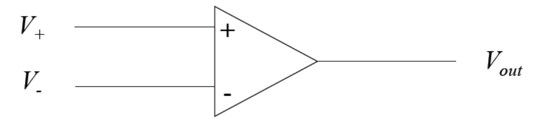
Control systems



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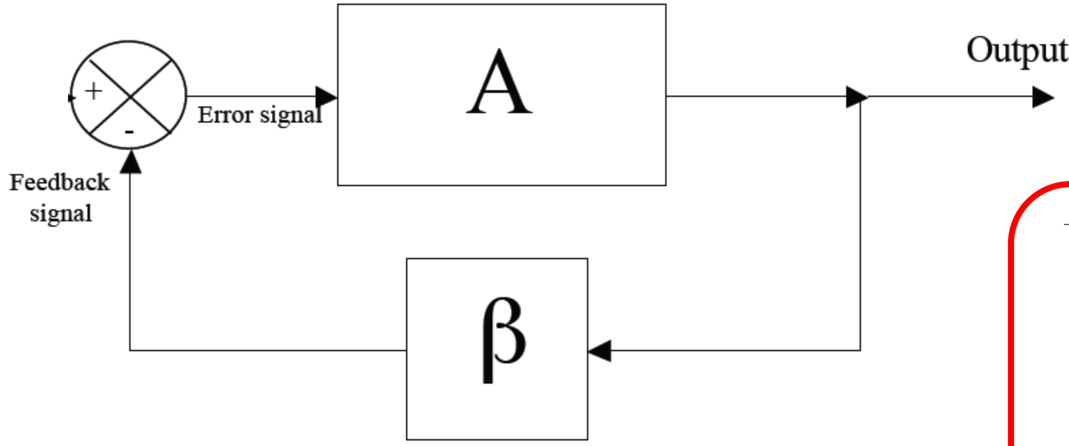
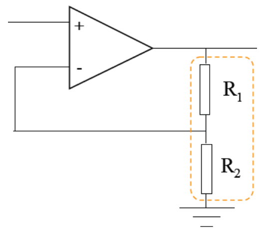




$$V_- = \beta V_{out}$$

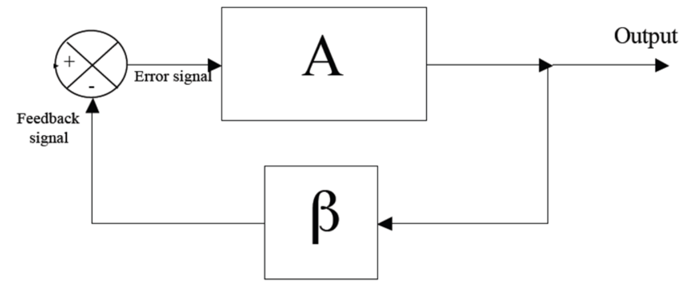
$$\boxed{\text{Gain} = \frac{A}{1 + A\beta}}$$

What happens when <u>Aβ = -1</u> ??

Answer: Closed-loop gain tends *to infinity*!

If gain = ∞ we can have output with no input signal

$A\beta$ = -1??



What does having $A\beta$ = -1 actually mean?

- The *magnitude* of the loop-gain $|A\beta| = 1$

  Any signal in the loop will keep the same amplitude every time it passes round the feedback loop

- The *phase-shift* of the loop-gain $\angle A\beta$ gives a 'total' phase-shift of 2π around the feedback loop

  Signal mixer in our block-diagram representation includes a phase-shift of π

These are the **'Barkhausen Criteria'** for stability

A and β can both have *frequency dependence* (magnitude and phase)

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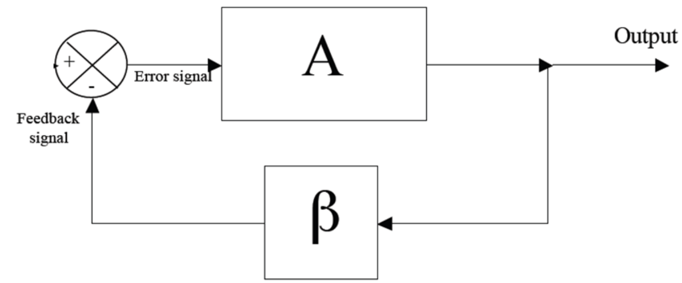
Special case: $A\beta = -1$



- The *magnitude* of the loop-gain $|A\beta| = 1$
- The *phase-shift* of the loop-gain $\angle A\beta$ gives a 'total' phase-shift of 2π around the feedback loop

Any electrical 'signal' circulating around the loop can be thought of as composed of many different frequency Fourier components

A and β will be different for each frequency: Barkhausen criteria are met only for a single Fourier component

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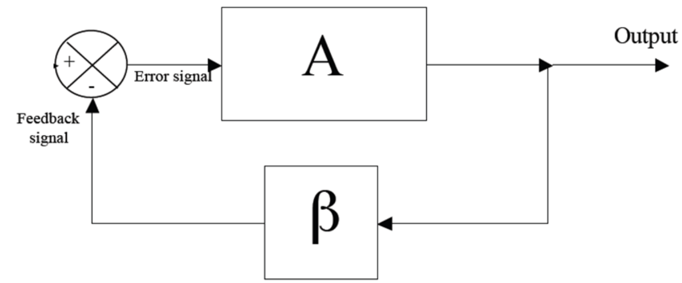
Special case: $A\beta = -1$



- The *magnitude* of the loop-gain $|A\beta| = 1$
- The *phase-shift* of the loop-gain $\angle A\beta$ gives a 'total' phase-shift of 2π around the feedback loop

If $|A\beta| < 1$ then the signal will decay in amplitude every pass of the feedback loop; any frequency components with $|A\beta| < 1$ will disappear

If phase-shift around the loop is not a multiple of 2π, signal de-phases (*c.f.* destructive interference). De-phased signal time-averages to zero; any frequency components with total phase not $2\pi n$ will disappear

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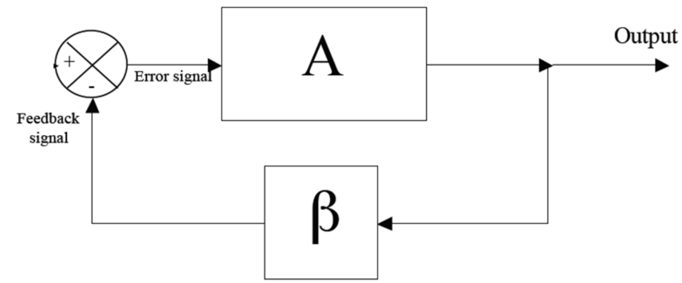
Special case: $A\beta = -1$

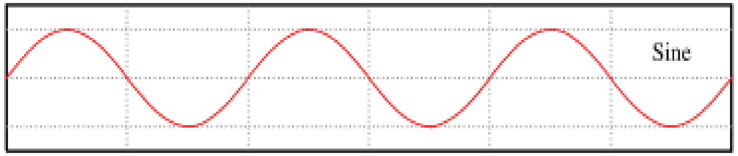


- The *magnitude* of the loop-gain $|A\beta| = 1$

- The *phase-shift* of the loop-gain $\angle A\beta$ gives a 'total' phase-shift of 2π around the feedback loop

Frequencies components where Barkhausen criteria are not met vanish

Only single frequency component remains – determined by phase behaviour of A and β; output has a (tuneable) single frequency…



The output of this circuit is a sine wave!

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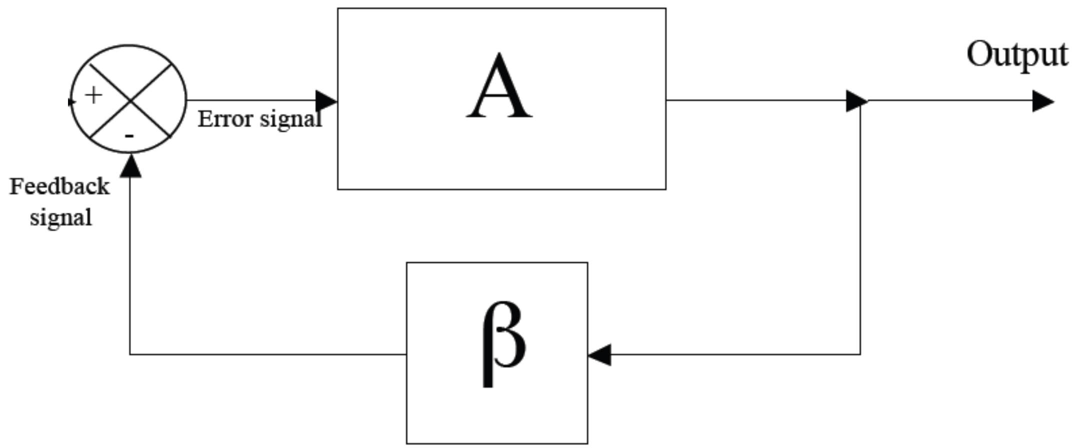
Control systems



$$\boxed{\text{Gain} = \frac{A}{1 + A\beta}}$$

What happens when *<u>Aβ < -1</u>* *??*

Again, can generate output with no signal input…

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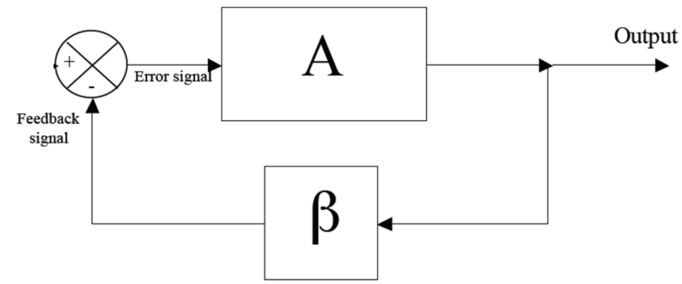
What about $A\beta$ < -1



What does having $A\beta$ < -1 actually mean?

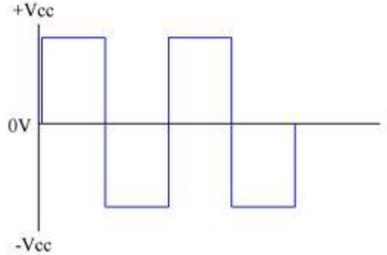
- The *magnitude* of the loop-gain $|A\beta| > 1$

  Any signal will be amplified every time it passes round the feedback loop

- The *phase-shift* of the loop-gain $\angle A\beta$ again gives 2π phase-shift around the feedback loop

  Again, all frequency components where this criterion is not met will de-phase, and time-average to zero

Single-frequency signal that saturates at the supply voltage – square-wave!



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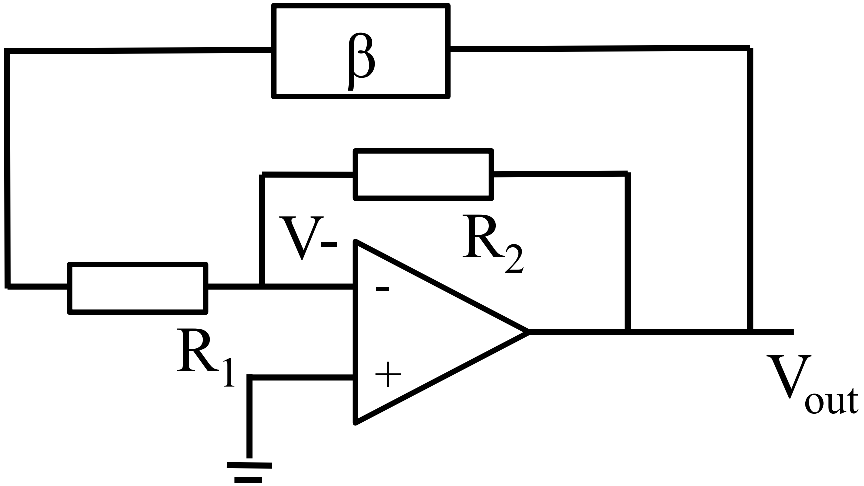
Op-amp oscillator implementation

$$V_{out} = -AV_{-}$$

$$V_{-} = \beta V_{out}$$



Inverting amplifier provides:

- Gain A
- Phase shift π

For stable sinusoidal output at a specified frequency, β must provide:

- Gain 1/A – so that Aβ = 1
- Phase shift π – so that total phase shift around the loop is a multiple of 2π

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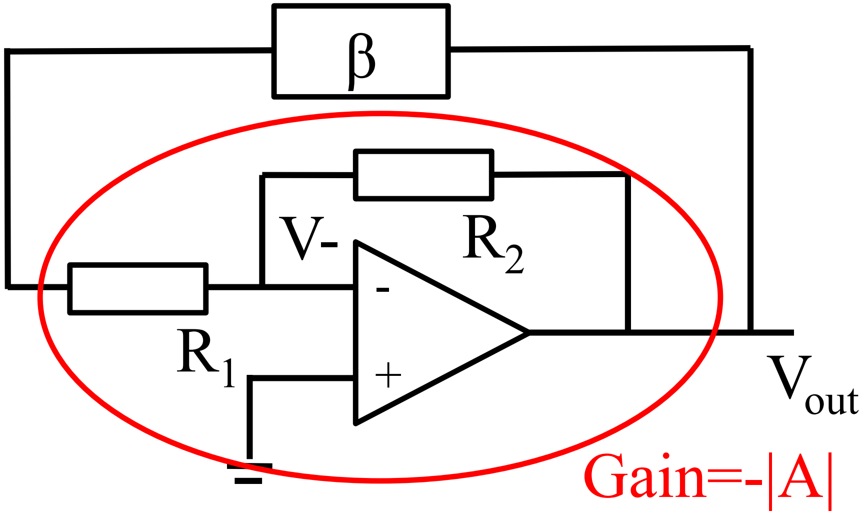
Op-amp oscillator implementation

$$V_{out} = -|A|V_-$$

$$V_- = \beta V_{out}$$



Simplest case:

- $R_1 = R_2$
- $|A| = 1$

Feedback component β is a unity-gain, frequency-dependent, phase-shifter:

- Phase shift π for one specific frequency *f* only
- |β| = 1 for all frequencies

Produces a sinusoidal output at frequency *f* !

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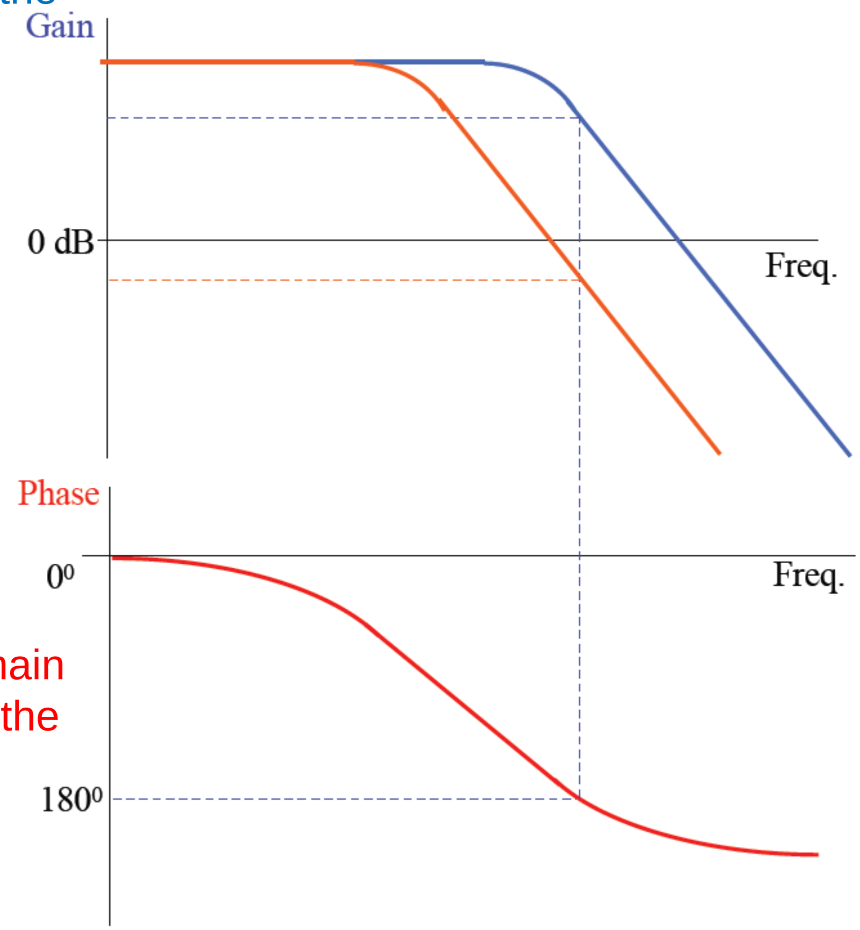
Stability vs. oscillation

If we *want* our circuit to oscillate, we can design the correct gain and phase-shift at the desired frequency



Loop-gain magnitude > 1 results in *saturation:* square-wave output at frequency ω with 180 degree phase shift across β

Loop-gain magnitude = 1 results in sinusoidally varying output at frequency ω with 180 degree phase shift across β

If we *don't want* our circuit to oscillate, i.e. to remain stable under all conditions, we must ensure that the loop-gain is < 1 (< 0 dB) at any frequency that produces 180 degree phase shift across β

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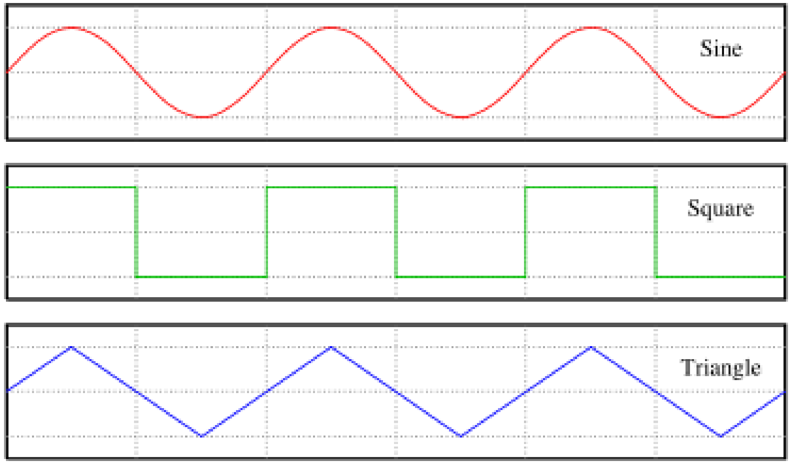
Function generator

Sine-wave: magnitude of loop-gain = 1 and total phase-shift = 360 degrees at desired frequency



Square wave: magnitude of loop-gain > 1 and total phase-shift = 360 degrees at desired frequency

Triangular wave is time-integral of square wave…

Triangle waveform: generated by feeding the output of a square-wave oscillator through an integrator (last week)

Amplitude of waveform can be tuned by another amplifier circuit with potentiometer (variable resistor) to tune the gain

Summary

Limitations of op-amps:

- High-frequency operation may be limited by *'slew-rate'* of output
- High-gain operation may be limited by '*saturation'* at supply rail voltages
  - This may be used to make a 'comparator' or 'Schmidt-trigger' circuit
- Positive-feedback can lead to exponential growth or oscillation of output – function generator
  - 'Barkhausen criteria' for output oscillation without input signal

Next lecture – modulation and demodulation

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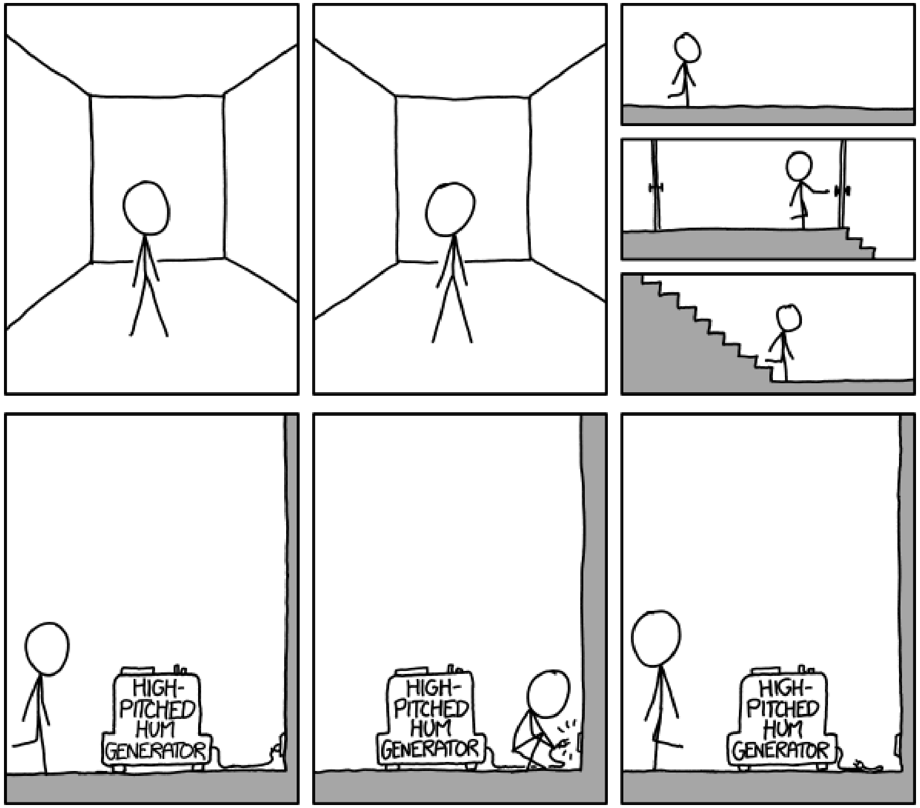
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