2.6 Large Signal Operation

Reading **Assignment**: 94-98

Recall that "real" amplifiers are only approximately linear!

If the input signal becomes too large, and/or the input signal changes too quickly, we begin to see some very non-linear behavior.

→ Non-linear behavior leads to a **distorted** ouput.

In other words, the output does not look like a copy of the input!

(A grotesque example of distortion)

The input signal cannot be **too big**:

HO: OUTPUT VOLTAGE SATURATION

The input signal cannot change **too fast**:

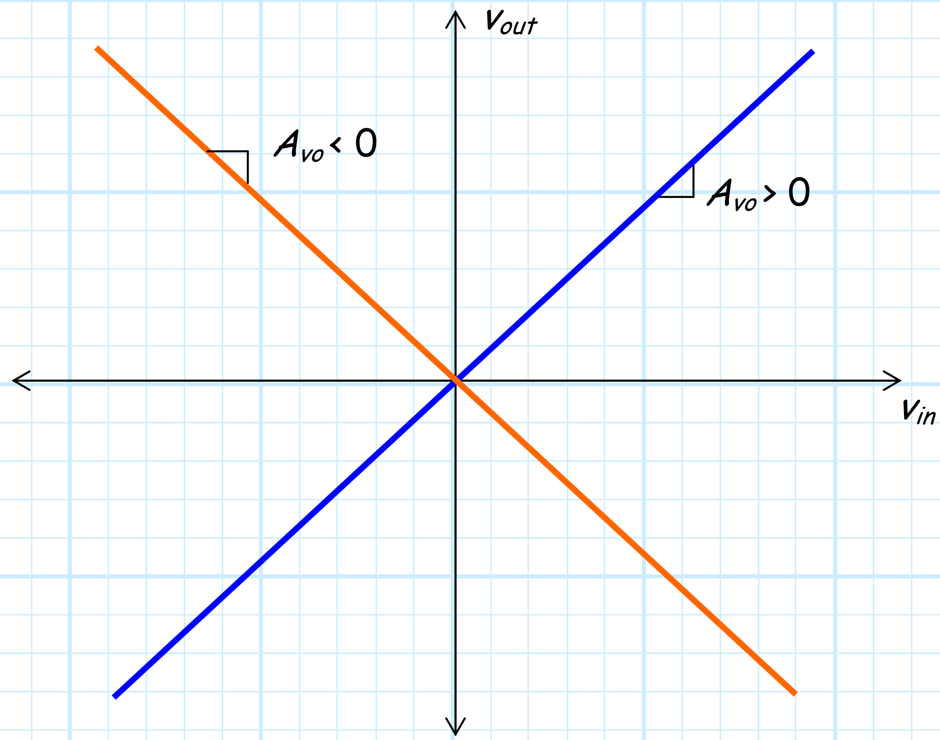
HO:SLEW RATE

The input signal certainly cannot be too be **and** change too fast!

HO: FULL POWER BANDWIDTH

Output Voltage Saturation

Recall that the **ideal** transfer function implies that the **output voltage** of an amplifier can be **very** large, provided that the gain A_{vo} and the input voltage v_{in} are large.



The output voltage is limited

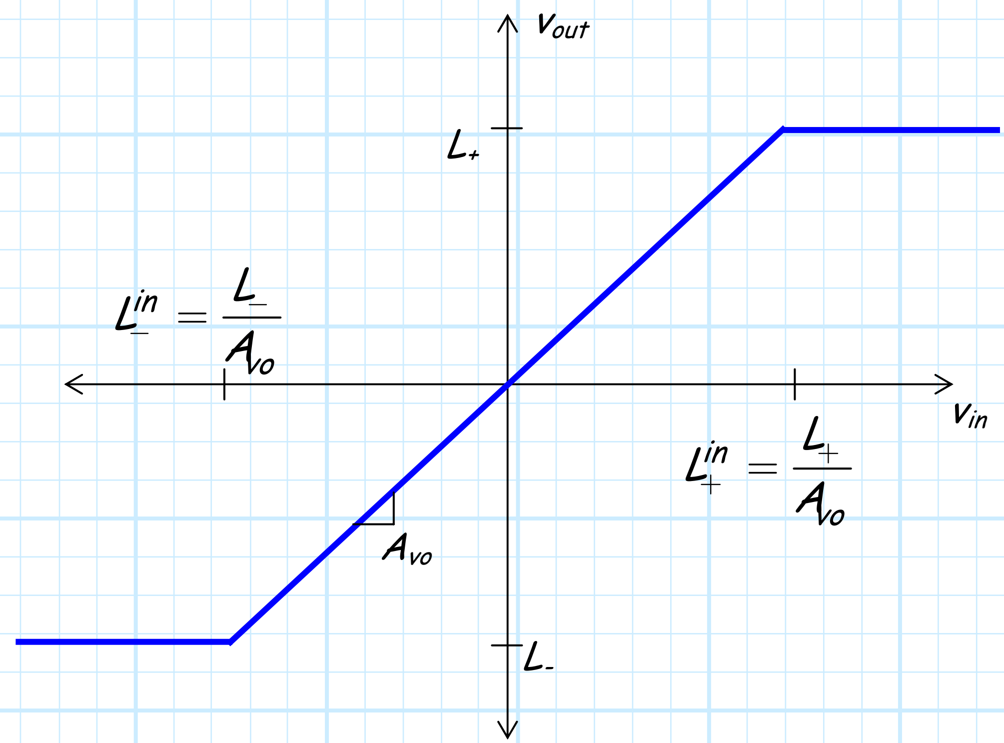
However, we found that in a "real" amplifier, there are **limits** on how large the output voltage can become.

The transfer function of an amplifier is more **accurately** expressed as:

$$v_{out}(t) = \begin{cases} L_+ & v_{in}(t) > L_+^{in} \\ A_{vo}\, v_{in}(t) & L_-^{in} < v_{in}(t) < L_+^{in} \\ L_- & v_{in}(t) < L_-^{in} \end{cases}$$

A non-linear behavior!

This expression is shown **graphically** as:



This expression (and graph) shows that electronic amplifiers have a **maximum** and **minimum** output voltage (L_+ and L_-).

If the **input** voltage is either too large or too small (too negative), then the amplifier **output** voltage will be equal to either L_+ or L_- .

If $v_{out} = L_+$ or $v_{out} = L_-$, we say the amplifier is in **saturation** (or compression).

Make sure the input isn't too large!

Amplifier saturation occurs when the **input** voltage is **greater** than:

$$v_{in} > \frac{L_+}{A_{vo}} \doteq L_+^{in}$$

or when the **input** voltage is **less** than:

$$v_{in} < \frac{L_-}{A_{vo}} \doteq L_-^{in}$$

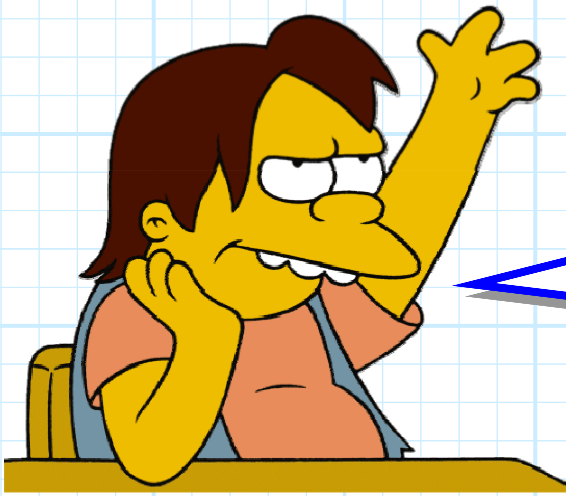
Often, we find that these voltage limits are **symmetric**, i.e.:

$$L_- = -L_+ \quad \text{and} \quad L_-^{in} = -L_+^{in}$$

For example, the output limits of an amplifier might be L_+ = 15 V and L_- = -15 V.

However, we find that these limits are also often **asymmetric** (e.g., L_+ = +15 V and L_- = +5 V).

Saturation: Who really cares?

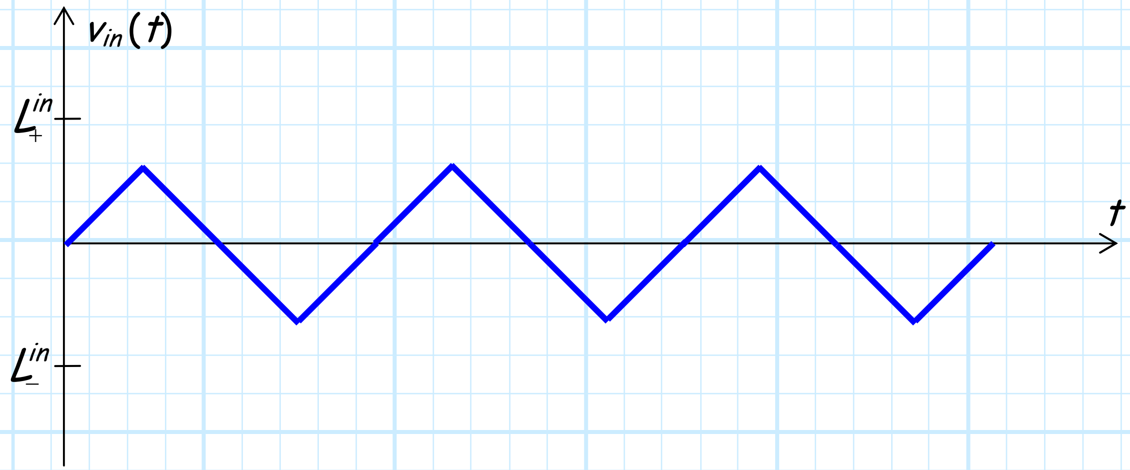


Q: *Why do we **care** if an amplifier saturates? Does it cause any **problems**, or otherwise result in performance **degradation**??*

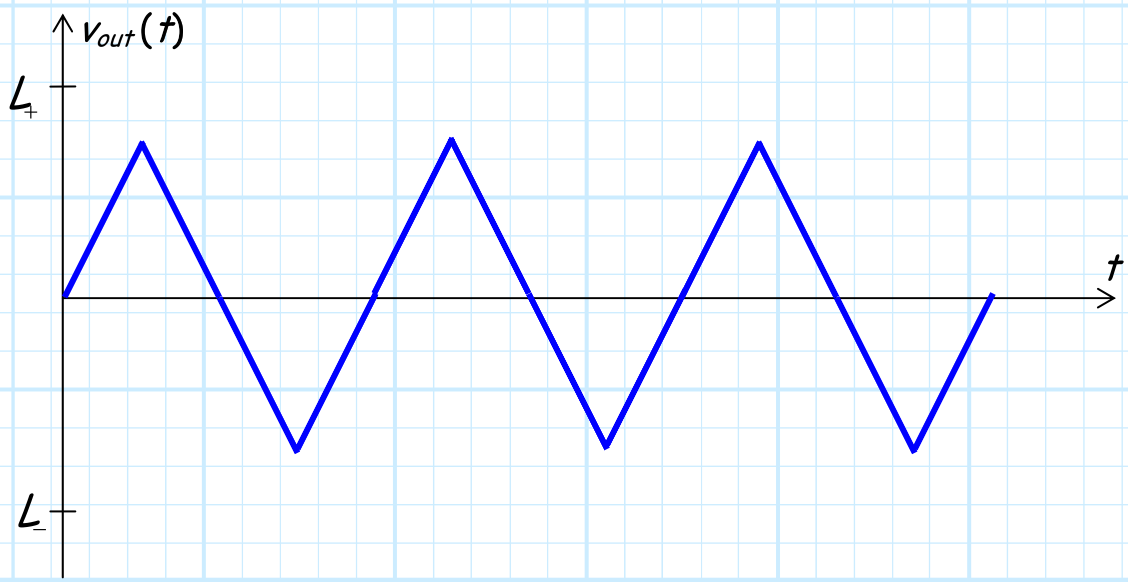
A: **Absolutely**! If an amplifier saturates—even momentarily—the unavoidable result will be a **distorted** output signal.

A distortion free example

For example, consider a case where the input to an amplifier is a **triangle** wave:

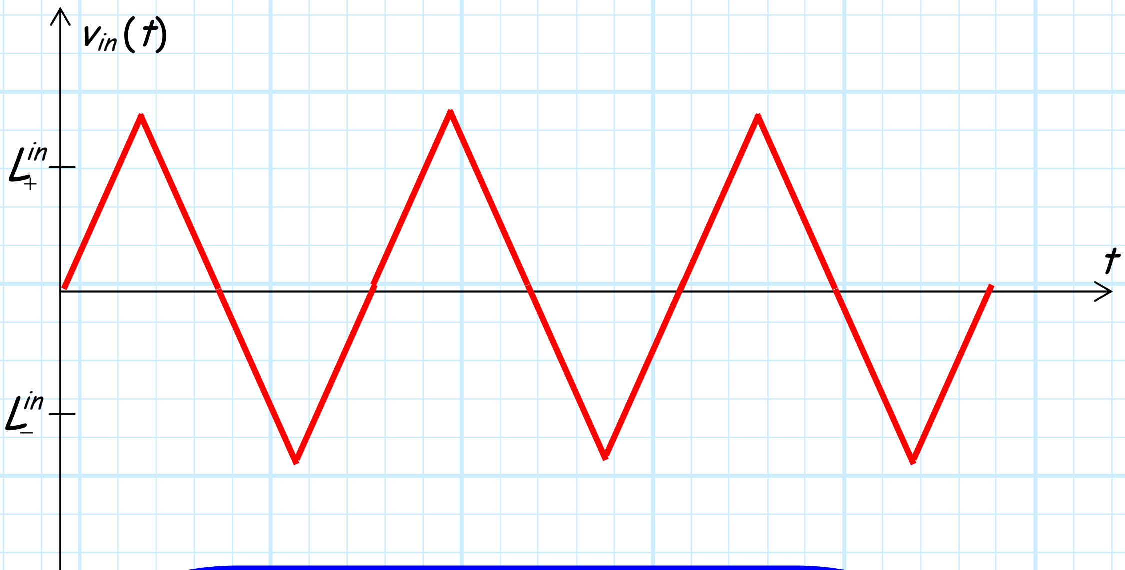


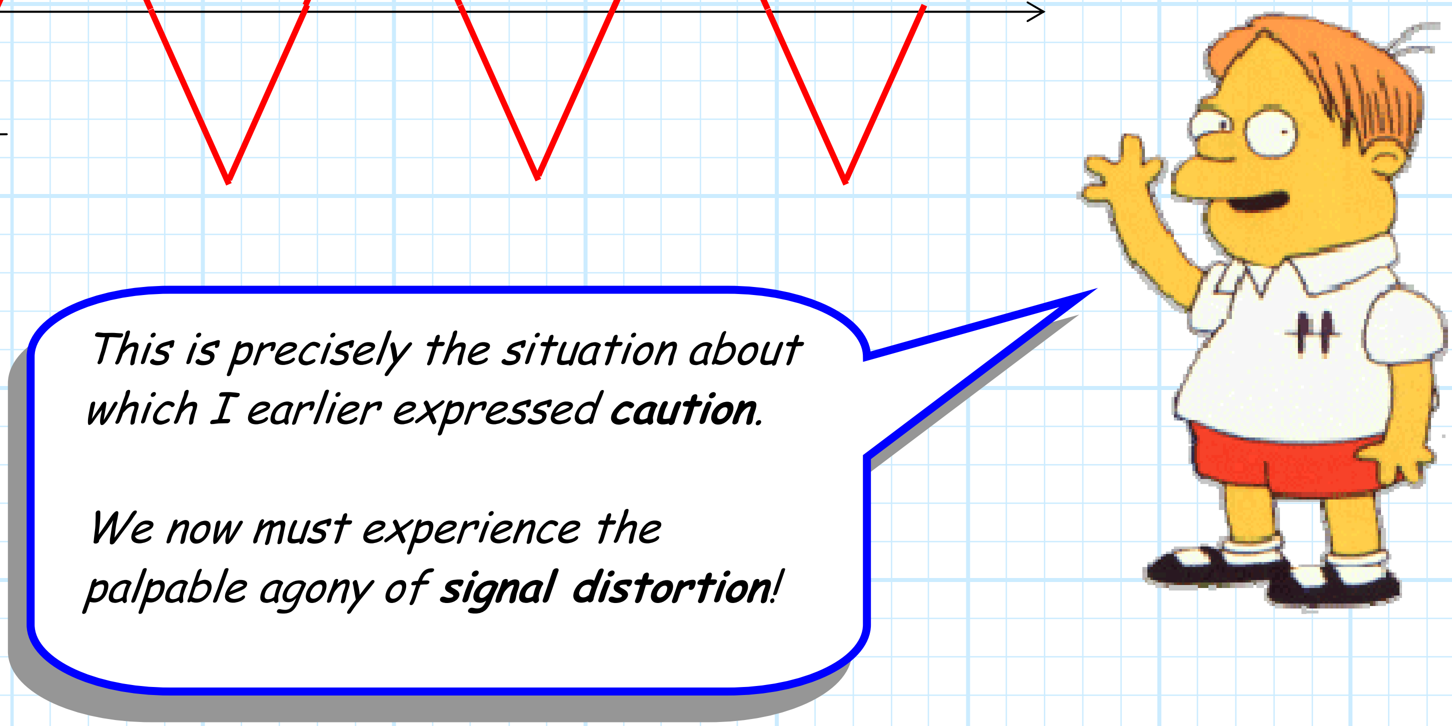
Since $L_-^{in} < v_{in}(t) < L_+^{in}$ for all time t, the **output** signal will be within the limits L_+ and L_- for all time t, and thus the amplifier output will be $v_{out}(t) = A_{vo}\, v_{in}(t)$:



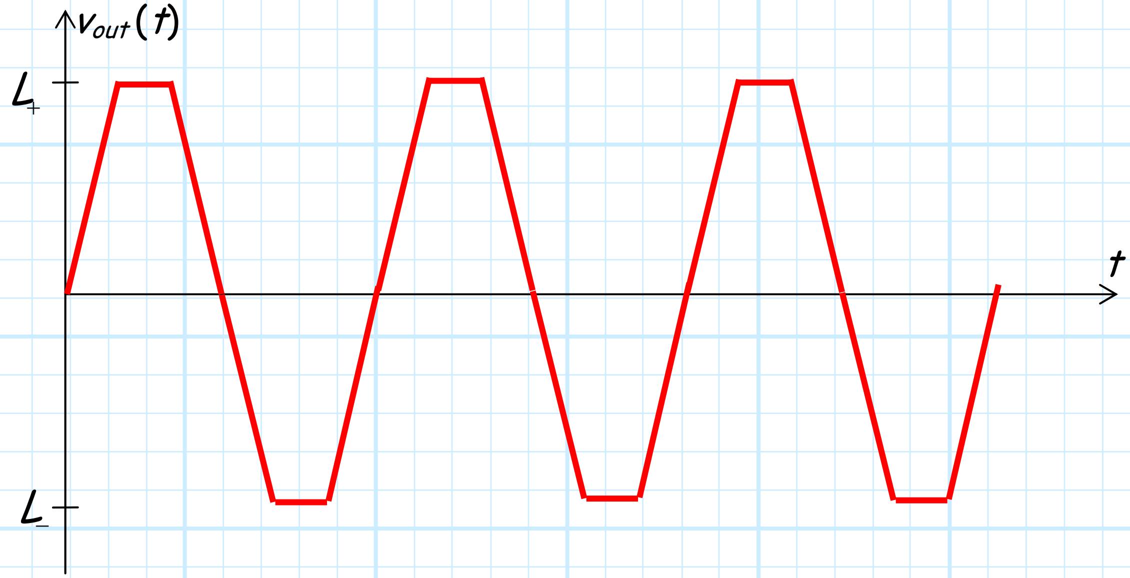
The input is too darn big!

Consider now the case where the input signal is much **larger**, such that $v_{in}(t) > L_+^{in}$ and $v_{in}(t) < L_-^{in}$ for some time t (e.g., the input triangle wave **exceeds** the voltage limits L_+^{in} and L_-^{in} some of the time):





Palpable agony



Note that this output signal is **not** a triangle wave!

For time t where $v_{in}(t) > L_+^{in}$ and $v_{in}(t) < L_-^{in}$, the value $A_{vo}\, v_{in}(t)$ is greater than L_+ and less than L_-, respectively.

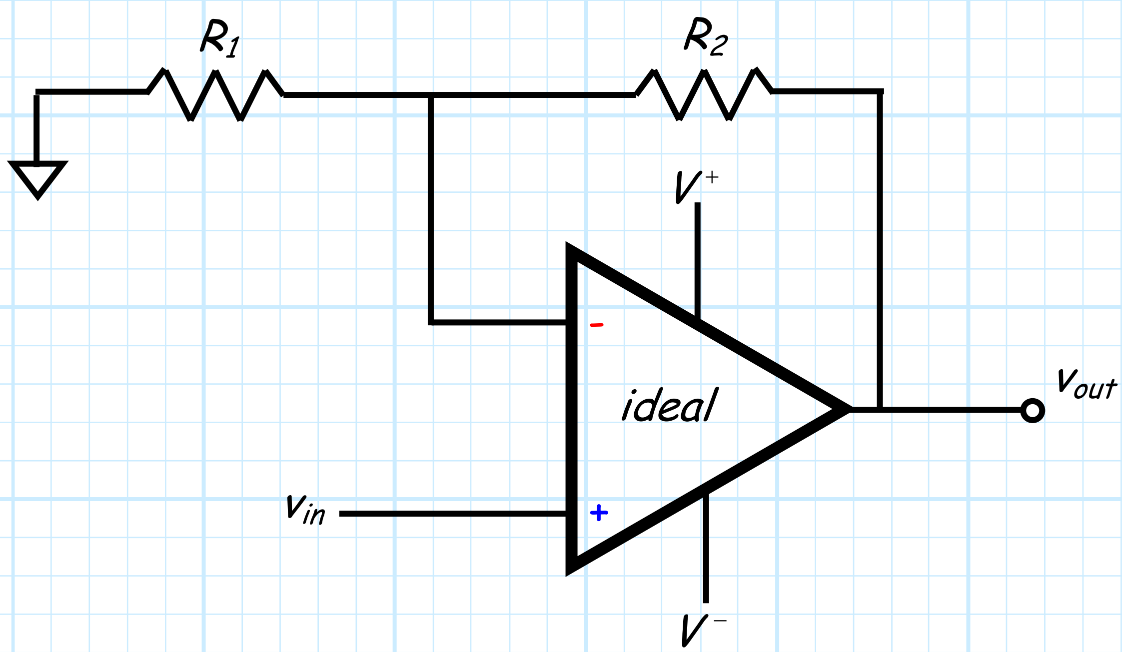
Thus, the output voltage is limited to $v_{out}(t) = L_+$ and $v_{out}(t) = L_-$ for these times.

As a result, we find that output $v_{out}(t)$ does **not** equal $A_{vo}\, v_{in}(t)$ —the output signal is **distorted**!

Amplifiers with op-amps

For amplifiers constructed with op-amps, the voltage limits L_+ and L_- are determined by the DC Sources V^+ and V^-:

$$L_+ \approx V^+ \qquad \text{and} \qquad L_- \approx V^-$$

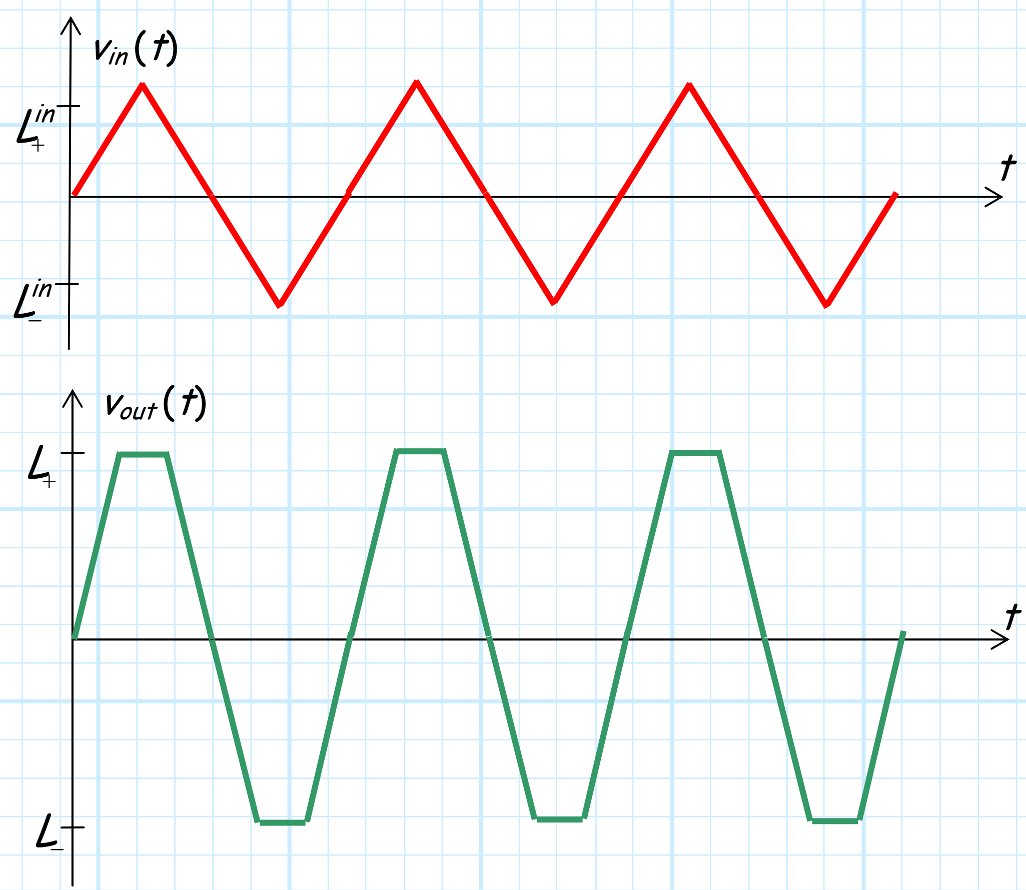


Slew Rate

We know that the output voltage of an amplifier circuit is **limited**, i.e.:

$$L_- < v_{out}(t) < L_+$$

During any period of time when the output tries to exceed these limits, the output will **saturate**, and the signal will be **distorted**! E.G.:



Limits on the time derivative

But, this is **not** the only way in which the output signal is **limited**, **nor** is saturation the only way it can be **distorted**!

A **very** important op-amp parameter is the **slew rate** (S.R.).

Whereas L_- and L_+ set limits on the values of output signal $v_{out}(t)$, the slew rate sets a limit on its **time derivative** !!!! I.E.:

$$-\text{S.R.} < \frac{d\, v_{out}(t)}{dt} < +\text{S.R.}$$

In other words, the output signal can **only change so fast**! Any attempt to exceed this fundamental op-amp limit will result in **slew-rate limiting**.

The red means distortion

So, in addition to **saturation**:

$$v_{out}(t) = \begin{cases} L_+ & \text{if} \quad A_{vo}\, v_{in}(t) > L_+ \\ A_{vo}\, v_{in}(t) & \text{if} \quad L_- < A_{vo}\, v_{in}(t) < L_+ \\ L_- & \text{if} \quad L_- > A_{vo}\, v_{in}(t) \end{cases}$$

we find the following **output** signal condition:

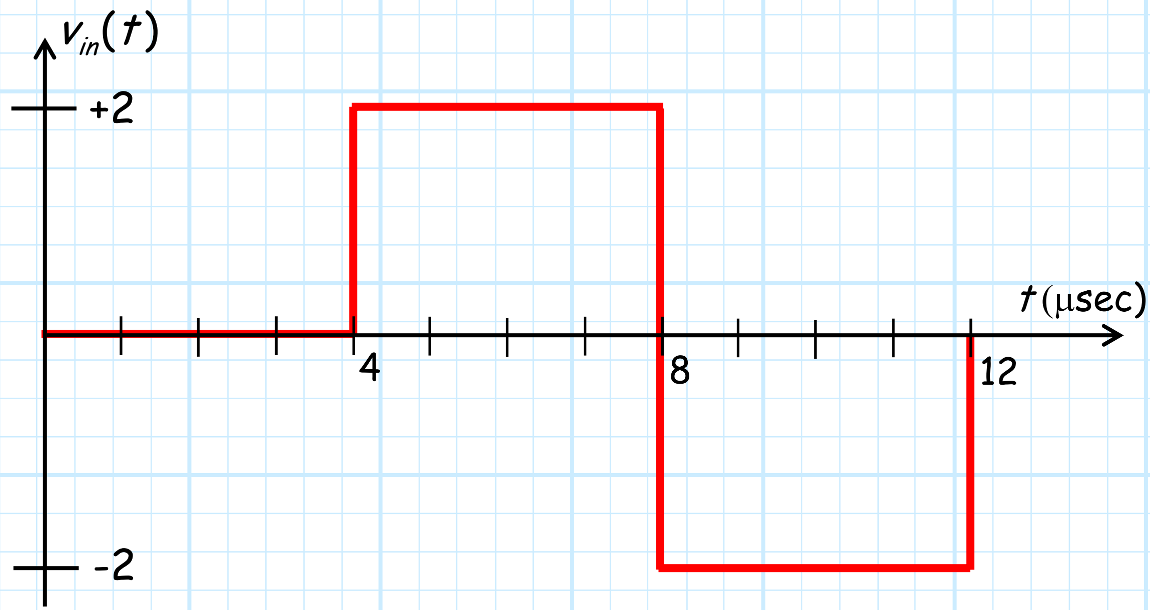
$$v_{out}(t) = \begin{cases} A_{vo}\, v_{in}(t) & \text{if} \quad \left| \dfrac{d\, A_{vo}\, v_{in}(t)}{dt} \right| < S.R. \\ \pm (S.R.)\, t + C & \text{if} \quad \left| \dfrac{d\, A_{vo}\, v_{in}(t)}{dt} \right| > S.R. \end{cases}$$

For example

For example, say we build a **non-inverting** amplifier with mid-band gain $A_{vo} = 2$.

This amplifier was constructed using an op-amp with a **slew rate** equal to 4V/μsec.

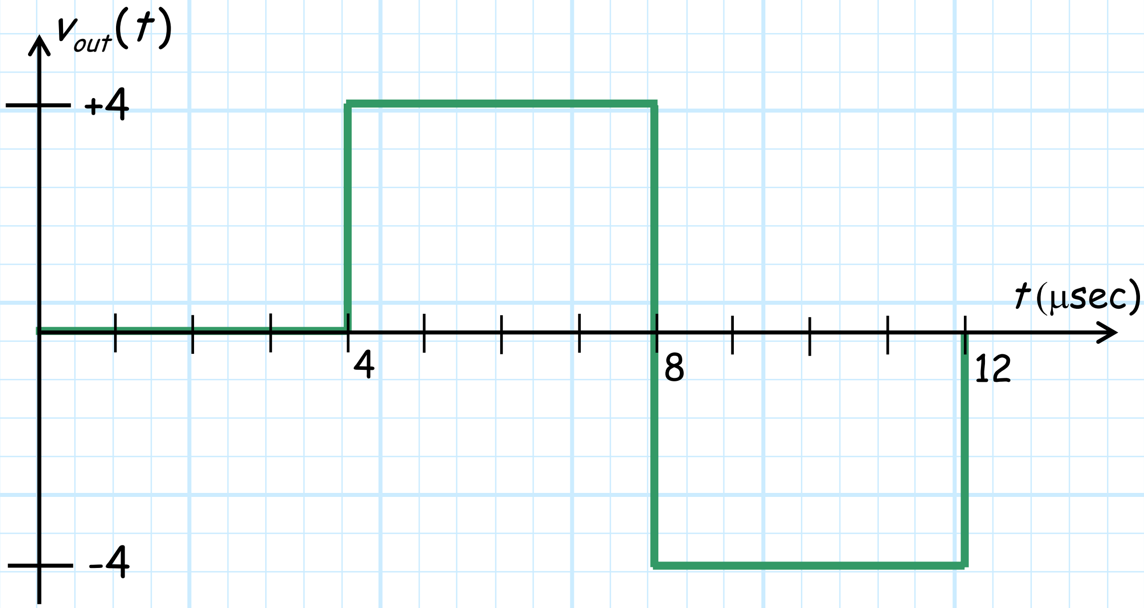
Q: *If we **input** the following signal $v_{in}(t)$, what will we see at the **output** of this amplifier?*



This is what it should look like

A: **Ideally**, the output would look exactly like the input, only multiplied by $A_{vo} = 2$:

$$v_{out}(t) = 2\, v_{in}(t) \quad \text{(ideal)}$$



Note that the time derivative of this output is **zero** at **almost** every time t:

$$\frac{d\,v_{out}(t)}{dt} = 0 \quad \text{for } almost \text{ all time } t$$

Now you see the problem!

The **exceptions** are at times t=4, t=8, and t=12 μsec, where we find that the time derivative is **infinite**!

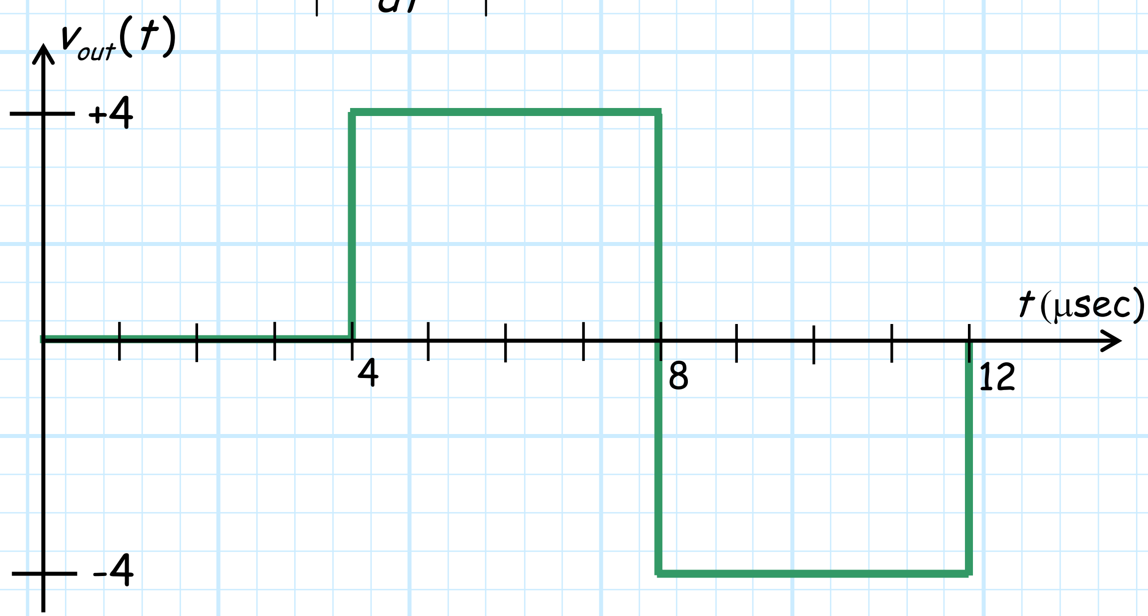
$$\frac{d\,v_{out}(t)}{dt} = \infty \quad \text{at times } t = 4 \text{ and } t = 12$$

and

$$\frac{d\,v_{out}(t)}{dt} = -\infty \quad \text{at time } t = 8$$

This is a **problem**!

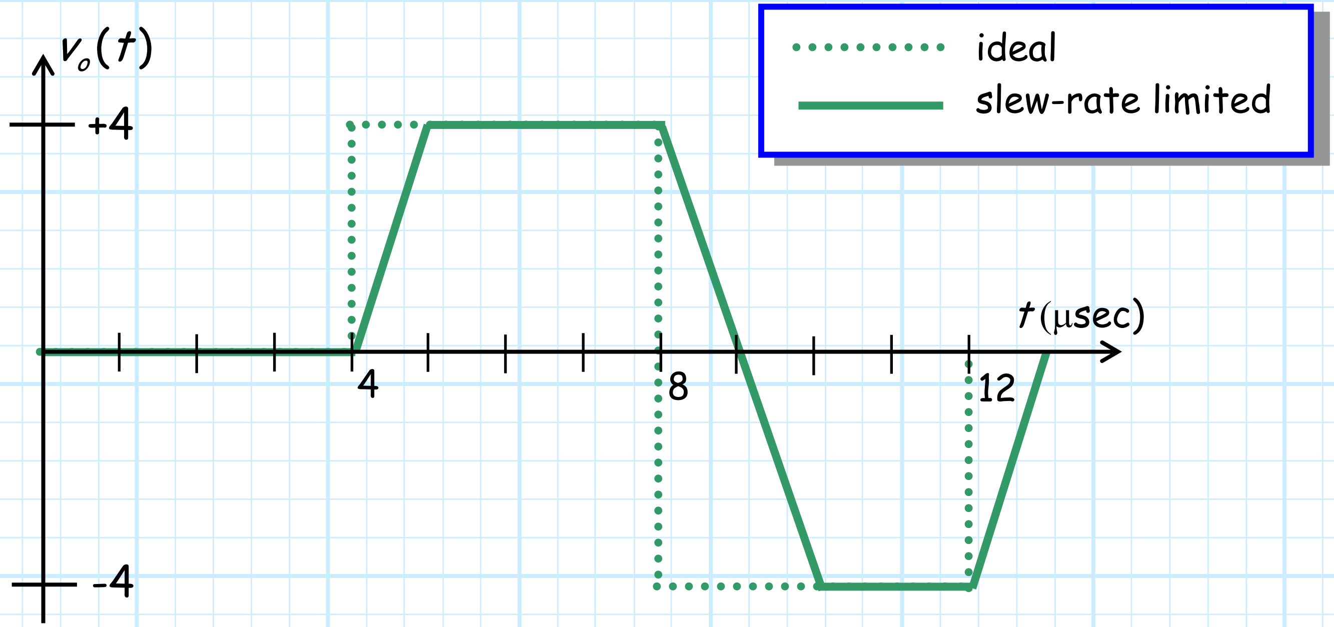
$$\left|\frac{d\,v_{out}(t)}{dt}\right| = \infty \quad > \quad 4V/\mu sec \text{ !!!!}$$



This is what it actually looks like!

Thus, the output signal **exceeds** the slew rate of the op-amp—or at least, it **tries** too!

The reality is that since the op-amp output **cannot** change at a rate greater than $\pm 4V/\mu sec$, the output signal will be **distorted**!



Note the derivative of the **actual** output signal is limited to a maximum value ($\pm 4V/\mu sec$) by the op-amp **slew rate**.

Full-Power Bandwidth

Consider now the case where the input to an op-amp circuit is **sinusoidal**, with frequency ω.

The **output** will thus likewise be sinusoidal, e.g.:

$$v_{out}(t) = V_o \sin\omega t$$

where V_o is the magnitude of the output sine wave.

Q: *Under what conditions is this output signal possible? In other words, might this output signal be **distorted**?*

A: First, the output will **not** be saturated **if**:

$$V_o \leq L_+ \approx V^+ \qquad \text{and} \qquad -V_o \geq L_- \approx V^- .$$

The time derivative

Q: *So, the output will not be distorted **if** the above statement is true?*

A: Be careful!

It **is** true that the output will **not** saturate if magnitude of the sinewave is smaller than the saturation limits.

However, this is **not the only way** that the signal can be distorted!

Q: *I almost forgot! A signal can **also** be distorted by **slew-rate limiting**. Could this problem possibly affect a sine wave output?*

A: Recall that the **slew rate** is a limit on the **time derivative** of the output signal.

The time derivative of our sine wave **output** is:

$$\frac{d\, v_{out}(t)}{dt} = \omega V_o \cos \omega t$$

The max and min

Note that the time derivative is proportional to the signal **frequency** ω.

Makes sense!

As the output signal frequency **increases**, the output voltage changes more **rapidly** with time.

Also note however, that this derivative is a likewise a function of **time**. The **maximum** value occurs when $\cos \omega t = 1$, i.e,:

$$\left. \frac{d\, v_{out}(t)}{dt} \right|_{max} = \omega\, V_o$$

while the **minimum** value occurs when $\cos \omega t = -1$, i.e.,:

$$\left. \frac{d\, v_{out}(t)}{dt} \right|_{min} = -\omega V_o$$

Thus, we find that the output signal will **not** be distorted if these values are within the **slew rate limits** of the op-amp.

A simple way to determine you are slew rate limited

In other words, to **avoid distortion** by slew rate limiting, we find:

$$\omega V_o \leq S.R.$$

and

$$-\omega V_o \geq -S.R.$$

Note that:

1) These two equations are **equivalent**!

2) The conditions that cause slew-rate distortion depend on **both** the **magnitude** V_o and the **frequency** ω of the output signal!

The frequency can only be so large

Now, recall that there are **limits** on the magnitude alone, that is:

$$V_o \leq L_+ \approx V^+$$

to avoid **saturation**.

Let's assume that the output sine wave is as large as it **can be** without saturating, i.e., $V_o = V^+$ and thus:

$$v_{out}(t) = V^+ \sin\omega t$$

We then find to avoid slew-rate limiting:

$$\omega V^+ < S.R.$$

Rearranging, a limit on the **maximum frequency** for this sine wave output (one with maximum amplitude) is:

$$\omega < \frac{S.R.}{V^+} \doteq \omega_M$$

Full-Power bandwidth

The value:

$$\omega_M = SR/V^+$$

is called the **full-power bandwidth** of the op-amp (given a DC supply V^+).

It eauals the **largest frequency** a **full-power** (i.e., $V_o = V^+$) sine wave can obtain without being distorted by **slew rate limiting**!

Thus, if the input signal to $\omega V^+ < S.R.$ an op-amp circuit is a sine wave, we **might** have to worry about slew rate limiting, **if** the signal frequency is greater than the full-power bandwidth (i.e., $\omega > \omega_M$).

I'll find out from the exam if you read this page

Please note these **important facts** about full-power bandwidth:

1) The analysis above was performed for a **sine wave** signal. It is explicitly accurate **only** for a sine wave signal. For some other signal, **you** must determine the time derivate, and then determine its maximum (or minimum) value!

2) Full-power bandwidth is **completely different** than the closed-loop amplifier bandwidth. For example, a signal with a frequency greater than the closed-loop amplifier bandwidth will **not** result in a distorted signal!

3) Distortion due to slew-rate limiting depends **both** on signal amplitude V^+ and signal frequency ω. Thus, as sine wave whose frequency is much greater than the full-power bandwidth (i.e., $\omega \gg \omega_M$) **may** be **undistorted** if its amplitude V^+ is sufficiently **small**.