

Variability and feedback

DAT116, Nov 15 2018

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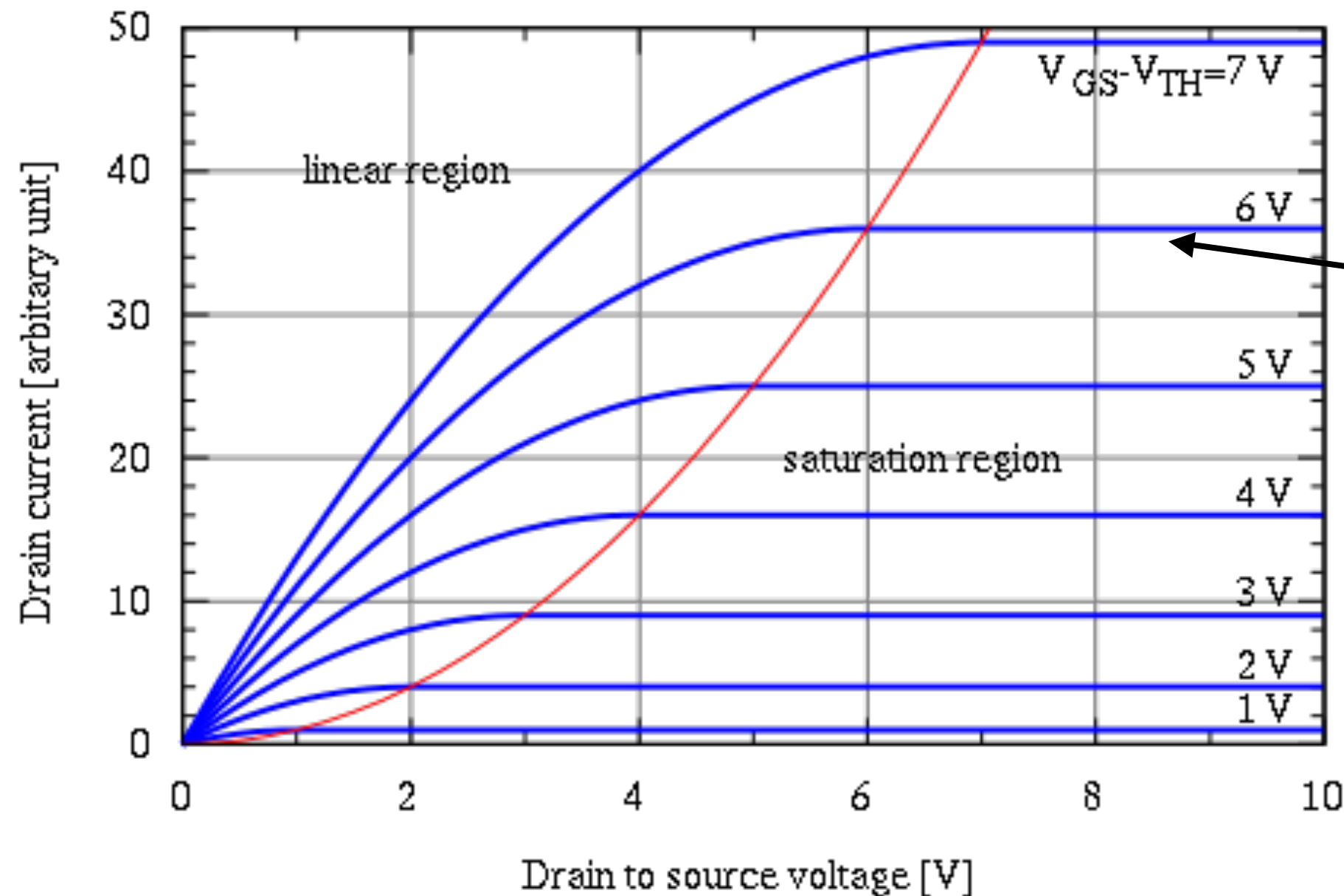
Lars Svensson

Preliminary!

Why variability and feedback?

- Sources of variability on Monday
- Use **matching** to reduce influence, at a cost of more area / power
- R, C, L ; [FET] V_T, g_m ; [BJT] V_{BE}, h_{fe}
- Gain is more difficult to control!
 - Depends strongly on output conductance (resistance) g_d ; r_d
 - Output resistance = how bad a current source is the transistor.

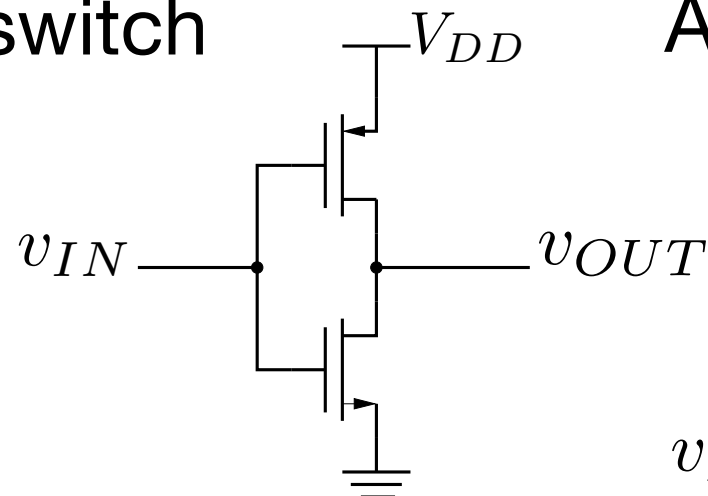
nMOS ideal transfer characteristics



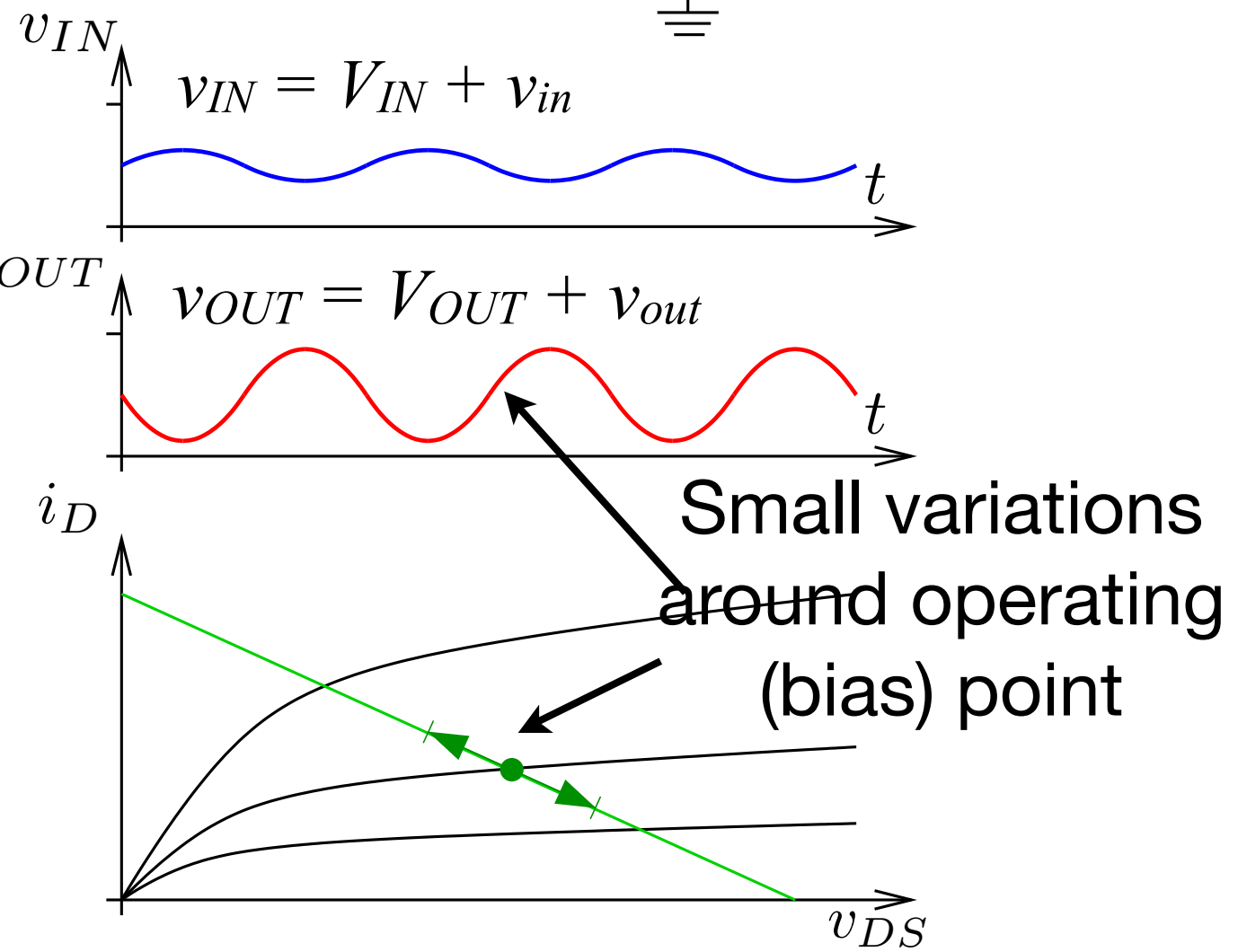
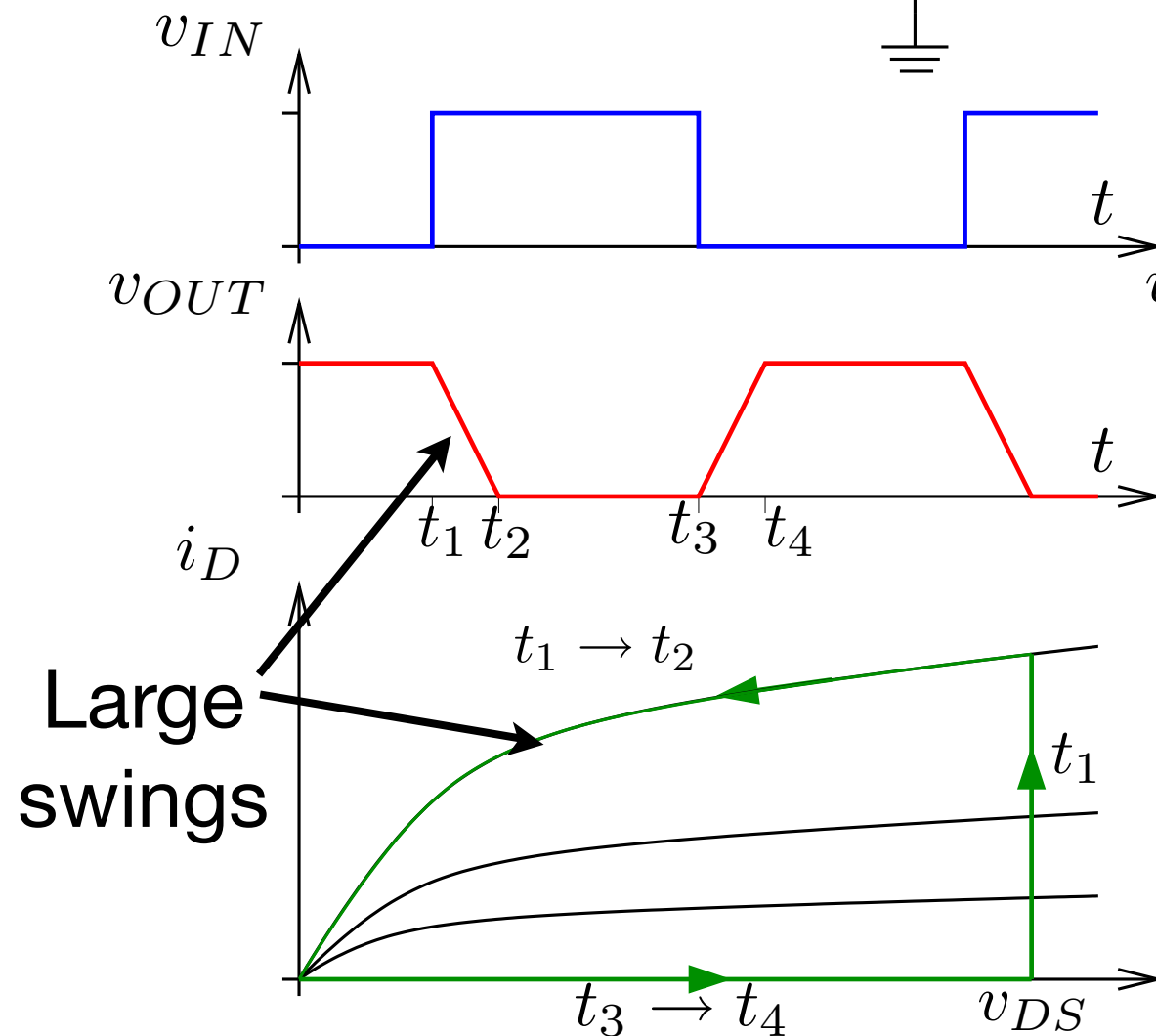
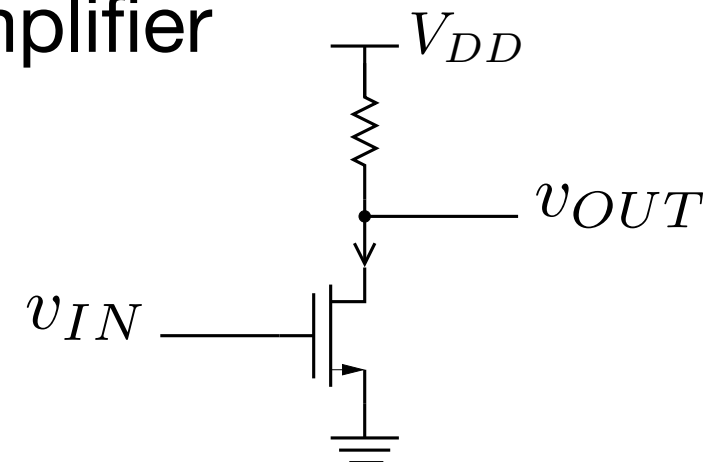
It is the slope
in saturation
that is
hard to control

An aside about transistor operation: digital vs analog

Digital: switch



Analog: amplifier



Why do we want accurate gain?

- Important for most analog/mixed circuits
 - Hint: ratio of largest and smallest value in signed 10-bit word is 512
 - For 10-bit data conversion, need to discriminate voltages / currents at similar accuracy

How expensive is gain?

- The cost (power, area, complexity and thus \$) depends on:
 - How high gain?
 - How accurate?
 - At what frequencies?
 - + some more factors (mainly linear range)

How bad is it?

OP27—SPECIFICATIONS

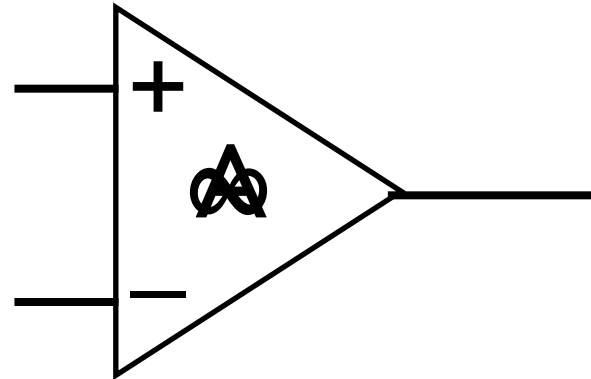
ELECTRICAL CHARACTERISTICS (@ $V_S = \pm 15\text{ V}$, $T_A = 25^\circ\text{C}$, unless otherwise noted.)

Parameter	Symbol	Conditions	OP27A/E			OP27F			OP27C/G			Unit
			Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
INPUT OFFSET VOLTAGE ¹	V_{OS}			10	25		20	60		30	100	μV
LONG-TERM V_{OS} STABILITY ^{2, 3}	V_{OS}/Time			0.2	1.0		0.3	1.5		0.4	2.0	$\mu\text{V}/\text{M}_O$
INPUT OFFSET CURRENT	I_{OS}			7	35		9	50		12	75	nA
INPUT BIAS CURRENT	I_B			± 10	± 40		± 12	± 55		± 15	± 80	nA
INPUT NOISE VOLTAGE ^{3, 4}	$e_{n\text{ p-p}}$	0.1 Hz to 10 Hz		0.08	0.18		0.08	0.18		0.09	0.25	$\mu\text{V p-p}$
INPUT NOISE Voltage Density ³	e_n	$f_O = 10\text{ Hz}$		3.5	5.5		3.5	5.5		3.8	8.0	$\text{nV}/\sqrt{\text{Hz}}$
		$f_O = 30\text{ Hz}$		3.1	4.5		3.1	4.5		3.3	5.6	$\text{nV}/\sqrt{\text{Hz}}$
		$f_O = 1000\text{ Hz}$		3.0	3.8		3.0	3.8		3.2	4.5	$\text{nV}/\sqrt{\text{Hz}}$
INPUT NOISE Current Density ^{3, 5}	i_n	$f_O = 10\text{ Hz}$		1.7	4.0		1.7	4.0		1.7		$\text{pA}/\sqrt{\text{Hz}}$
		$f_O = 30\text{ Hz}$		1.0	2.3		1.0	2.3		1.0		$\text{pA}/\sqrt{\text{Hz}}$
		$f_O = 1000\text{ Hz}$		0.4	0.6		0.4	0.6		0.4	0.6	$\text{pA}/\sqrt{\text{Hz}}$
INPUT RESISTANCE	R_{LP}			1.2	6		0.04	5		0.7	4	M Ω

Accuracy by feedback!

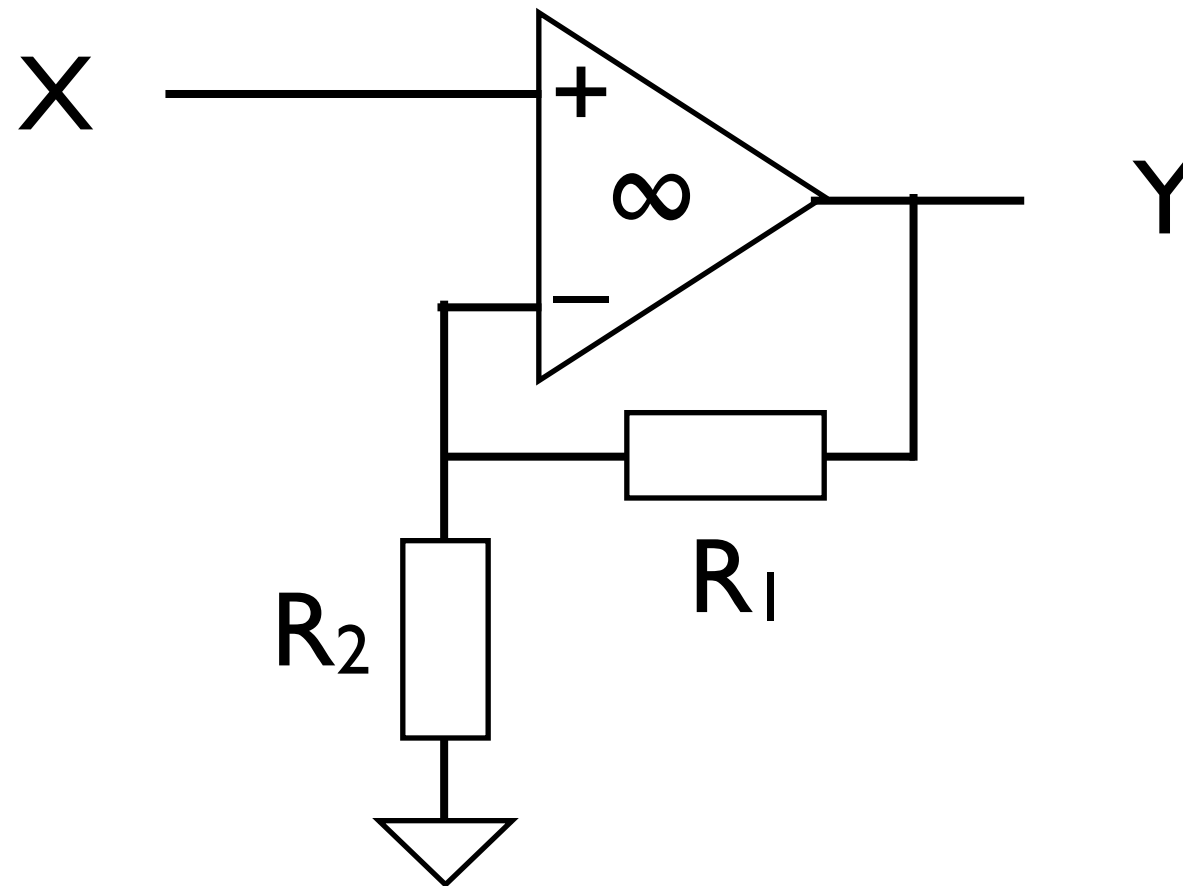
- Derive gain accuracy from **passive** components (R or C)
- Much more precise than **active** components (transistors)
- Pay with gain magnitude for improved accuracy
- That is: accurate but lower gain!
- Another issue: stability in feedback systems; note really dealt with in this course

Ideal amplifier model



- Output takes any voltage, sinks/sources any current
- No current into inputs, no voltage across
- Gain A towards ∞

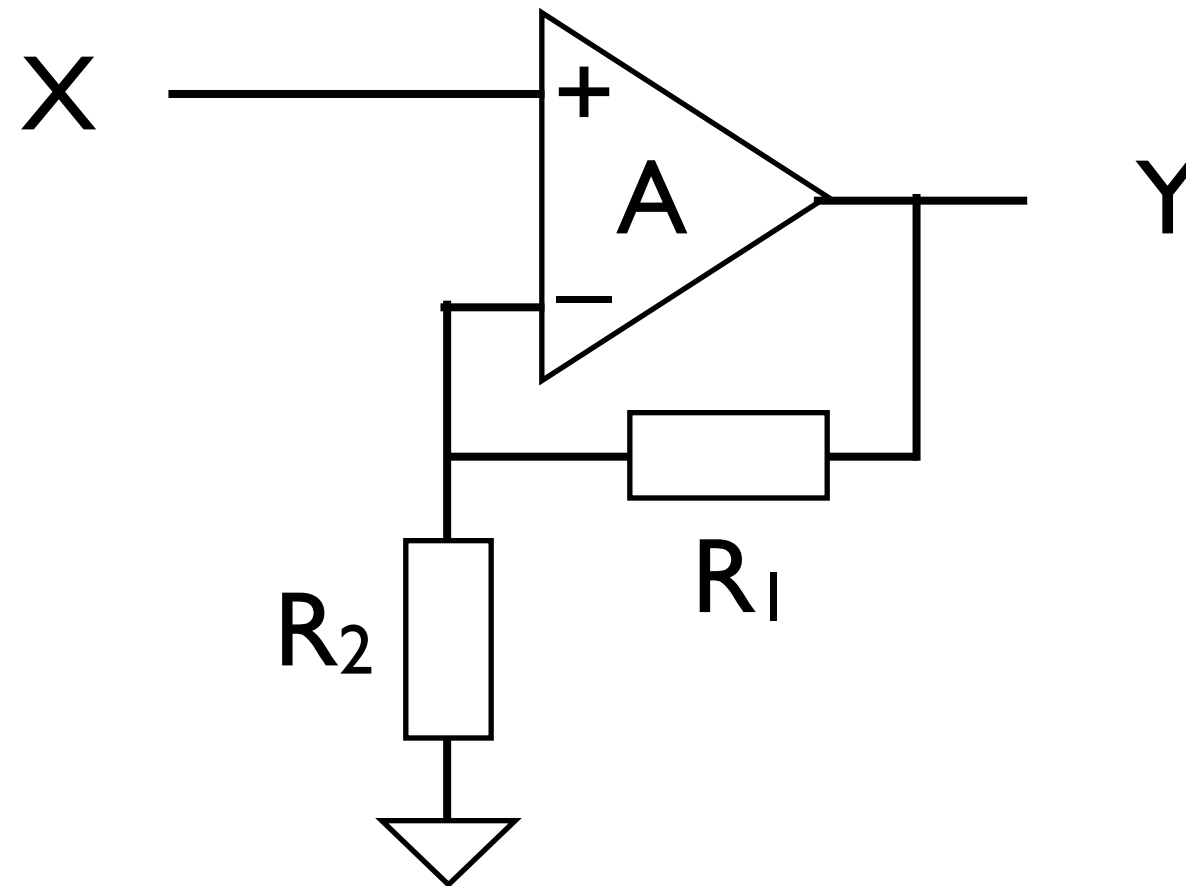
Example: voltage amplifier



- Voltage divider + amplifier!

$$X = Y \frac{R_2}{R_1 + R_2} \Rightarrow \frac{Y}{X} = \frac{R_1 + R_2}{R_2}$$

Example: voltage amplifier



$$Y = A\left(X - Y \frac{R_2}{R_1 + R_2}\right)$$

$$Y + AY \frac{R_2}{R_1 + R_2} = AX \quad \Rightarrow$$

$$Y = \frac{AX}{1 + \frac{AR_2}{R_1 + R_2}}$$

Let A grow large

- Let $R_2 / (R_1 + R_2) = \beta$
- $Y = X \cdot A / (1 + AR_2 / (R_1 + R_2)) =$
 $X \cdot A / (1 + A\beta) \approx$
 $\approx X \cdot A / (A\beta) =$
 $= X / \beta$ ✓
- When is “ $\approx$ ” allowed?
- Error magnitude?

Discrepancy

- Deviation from “ideal” ($A = \infty$) performance

- $$\frac{Y}{X} = \frac{A}{1 + A\beta} \approx \frac{1}{\beta}$$

- Clearly, for approximation to hold, $A\beta \gg 1$

- Discrepancy:

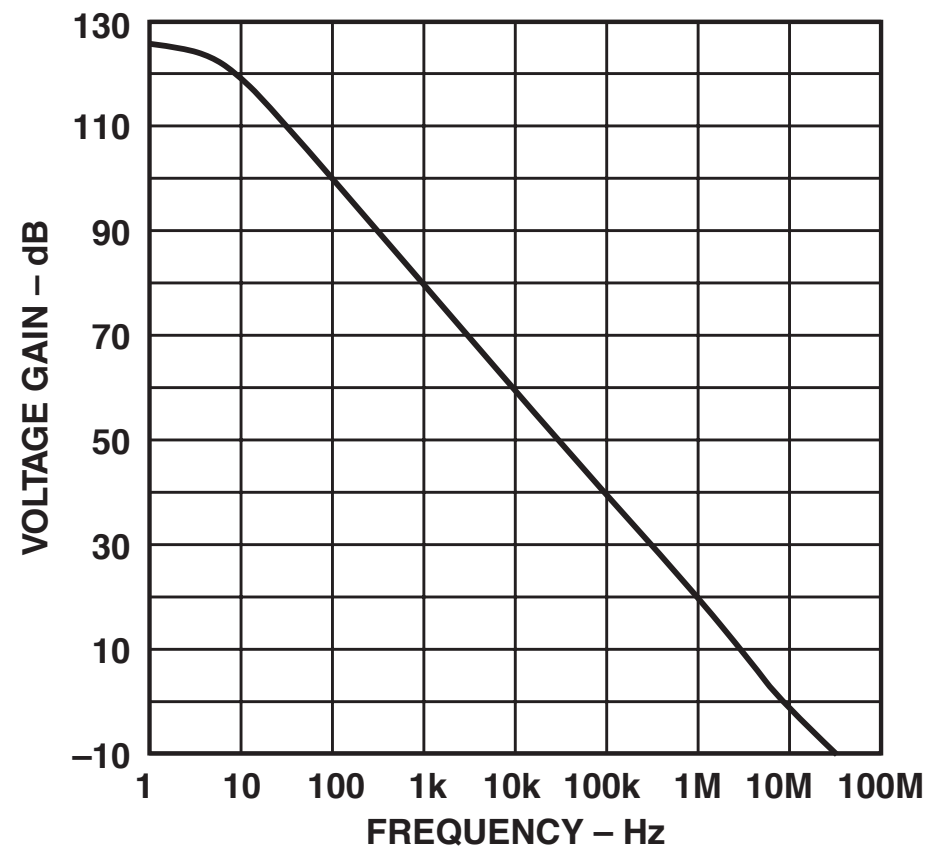
- $$D = \frac{A}{1 + A\beta} / \frac{1}{\beta} = \frac{A\beta}{1 + A\beta}$$

- $D < 1$; but close to 1 when $A\beta \gg 1$

Example

- We wish $Y / X = 100$
- Use $\beta = 1 / 100 = 0.01$
- We wish gain error to be $< 1\%$
- Requirement is $D > 0.99$
- $D = A\beta / (1 + A\beta)$
- Determine required A:
- $A = D / (\beta(1 - D)) \approx 10^2 \cdot 10^2 = 10^4$
- ... or 80 dB

Dominant pole

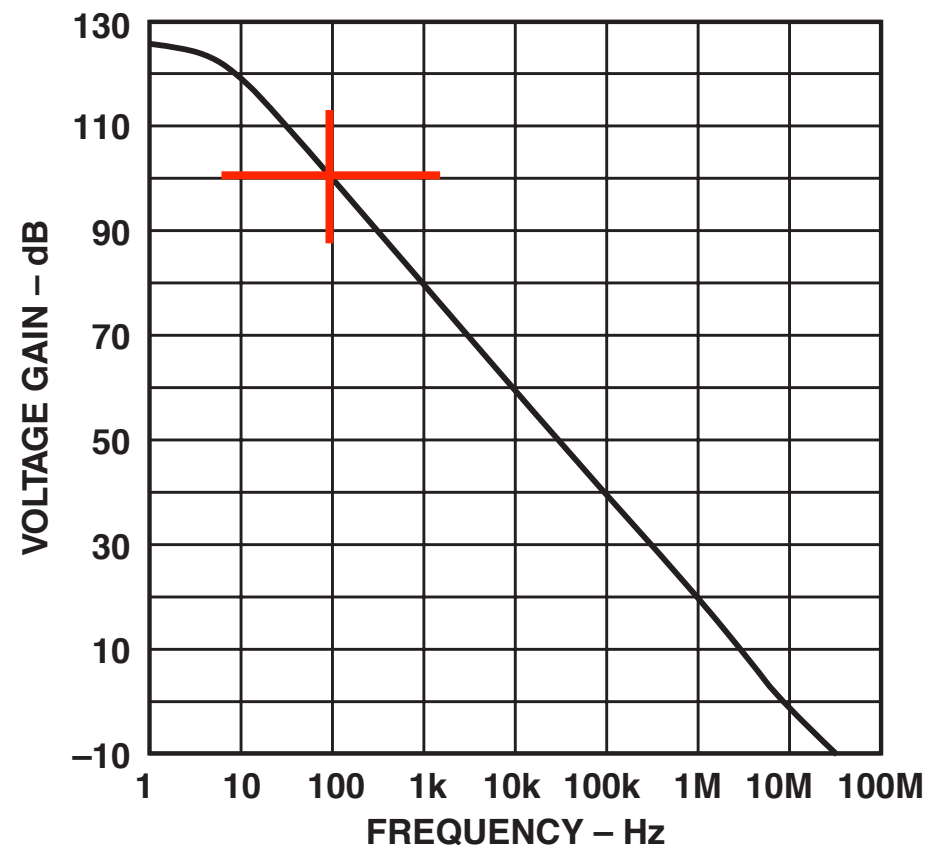


TPC 16. Open-Loop Gain vs. Frequency

- “Standard” op-amp transfer function
Bode plot

[OP27]

GBW = gain-bandwidth product

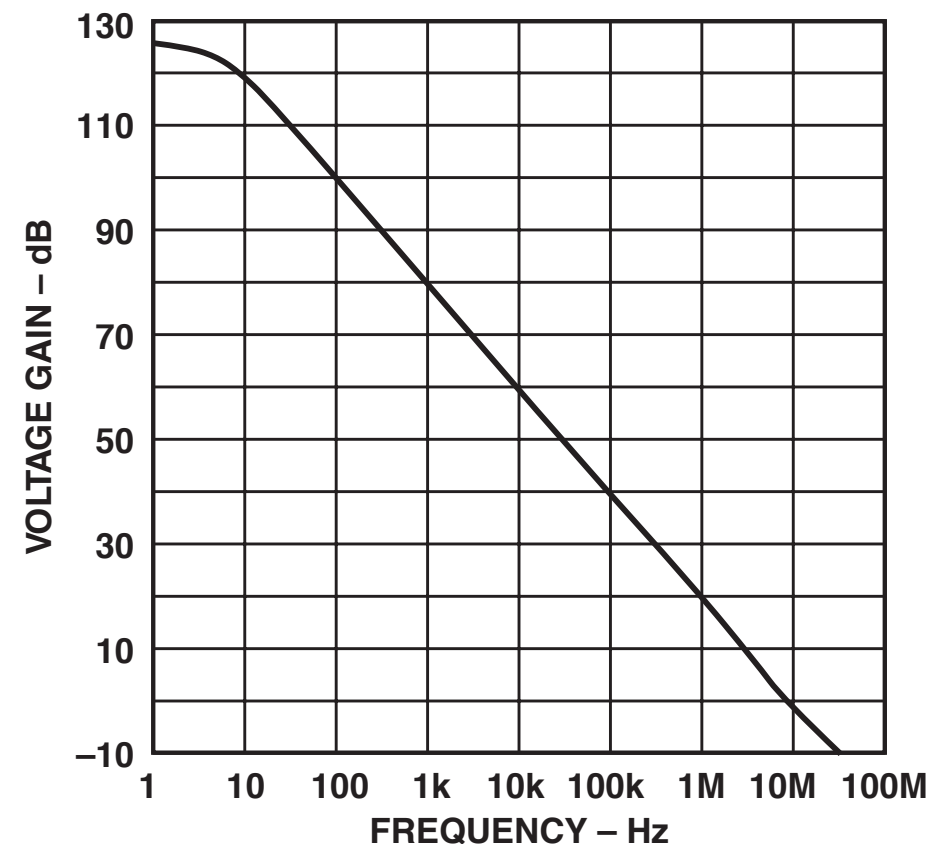


TPC 16. Open-Loop Gain vs. Frequency

- Standard parameter
 - Constant regardless of β

Limitations

- Corrective power as function of frequency?
- Best at low frequencies, since higher gain!
- 80 dB only up to 1kHz!
- Can't get $Y / X = 100 \pm 1\%$ at higher frequencies with OP27!



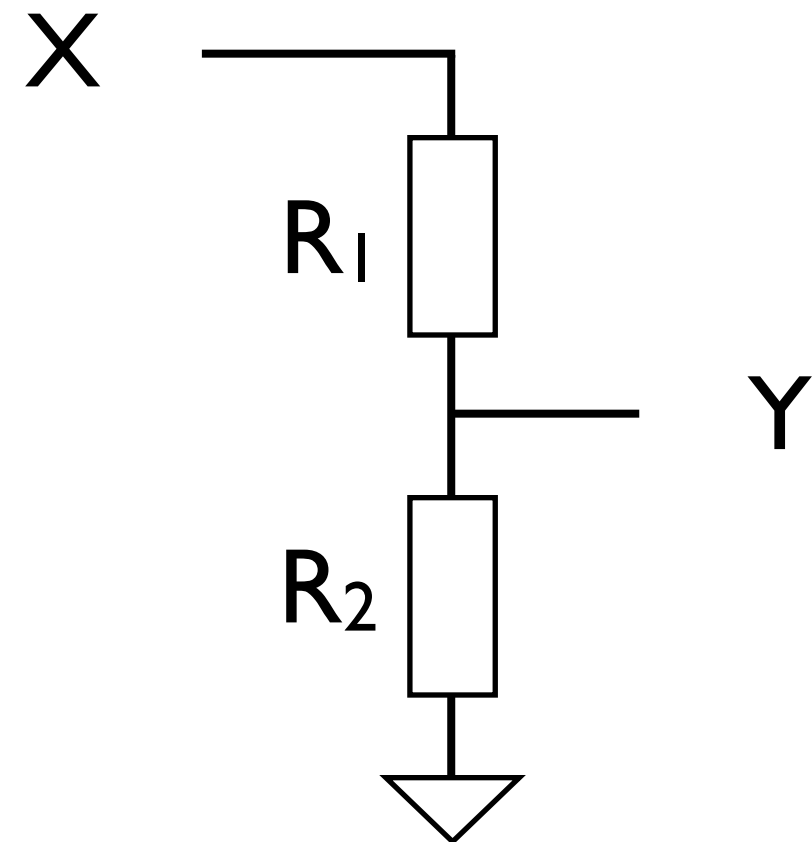
TPC 16. Open-Loop Gain vs. Frequency

What about the Rs?

- Voltage divider

$$\frac{Y}{X} = \frac{R_2}{R_1 + R_2}$$

- Transfer set by ratio of resistors
- Ratios more accurate than single values!



Mismatch influence?

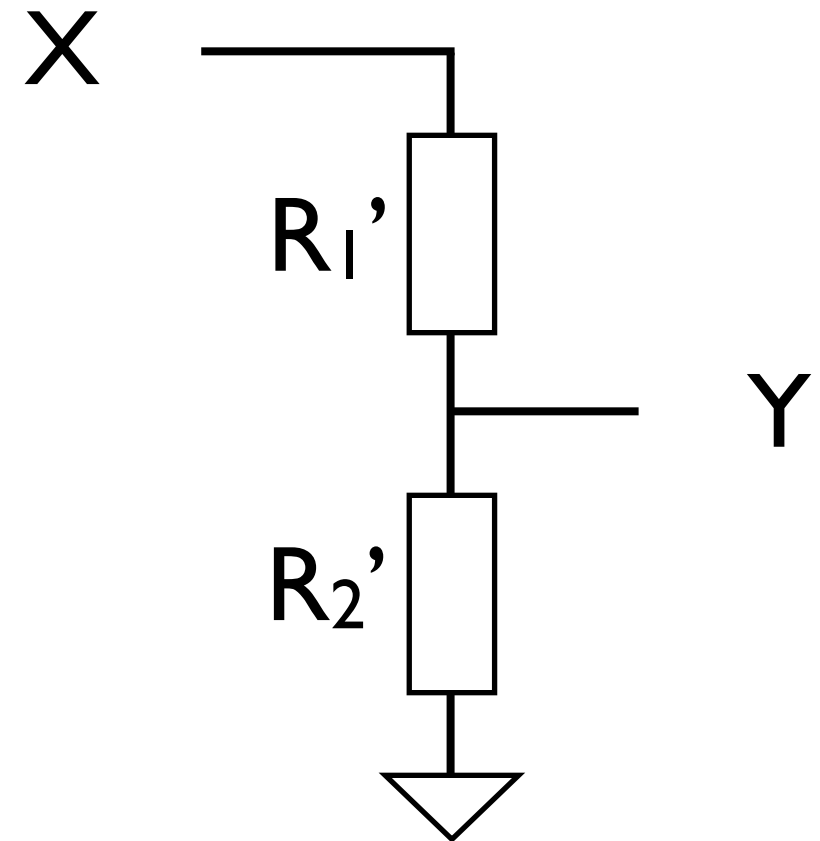
- We wish $\frac{Y}{X} = \frac{R_2}{R_1 + R_2} = \frac{1}{r}$
- so $R_1 = (r - 1) R_2$

- Assume worst deviation d:

- $R_1' = (1 - d) R_1$
- $R_2' = (1 + d) R_2$

- Then:
$$\begin{aligned} \frac{Y}{X} &= \frac{R_2'}{R_1' + R_2'} = \frac{R_2}{\frac{1-d}{1+d} R_1 + R_2} \\ &= \frac{1}{\frac{(1-d)(r-1)}{1+d} + 1} \approx \frac{1}{\frac{r-1}{1-2d} + 1} \end{aligned}$$

- For large r, a $\pm 1\%$ tolerance can affect ratio by $\pm 2\%$



Example, again

- We wish $Y / X = 100$
 - $\beta = 1 / 100 = 0.01$
- We wish gain error to be $< 1\%$
 - ...
 - 80 dB gain up to max frequency
- But also errors in β due to passives!
 - Distribute error budget
 - $0.5\% + 0.5\%$, or cheaper alternative

Reflection...

- How design to a given performance ...
 - ... with a given precision?
- Start with feedback network
 - Design/select amplifier that is “good enough”
- If not possible / affordable, split into several stages
 - Easier to provide $2 \cdot 10x$ than $100x$

Sources of variability

- “PVT”:
 - Process (addressed through matching)
 - Voltage
 - Temperature
- “All” these affect active circuits more than passive ones
 - Ratios of passives especially stable

Other performance measures

- Voltage gain may be stabilized with passive feedback
- Current gain: other topologies, similar calculations
- Frequency-dependent gain: no simple ratios (how match R vs C?)
- Week 4.
- Input/output impedances?
 - Also possible with two feedback loops

Time scales

- Static / years
 - Process corners, lithography, dopants
- Seconds
 - Supplies, temperature, 1/f noise
- Microseconds
 - IR drops, temperature gradients
- Picoseconds
 - IR drops, jitter, thermal noise



Feedback less effective

Summary

- Use feedback to control variability
 - Hide variations in active parts
 - Improvement set by gain given up
- Use ratios of passives to determine performance whenever possible
- Design feedback network first
 - Then select or design active parts:
 - How high open-loop gain and at what frequencies?
 - May have to split in more stages if high requirements