Lecture 07: Op Amp Speed

0. Review
1. Op Amp Speed
2. Gain Bandwidth
3. Slew Rate

Textbook reading:

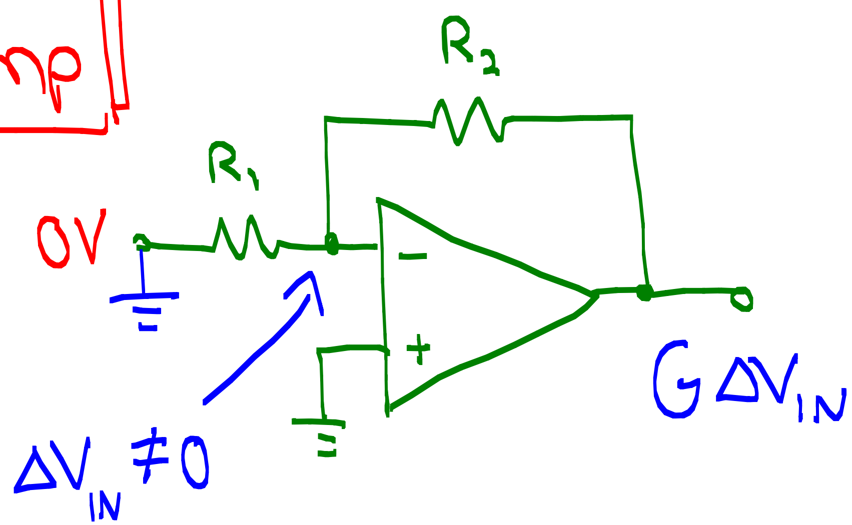
14-1 Amplifier Freq Response
14-9 Rise Time - BW relationship
16-2 The 741 Op Amp (Slew rate sub-section)

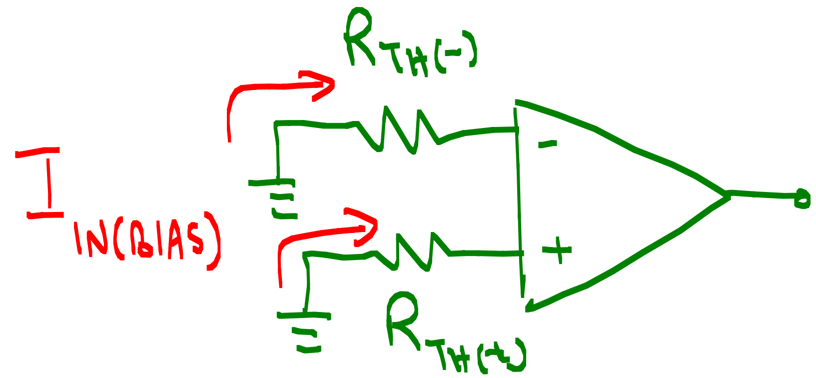
- PreLab 3: Multisim schematic + AC sweep
- HW3 due next Fri (Oct 11) in box outside my office.
  - → No class Oct 8 + 10
    Finish Lab 3 on your own (see handout)
- Quiz 3 (Oct 15)
- Exam #1 (Oct 17)
  - → HW1, 2, 3
  - → QZ1, 2, 3
  - → Sample exam on course website

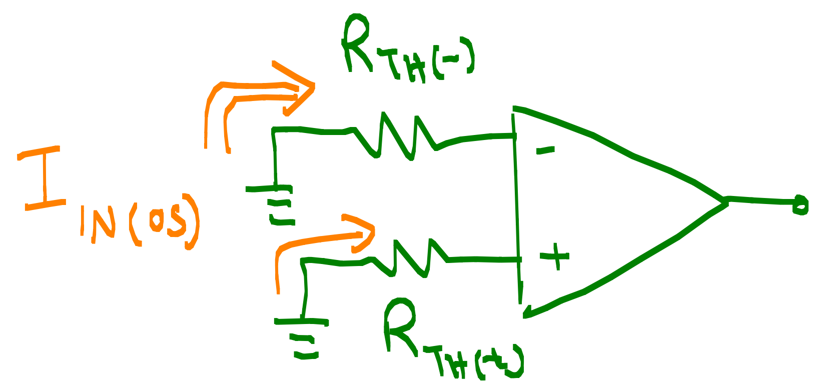
0. Review

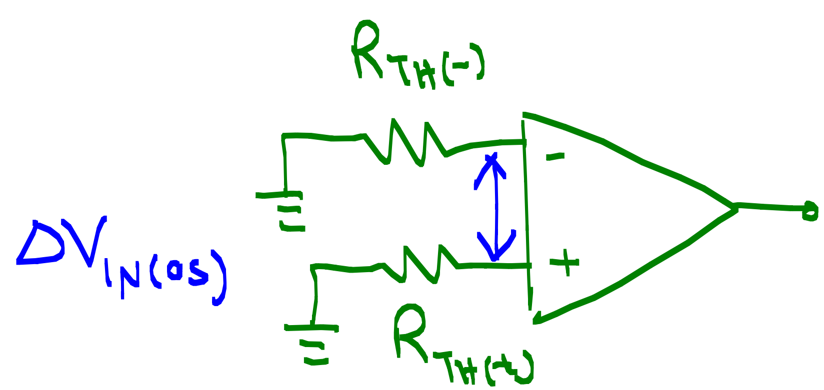
- **Output Voltage Error**

Real op Amp









① Input bias current : $I_{IN(BIAS)} \times \left[R_{TH(-)} - R_{TH(+)}\right]$

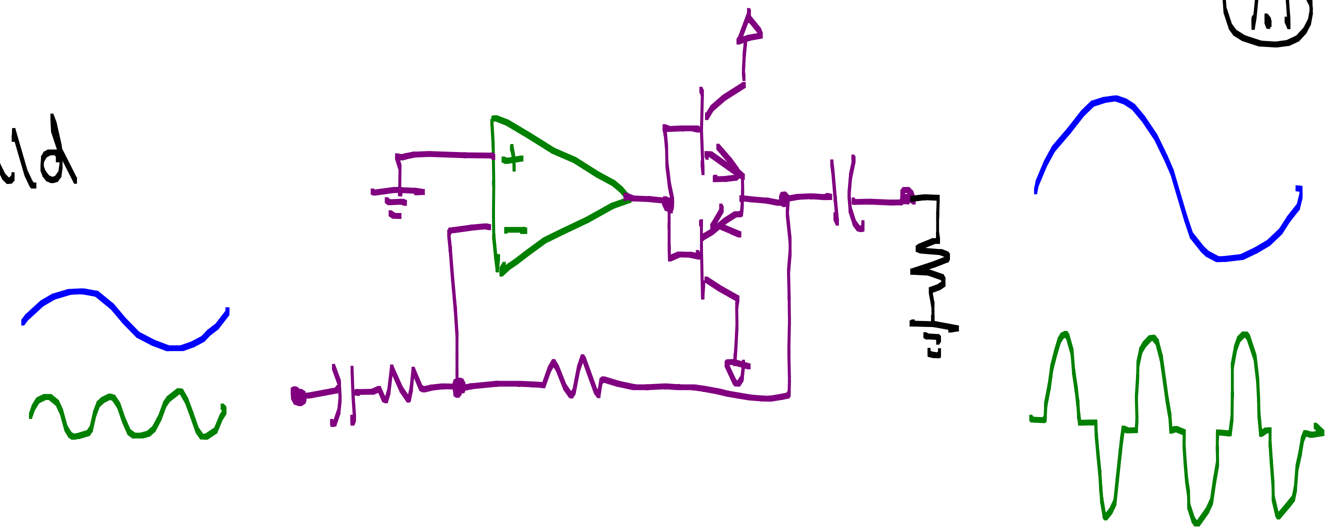
② Input offset current : $I_{IN(OS)} \times \dfrac{R_{TH(-)} + R_{TH(+)}}{2}$

③ Input offset voltage : $V_{IN(OS)}$

1. Op Amp Speed

- In Lab 2, crossover distortion would be much worse at MHz freq

→ op amp couldn't provide enough dV/dt !



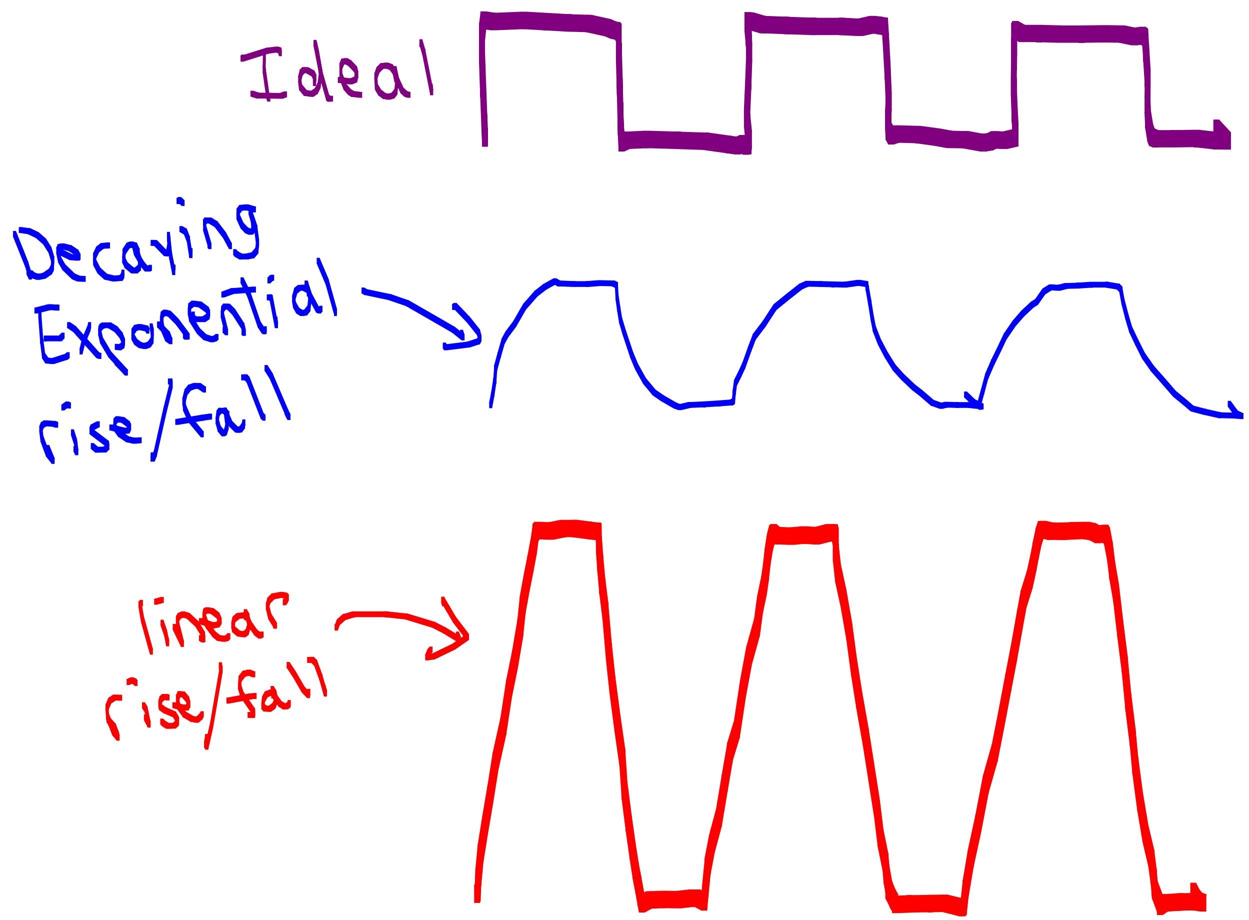
Q: What limits the op amp speed?

A: Depends on ...

① Gain-Bandwidth Product

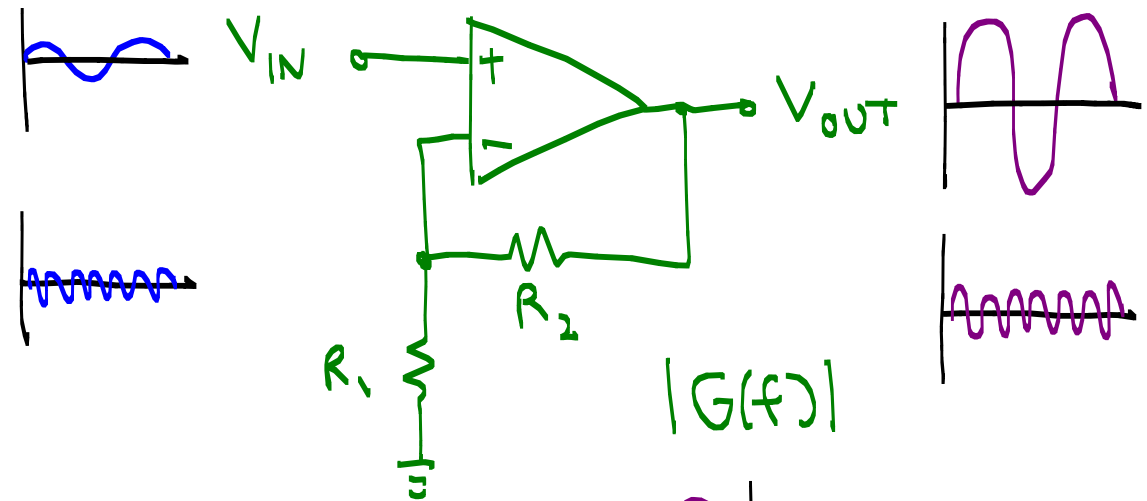
② Slew Rate

③ Waveform Type (square, triangle, sine, etc.)

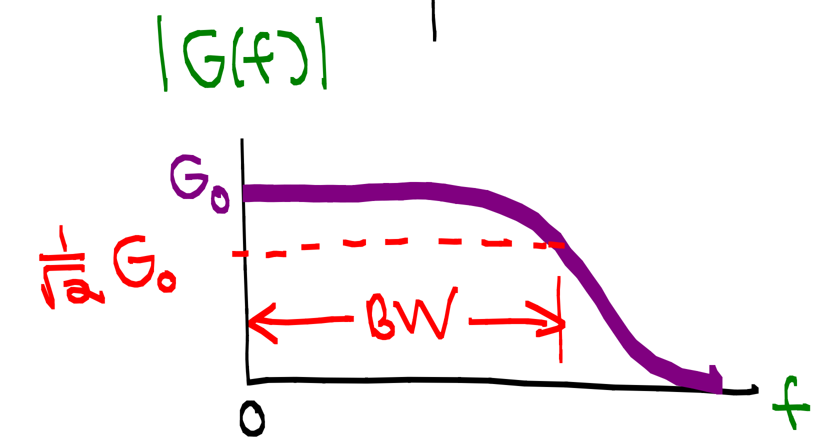


2. Gain-Bandwidth Product

- Consider our non-inverting amplifier.



Q: What is its bandwidth?



A: It depends on the voltage gain!

$$[\text{Gain}] \cdot [\text{Bandwidth}] = \text{constant}$$

Gain-bandwidth Product

$$G \cdot BW = f_{unity}$$

We'll discuss this more when we cover negative feedback

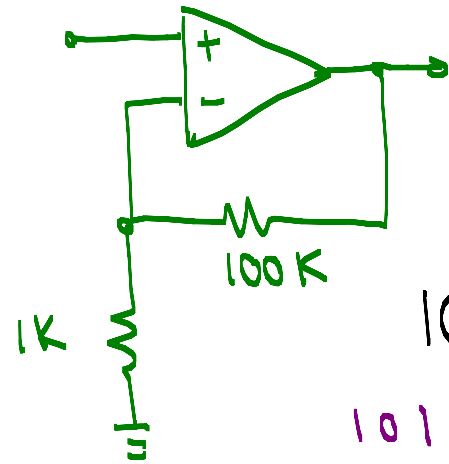
Example: $f_{unity} = 1\,\text{MHz}$

G	BW
1	1 MHz
10	0.1 MHz
100	0.01 MHz

← Max signal freq for desired gain

- GBW product depends on the op amp!

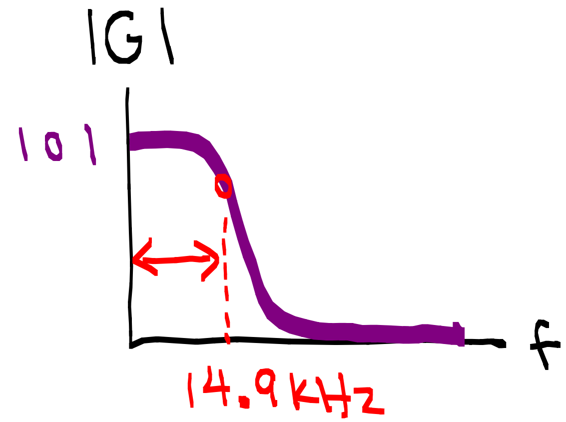
Example



741

$$G = 1 + \frac{100K}{1K} = 101$$

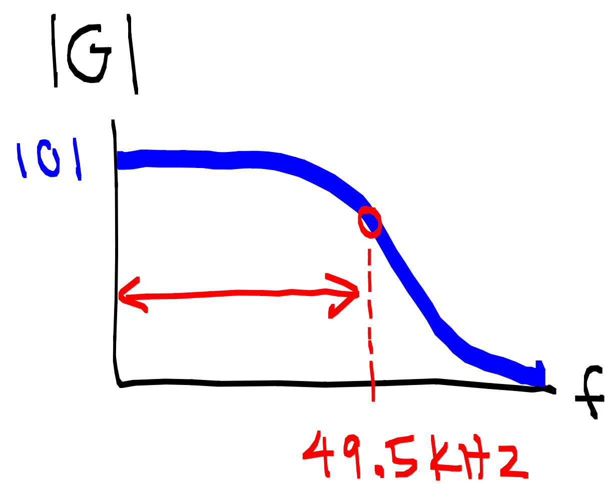
$$BW = \frac{1.5\,MHz}{101} = \boxed{14.9\ kHz}$$



LF356

$$G = 1 + \frac{100K}{1K} = 101$$

$$BW = \frac{5\,MHz}{101} = \boxed{49.5\ kHz}$$



"General Purpose" op amps

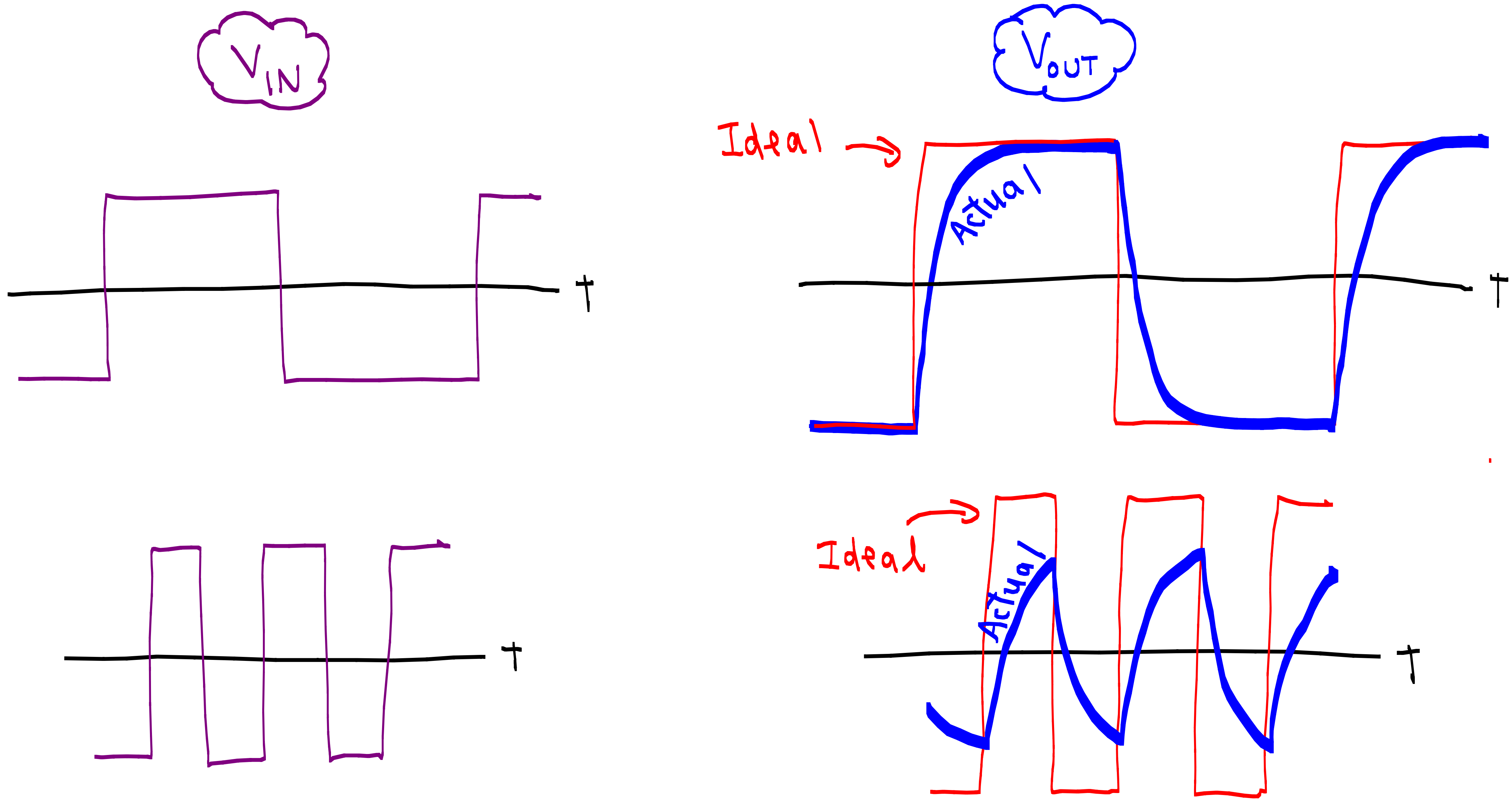
Op Amp	GBW
LM741	1.5 MHz
LF411	4 MHz
LF356	5 MHz
LT1128	20 MHz

(Other op amps have GBW > 100 MHz!)

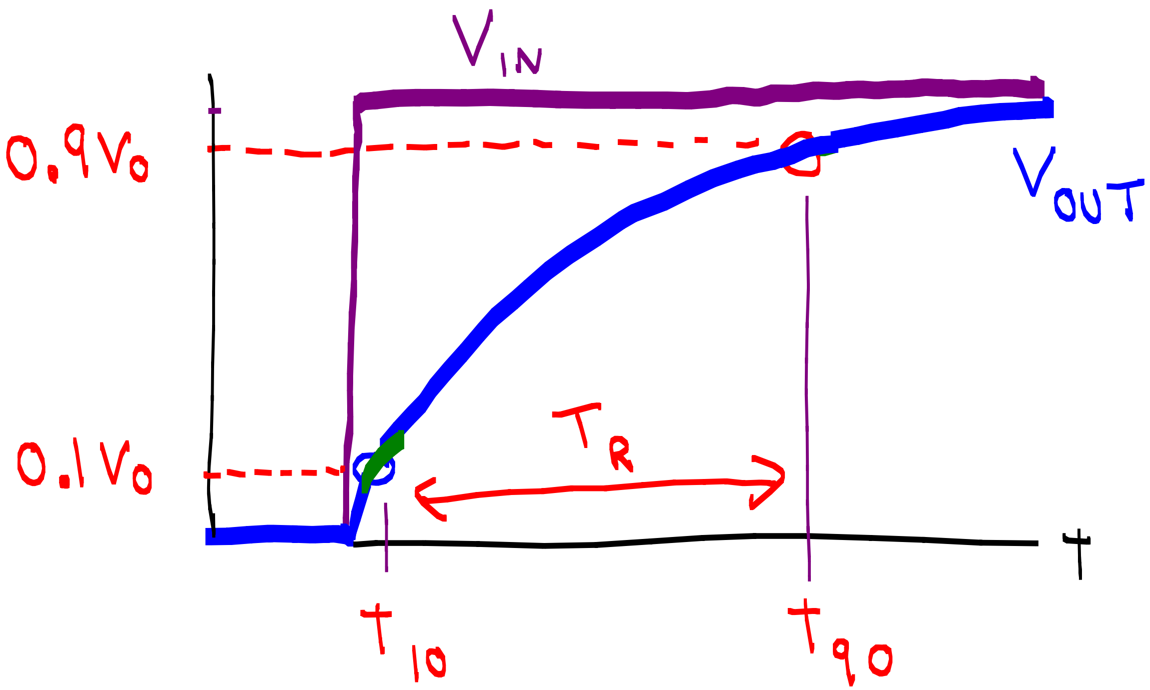
↑ Tricky to use

↑ Need careful PCB layout

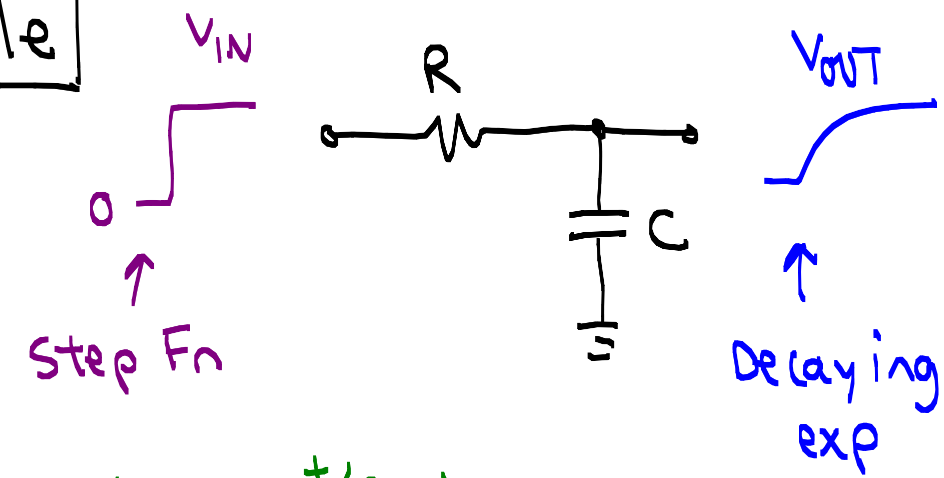
- For many non-sinusoidal signals (e.g. square wave), time-domain response is more meaningful.



• **Rise Time** $T_R = t_{90} - t_{10}$



Example



→ $V_{OUT} = V_{IN} * \left(1 - e^{-t/RC}\right)$

→ Rise Time: $T_R = t_{90} - t_{10} = RC \ln 9$

$f_c = \frac{1}{2\pi RC}$

⇒ $T_R = \frac{1}{2\pi f_c} \cdot \ln 9 = 0.35 \frac{1}{f_c}$

☆ $T_R = 0.35/BW$

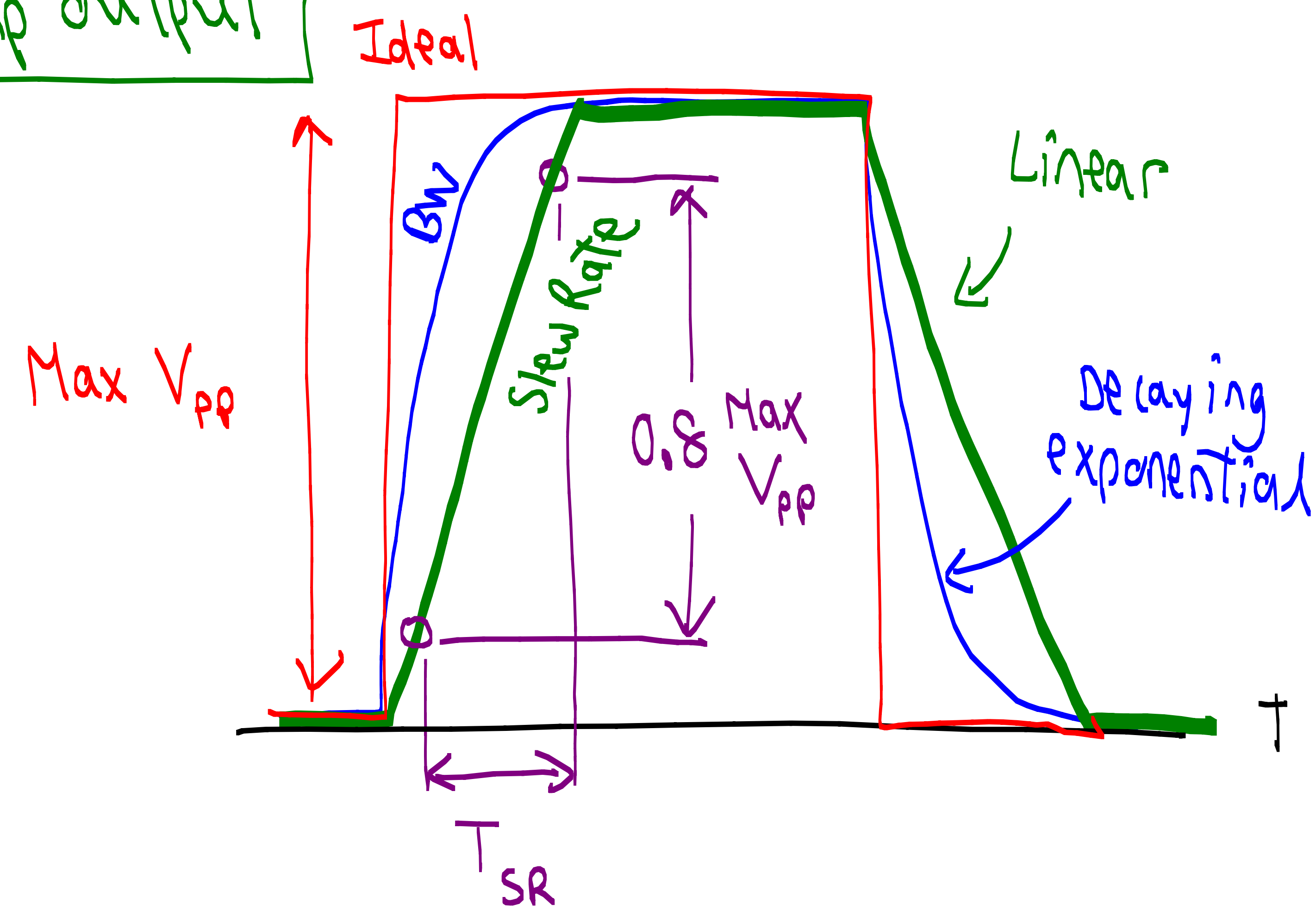
3. Slew Rate (SR)

Slew Rate = Max Slope of op amp output

$(V/\mu s)$ $\qquad \frac{dV_{OUT}}{dt}$

If op amp is SR limited, then a square pulse has a trapezoidal shape.

$$T_{SR} = \frac{0.8\,\text{Max}\,V_{pp}}{SR}$$

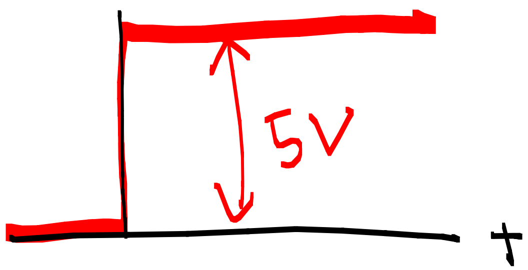


Example: Op amp: GBW = 2 MHz, $S_R = 1\ V/\mu s$

Input: $V_{IN} = 0.5 \times H(t)$ ← step fn

$G = 10$

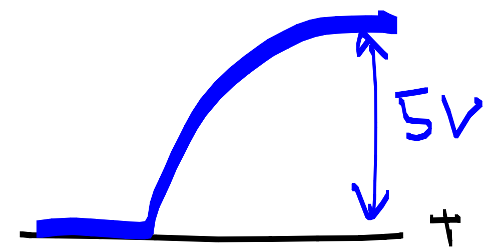
Ideal



Actual V_{OUT} is limited by BW or SR

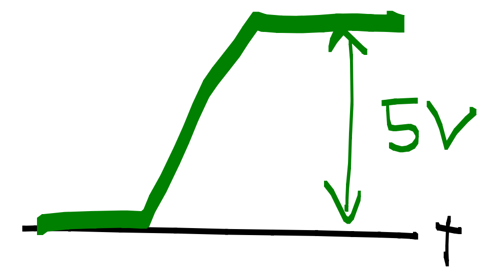
① $BW = \dfrac{2MHz}{10} = .2MHz$

$\Rightarrow T_R = \dfrac{.35}{.2MHz} = 1.75\mu s$



② Max $V_{pp} = 5V$

$\Rightarrow T_{SR} = \dfrac{0.8 \times 5V}{1V/\mu s} = \boxed{4\mu s}$

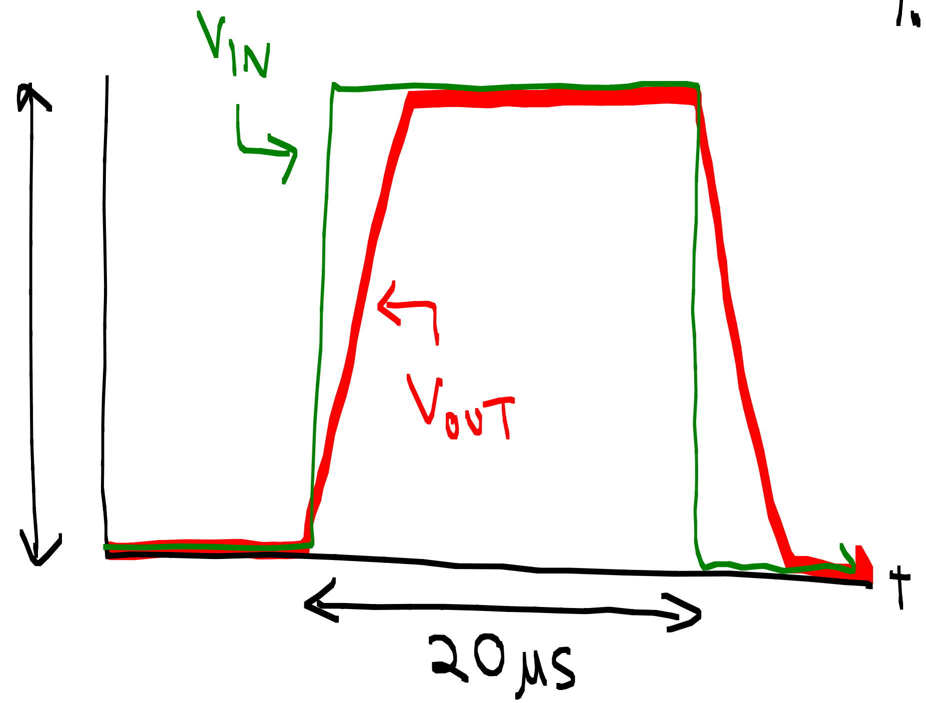


✲ Longer time value determines op amp output!

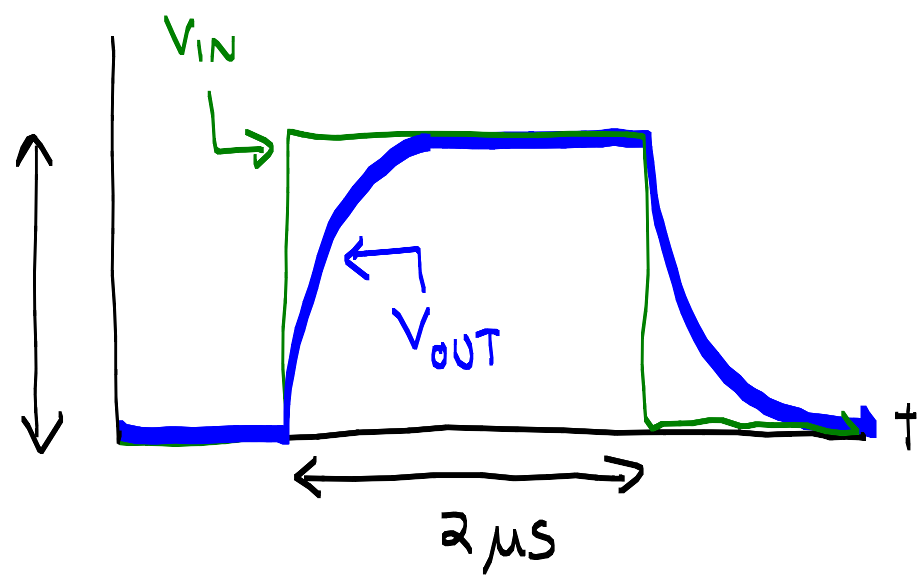
- **Bandwidth vs. Slew Rate**
  - Typically involves large signals
  - SR distortion has linear ramp
  - Typically involves small signals
  - For pulsed signals, BW distortion has exponential decay

Example

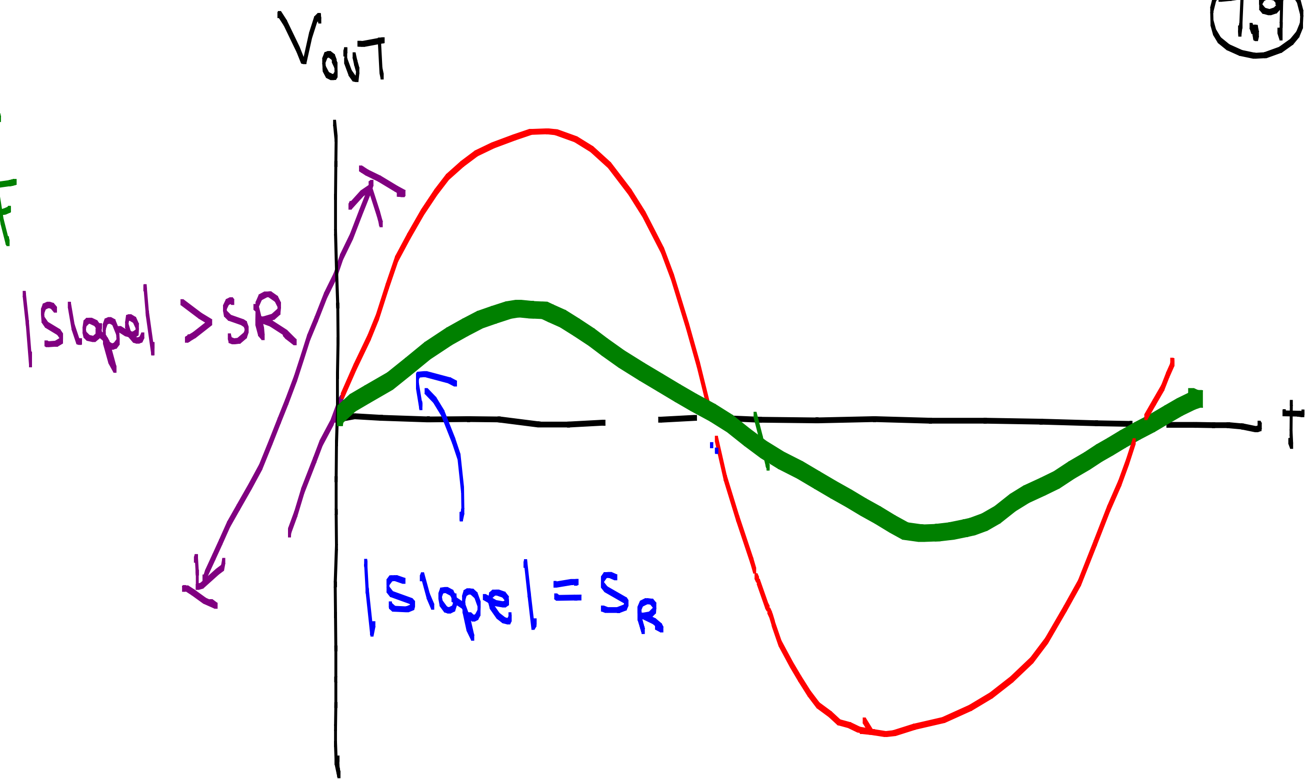
10V



0.1V



③ For sine waves, SR limitation causes distortion. ← op amp's max $\frac{dV}{dt}$ not high enough



$$V_{OUT} = V_p \sin 2\pi f_o t$$

$$\frac{dV_{OUT}}{dt} = \boxed{2\pi f_o V_p} \cos 2\pi f_o t$$

↑ Distortion occurs if $SR < 2\pi f_o V_p$

- **Power Bandwidth:** $SR = 2\pi f_{MAX} V_p$ → $\boxed{f_{max} = \frac{SR}{2\pi V_p}}$ (Only valid for sine wave)

↑ Also called "Large Signal" BW

Max sine wave freq without SR distortion.

← Larger V_p means smaller f_{max}!

Example

Op amp: GBW = 2 MHz

SR = 1 V/μs

Signal: $V_{in} = \sin 2\pi f_o t$

$f_o = 100$ kHz

$G = 10$

① Check f_o vs. BW:

$$BW = \frac{2\text{ MHz}}{10} = 200\text{ kHz}$$

- Since $f_o = 100\text{ kHz} < BW$, we are <u>not</u> limited by BW!

② Check f_o vs. power bandwidth:

Formula only valid for <u>sine wave</u>! →

$$\boxed{f_{Power} = \frac{SR}{2\pi V_p}} = \frac{1\text{ V}/\mu s}{2\pi(10V)} = .016\ \frac{1}{\mu s} = .016\text{ MHz}$$

$$= 16\text{ kHz} < f_o!$$

⇒ Slew rate limited