Unit 1: Transistors and Circuits

Lecture 1.3: Analog/RF Circuits

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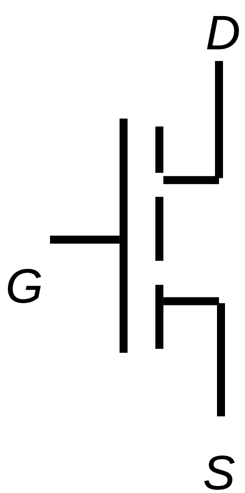
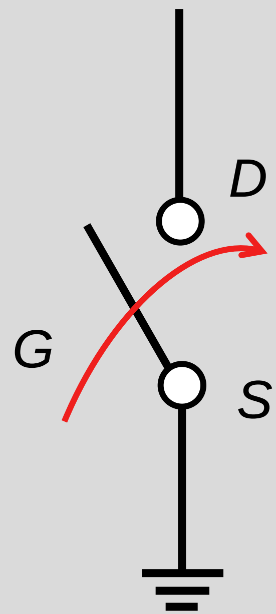
Applications of MOSFETs

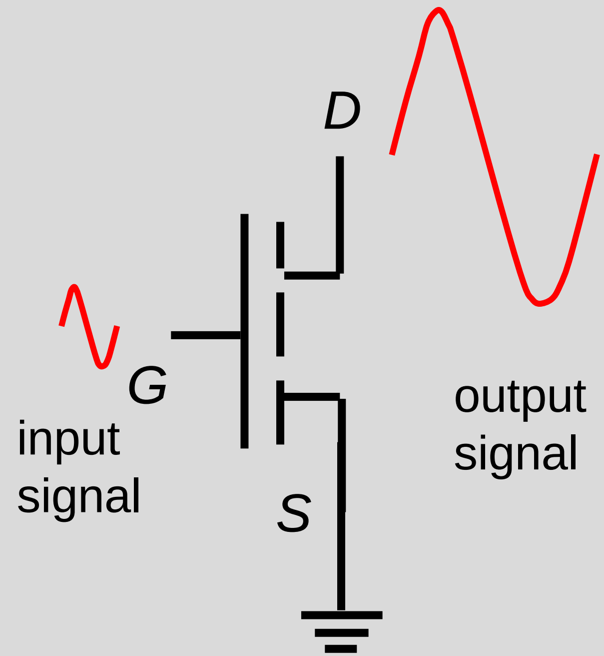
symbol



digital



analog



Why analog /RF? Why CMOS?

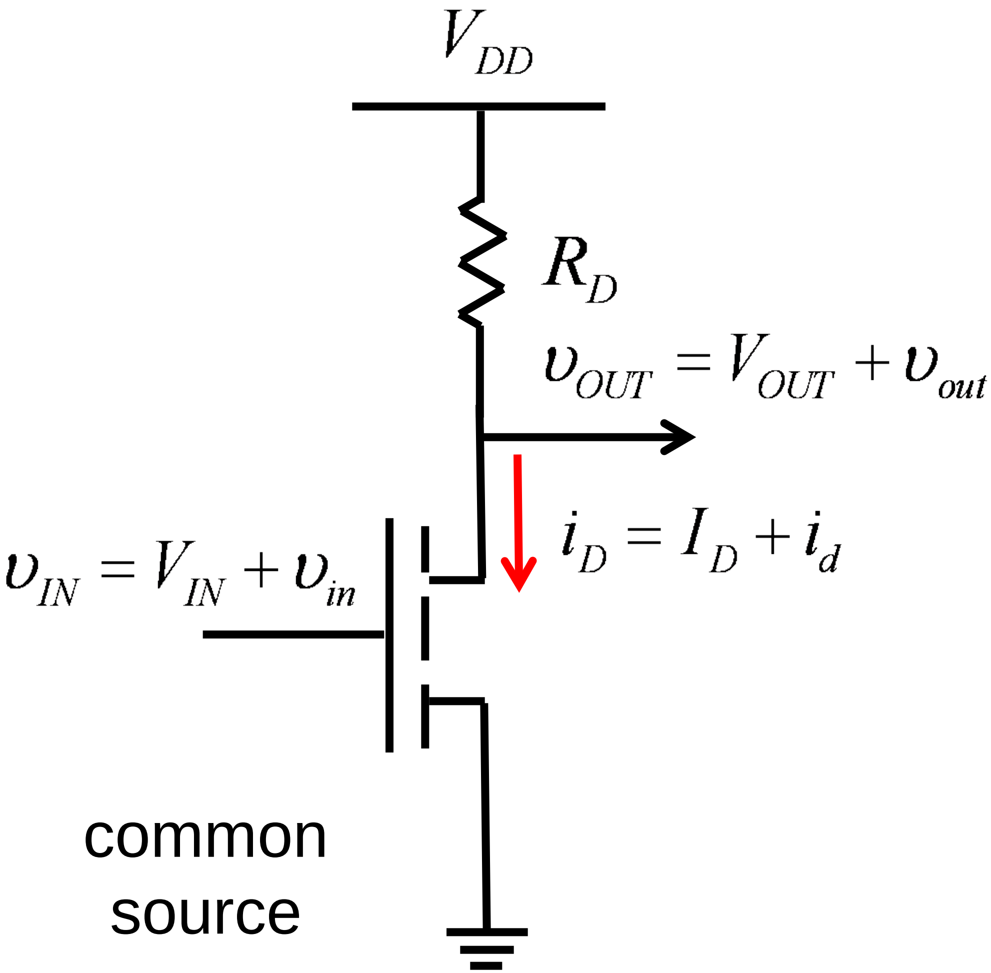
Many applications involve analog / RF signals:

1) many natural signals are analog (sensors)
2) disk drive electronics
3) wireless receivers and transmitters
4) optical receivers
5) microprocessors / memories

CMOS:

1) many systems are both analog and digital
2) CMOS dominant for digital electronics
3) CMOS performance is acceptable for many analog applications (but not, generally as good as bipolar)

Basic CS Amplifier



common source

$$I_D = f\left(\upsilon_{GS}, \upsilon_{DS}\right)$$

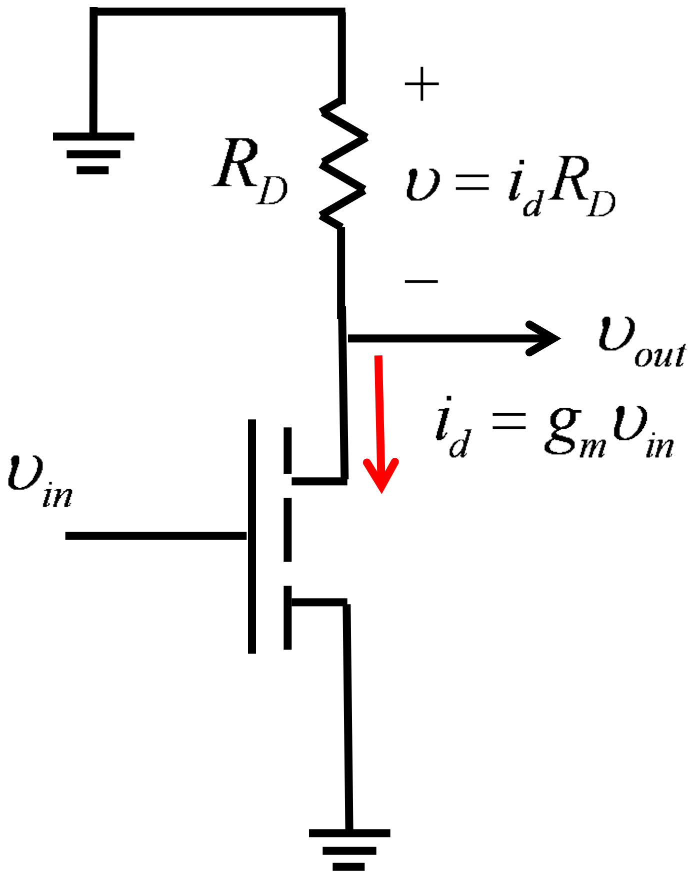
$$i_d = g_m \upsilon_{gs}$$

$$g_m = \frac{i_d}{\upsilon_{gs}} = \frac{\delta I_D}{\delta V_{GS}} \approx \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}$$

$$\boxed{g_m \equiv \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}}$$

Basic CS Amplifier: ac analysis

ac ground



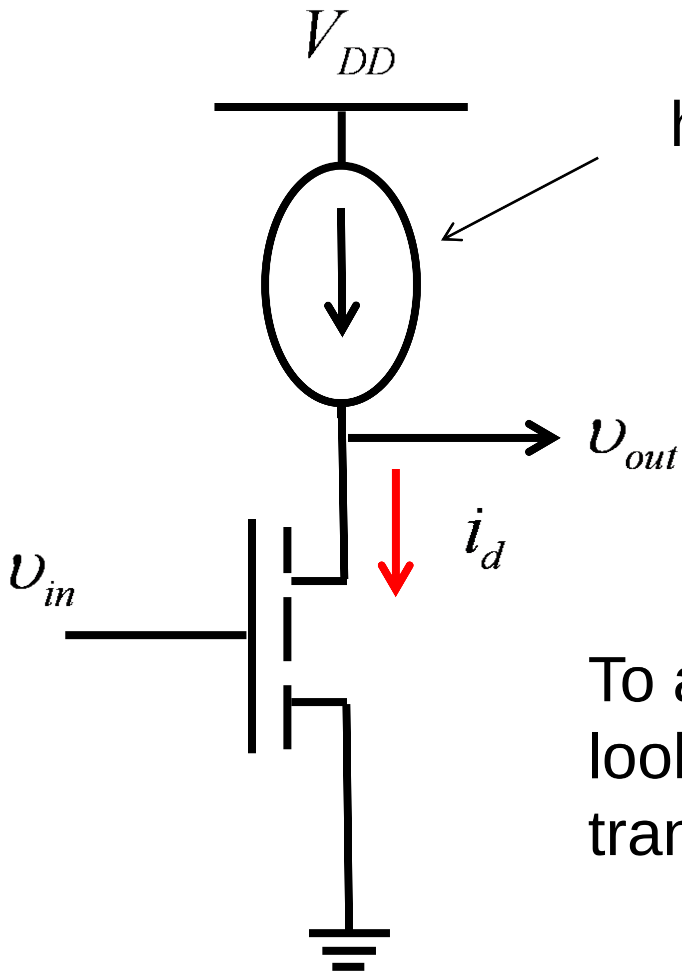
$$\upsilon_{out} = -i_d R_D = -g_m R_D \upsilon_{in}$$

$$A_\upsilon = \frac{\upsilon_{out}}{\upsilon_{in}} = -g_m R_D$$

Transconductance is an important analog figure of merit.

It is a measure of the transistor’s ability to amplify.

Maximum gain



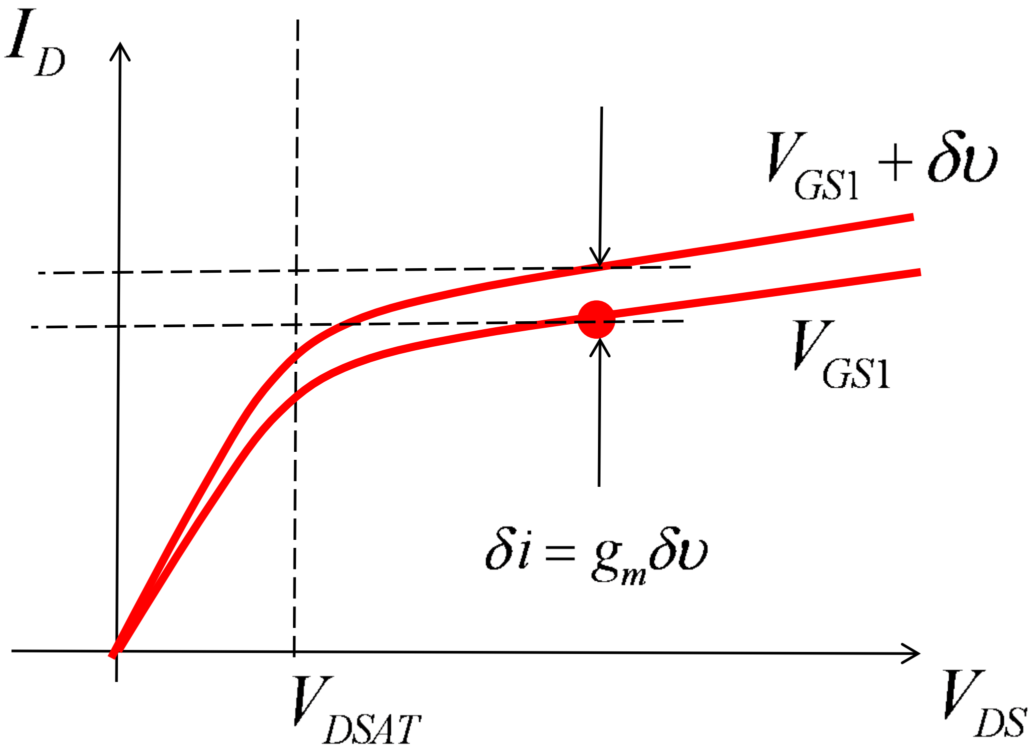
high impedance current source

$R_D \to \infty$

$\boxed{A_\upsilon(\max) = ?}$

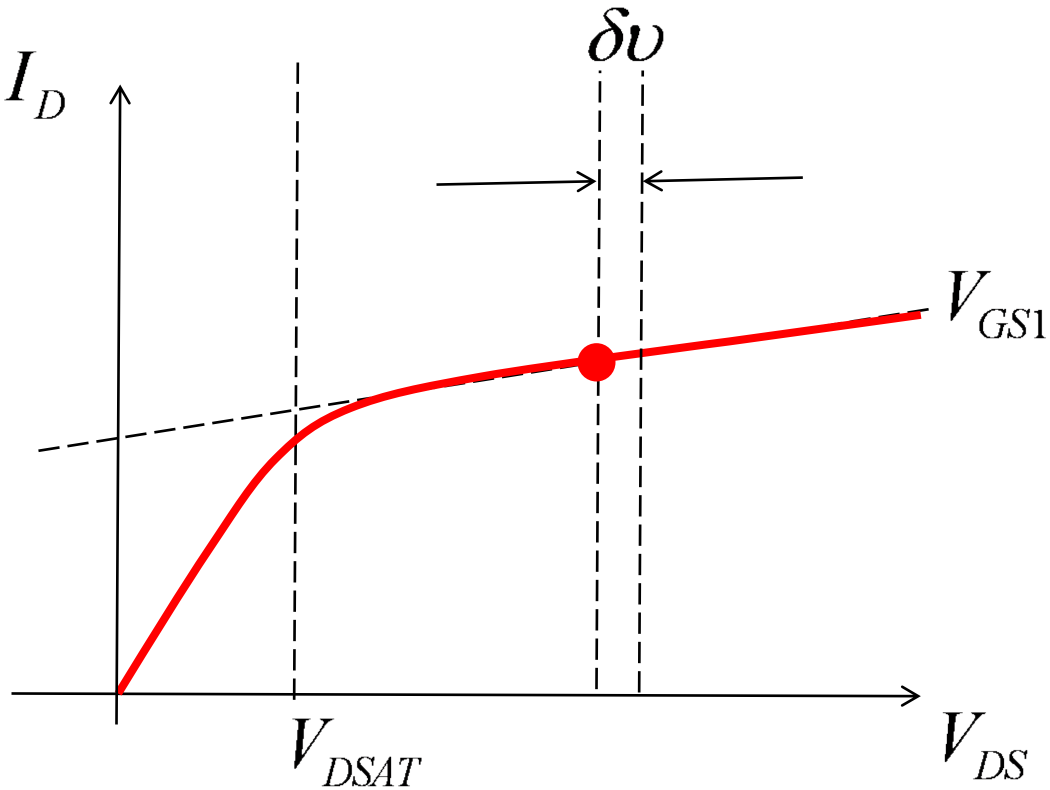
To answer this question, we need to look a little more carefully at the transistor.

Transconductance



$$g_m \equiv \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}$$

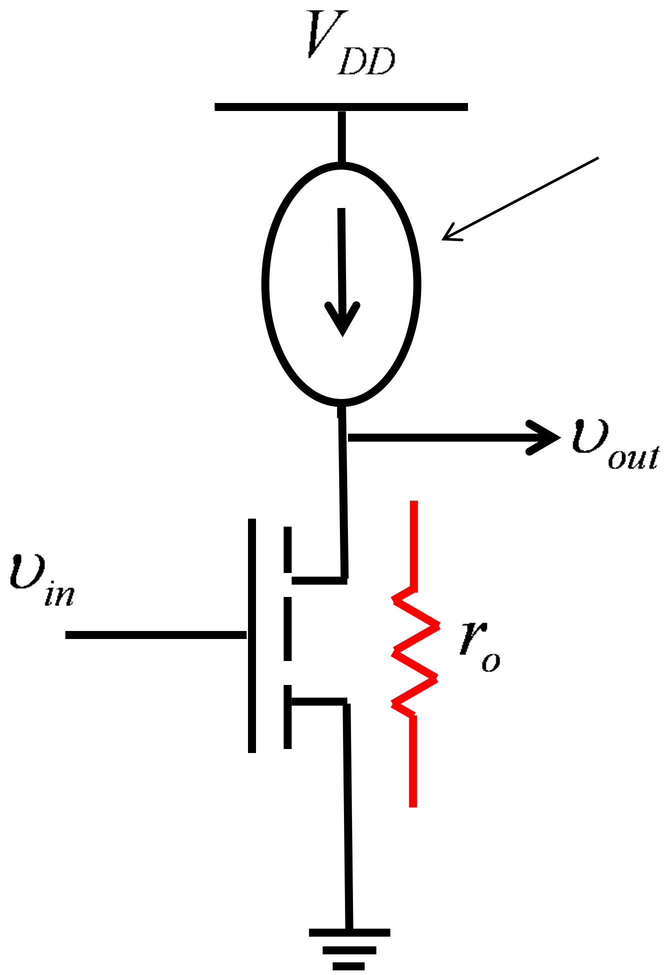
Output resistance



$$\delta i = \frac{\delta\upsilon}{r_0}$$

$$r_o \equiv \left[\partial I_D / \partial V_{DS}\Big|_{V_{GS}} \right]^{-1}$$

Maximum gain



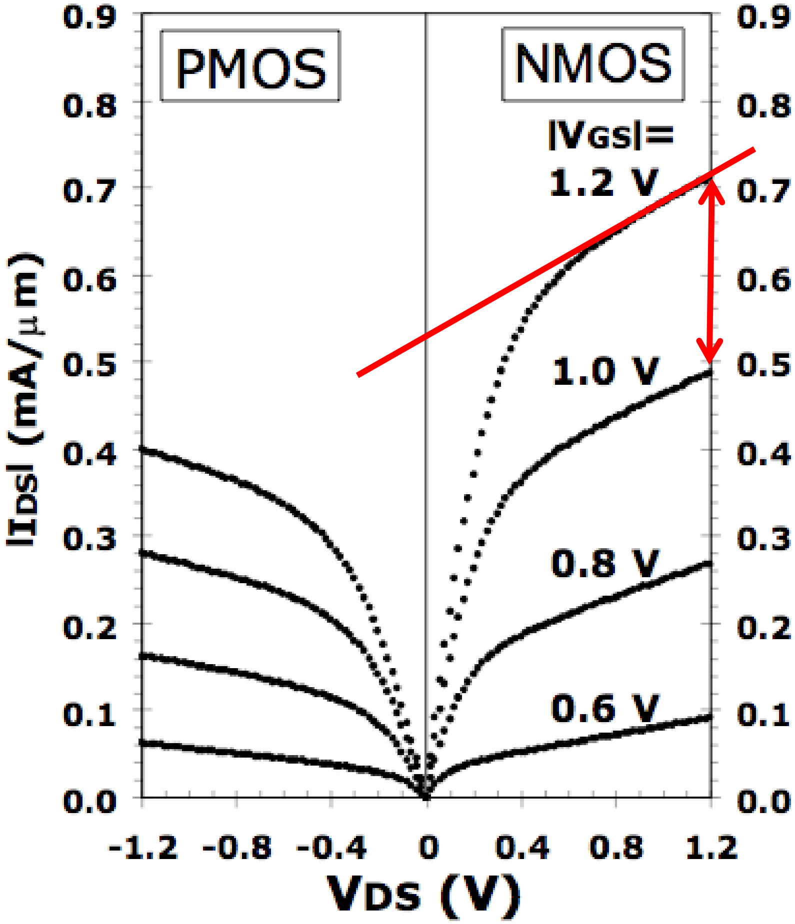
high impedance current source

$$\boxed{A_v(\max) = -g_m r_0}$$

The **output resistance**, r_0, of the MOSFET is an important figure of merit.

So is the **self gain**, $g_m r_0$.

Self-gain for 65 nm digital CMOS



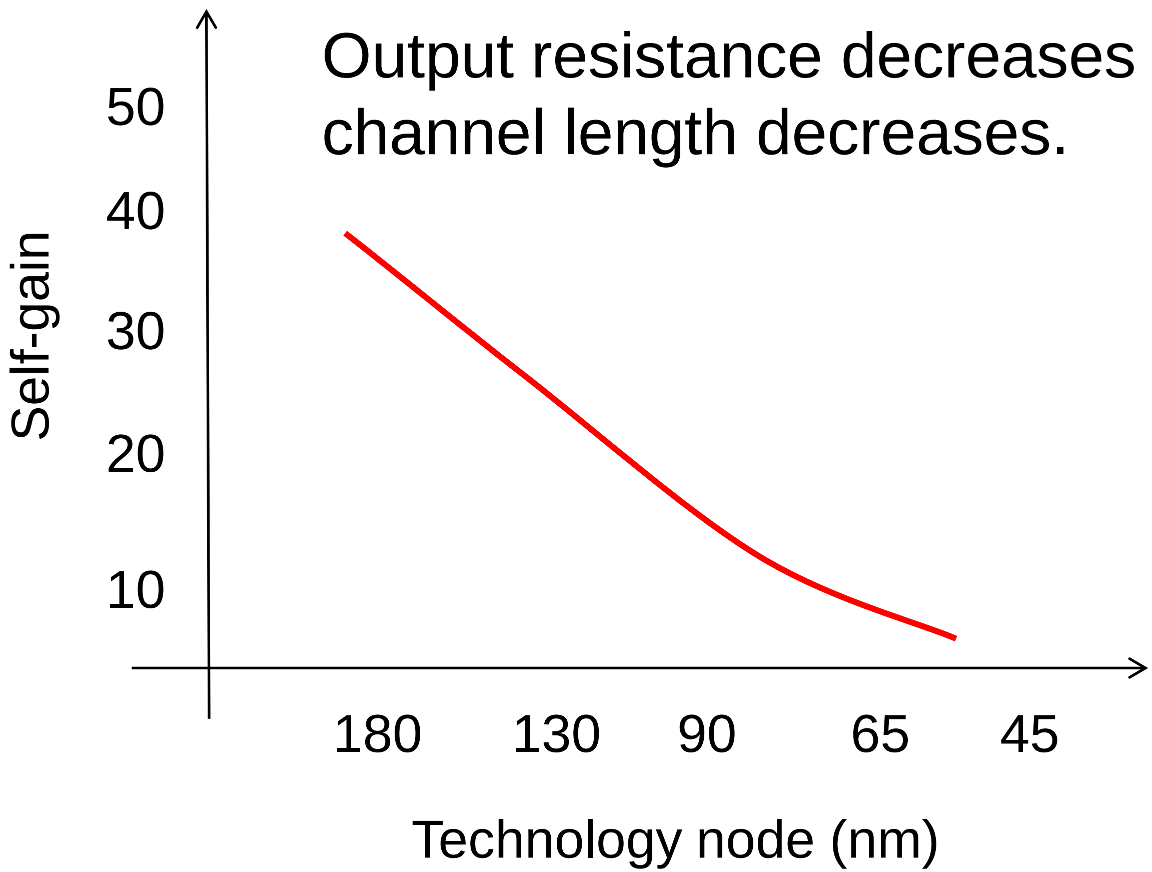
$$g_m \approx \frac{0.2\ \mathrm{mA}/\mu\mathrm{m}}{0.2\ \mathrm{V}} = 1\ \mathrm{mS}/\mu\mathrm{m}$$

$$r_o \approx \frac{1.2\ \mathrm{V}}{0.18\ \mathrm{mA}/\mu\mathrm{m}} \approx 7\ \mathrm{K}\Omega\text{-}\mu\mathrm{m}$$

$$\left|A_\upsilon(\max)\right| = g_m r_o \approx 7$$

C.-H. Jan. et al., 2005 IEDM

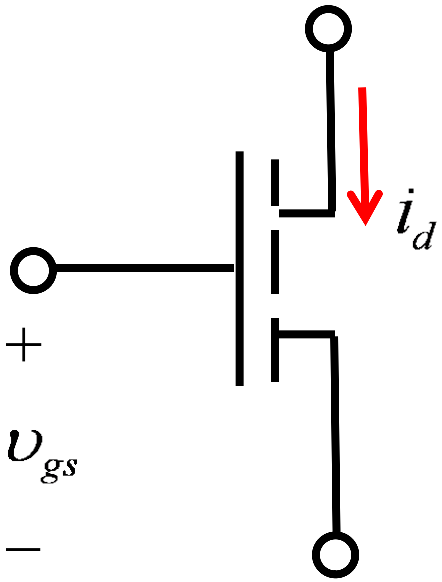
Self-gain vs. scaling

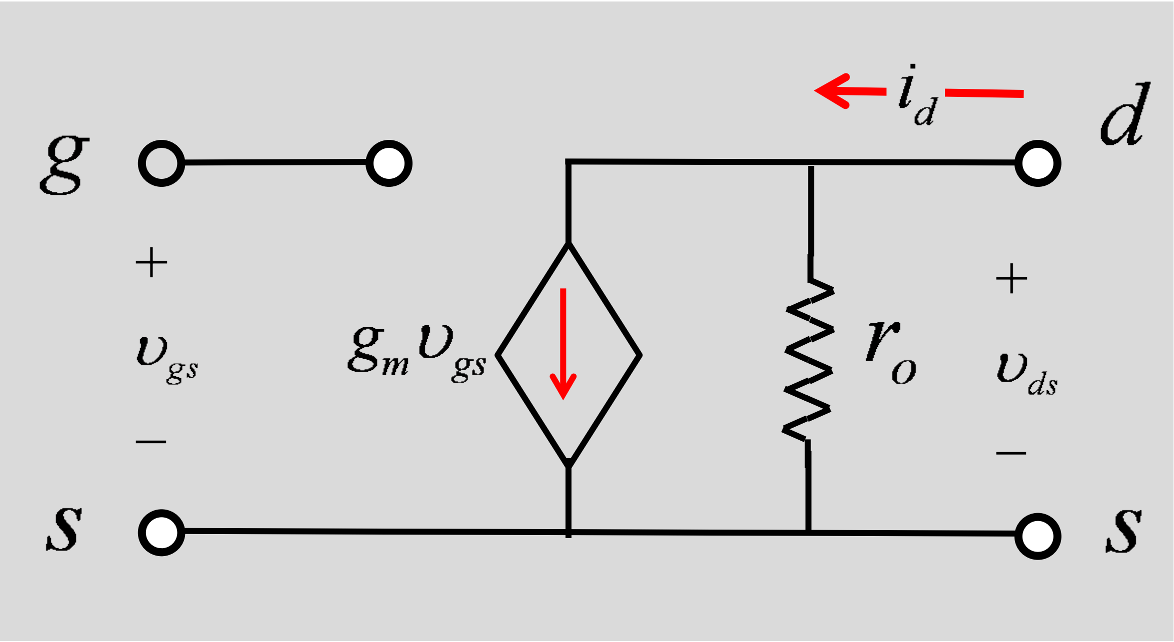


Analog designers are frequently forced to use non-minimum length (NML) devices.

High frequency performance

Small-signal, **low frequency** equivalent circuit



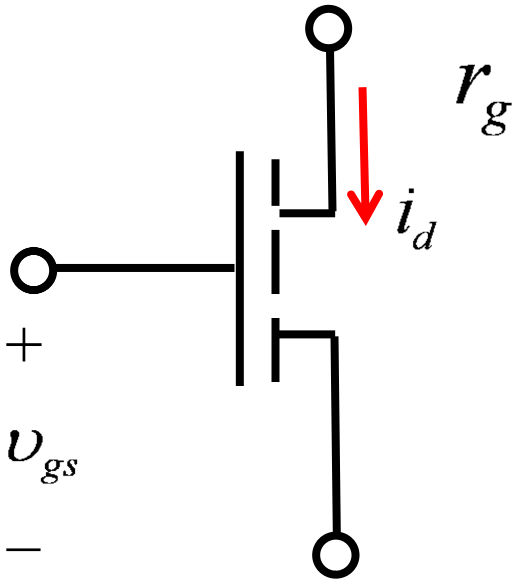


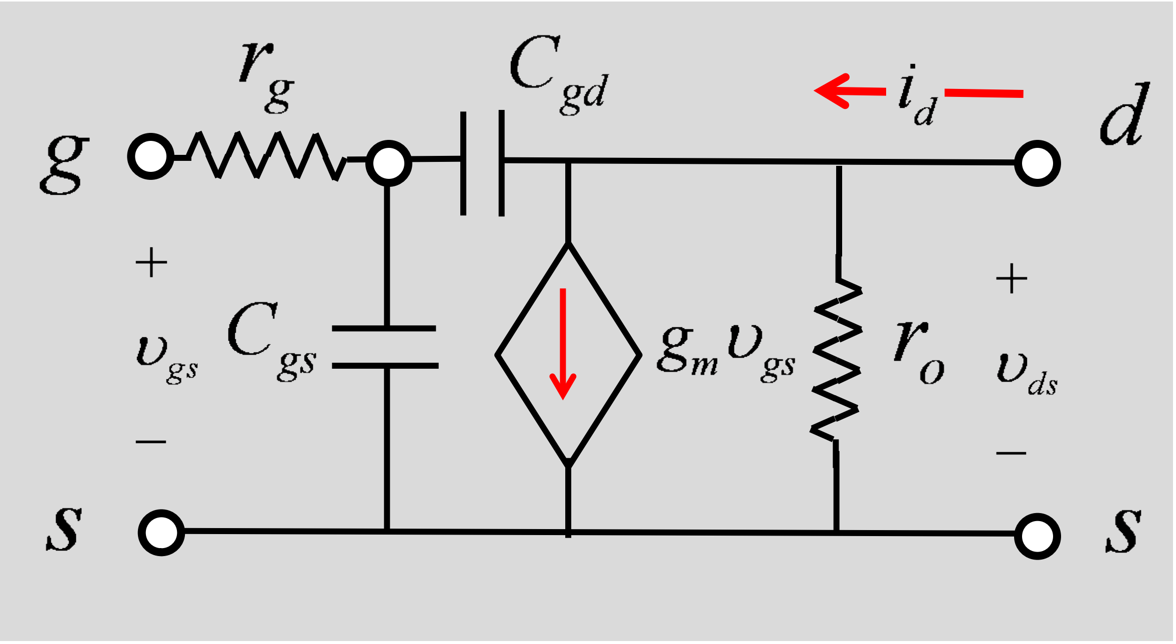
$$i_d = g_m \upsilon_{gs} + \upsilon_{ds}/r_0$$

Lundstrom: 2018

High frequency performance

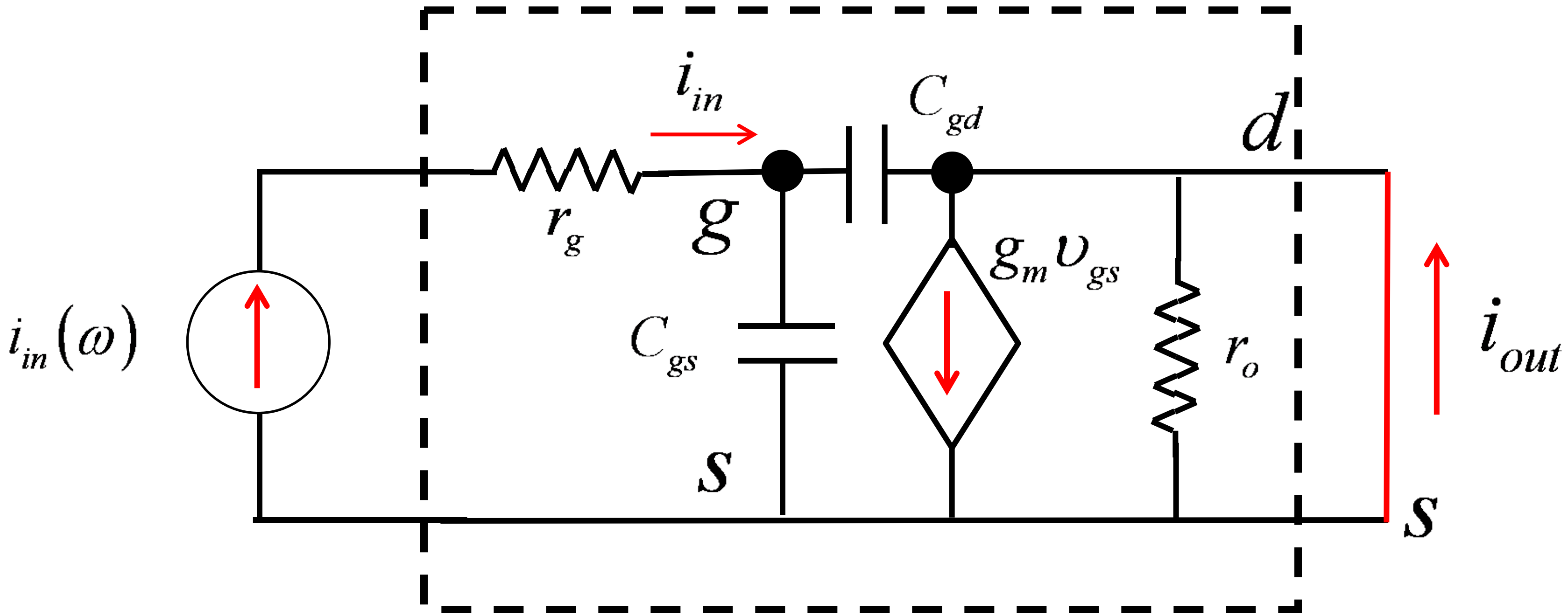
Small-signal, **high frequency** equivalent circuit





$$i_d = g_m \upsilon_{gs} + \upsilon_{ds}/r_0$$

Short circuit current gain



$$i_{out} + \left(j\omega C_{gd}\right)\upsilon_{gs} = g_m \upsilon_{gs} \rightarrow i_{out} \approx g_m \upsilon_{gs}$$

$$\upsilon_{gs} = i_{in} \frac{1}{j\omega\left(C_{gs} + C_{gd}\right)}$$

$$i_{out} \approx \frac{g_m}{j\omega C_{TOT}} i_{in}$$

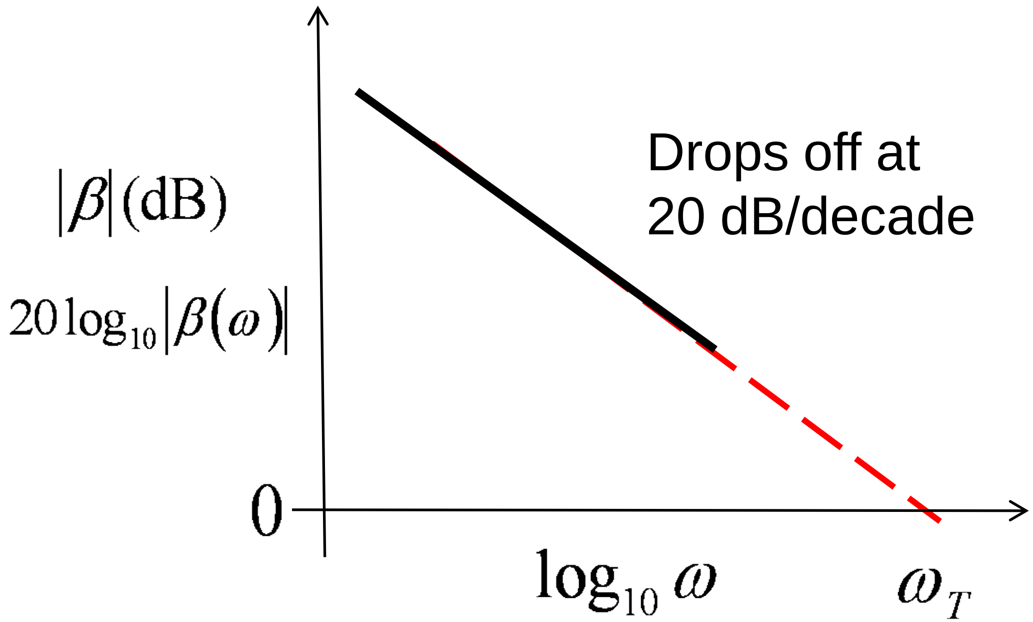
Gain-bandwidth product

$$i_{out} \approx \frac{g_m}{j\omega C_{TOT}} i_{in}$$

$$|\beta(\omega)| \approx \frac{g_m}{\omega C_{TOT}}$$

$$|\beta(\omega_T)| = 1 = \frac{g_m}{\omega_T C_{TOT}}$$

$$\boxed{\omega_T = \frac{g_m}{C_{TOT}} = 2\pi f_T}$$



Gain-bandwidth product

$$\boxed{\omega_T = 2\pi f_T = \frac{g_m}{C_{TOT}}}$$

The **gain-bandwidth product** is an important figure of merit for high frequency transistors.

f_{MAX}

$$f_T = \frac{g_m}{2\pi C_{TOT}}$$

insensitive to r_g and r_o

independent of W

channel length scaling increases f_T

$$f_{MAX} \approx \frac{\omega_T}{\sqrt{4 r_g \left(1/r_o + \omega_T C_{gd} \right)}}$$

sensitive to parasitics

- r_g
- r_o
- C_{gd}

Another figure of merit is f_{MAX}, the ***maximum frequency of oscillation*** or the ***unity power gain.***

Analog figures of merit

transconductance

self gain

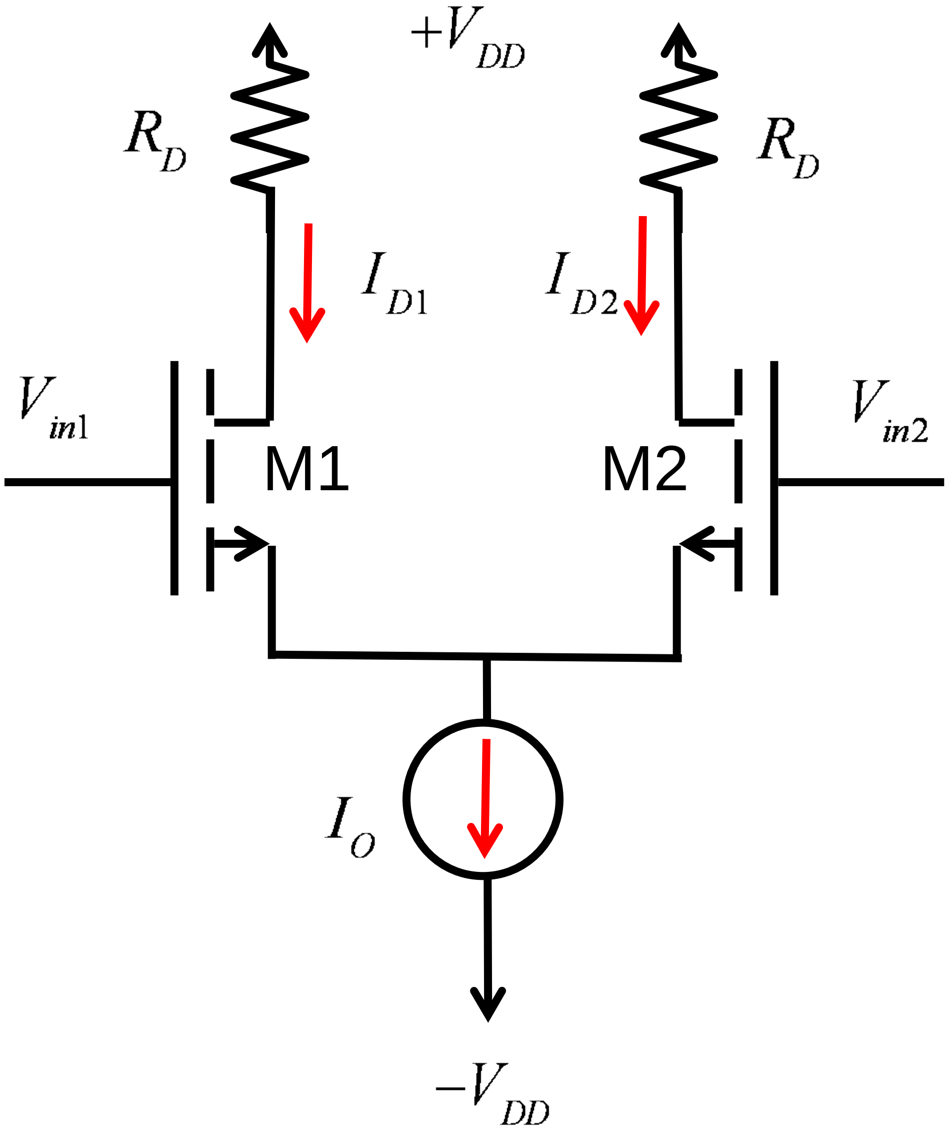
f_T and f_{MAX}

device noise

device mismatch

device linearity

Source coupled pairs



Summary

Small signal transconductance is an important figure of merit for a transistor.

Self-gain ($g_m r_0$) is another important figure of merit.

f_T and f_{max} are key figure of merit for RF applications.

Other important device parameters are noise, mismatch, and linearity.

Next topic: Device metrics

Now that we understand what's important for digital and analog circuits, we can define an easily-measured, relevant set of **device metrics**.