# The MOSFET Amplifier (1)

Lecture 7
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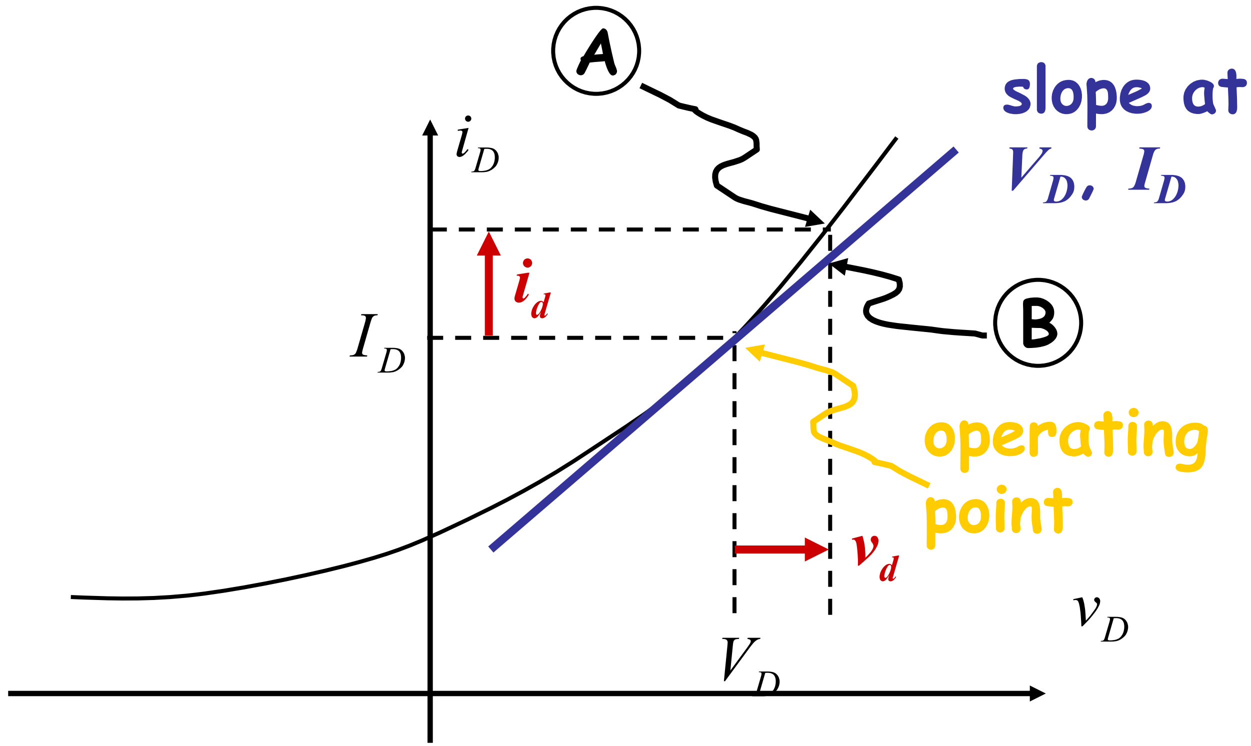
***Slide credits**: Prof. Anant Agarwal at MIT*

# Review

- **Nonlinear circuits**
  - We can use the node method (or others) with nonlinear equations.
  - Incremental analysis **“linearizes”** the circuit for small signals.




**We are approximating A with B!**

# Outline

**Textbook: 7.1, 7.2, 7.3, 7.4**

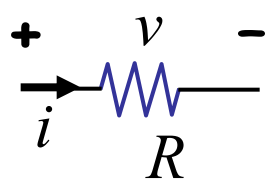
- **(Review of) Dependent Sources**
- **Why Amplify?**
- **Signal Amplification**
- **Actual MOSFET Characteristics**
- **MOSFET SCS Model**

# Dependent Sources

- Independent source

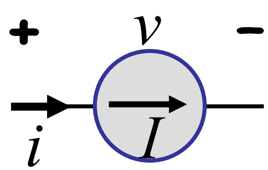
**Seen previously**

**Resistor**




$i = \frac{v}{R}$

**Independent Current source**



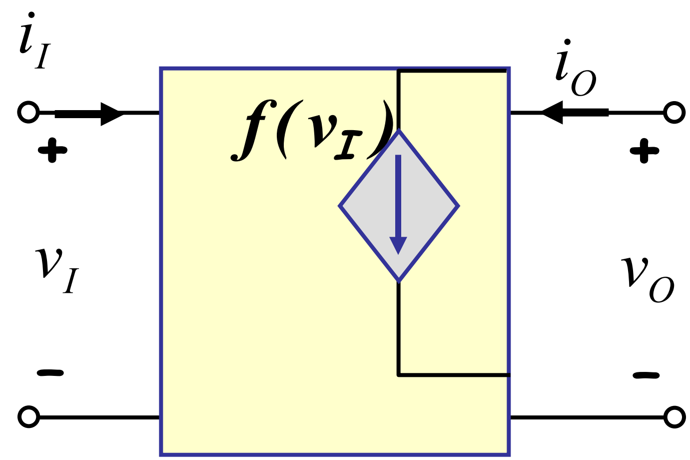

$i = I$

**2-terminal 1-port devices**

- Dependent source

**control port**

**output port**



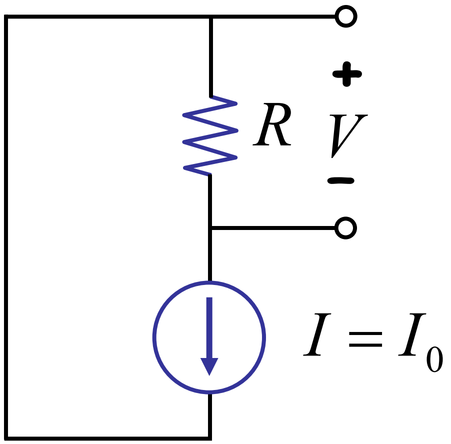

**2-port device**

**e.g., Voltage Ctrl'd Current Source**
**Current at output port is a function of voltage at the input port**

# Dependent Sources

- **Example 1 (independent source): Find V**

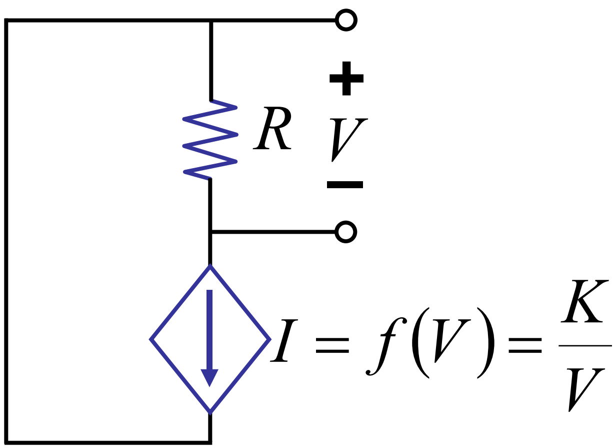
independent current source



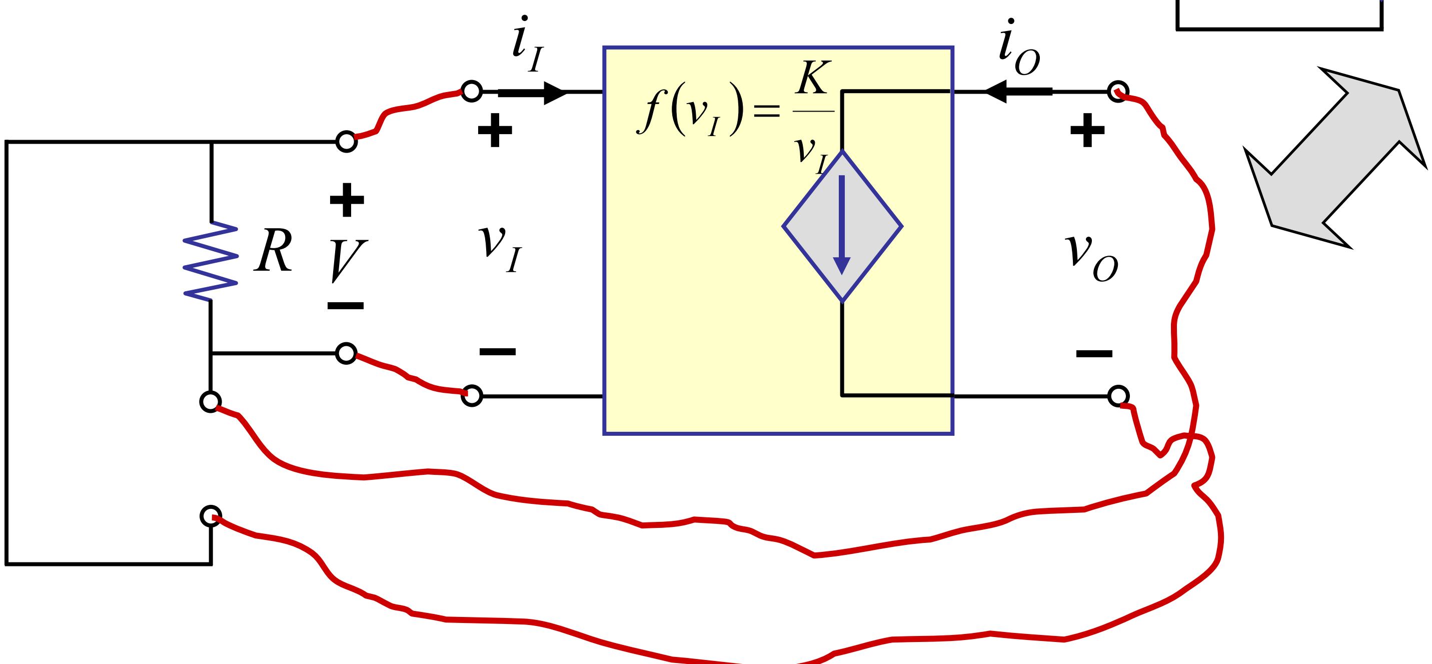

$V =$

# Dependent Sources

- **Example 2 (dependent source): Find V**

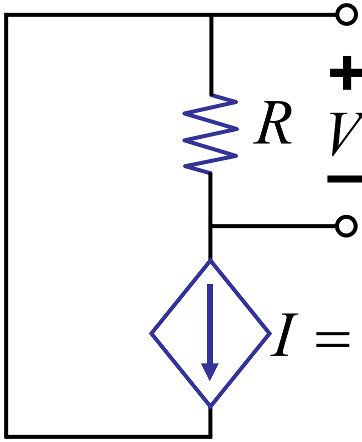



**voltage controlled current source**



# Dependent Sources

- **Example 2 (dependent source): Find V**




$$I = f(V) = \frac{K}{V}$$

voltage controlled current source

e.g. $K = 10^{-3}\ Amp \cdot Volt$

$R = 1k\Omega$

$$V = IR = \frac{K}{V} R$$

or $V^2 = KR$

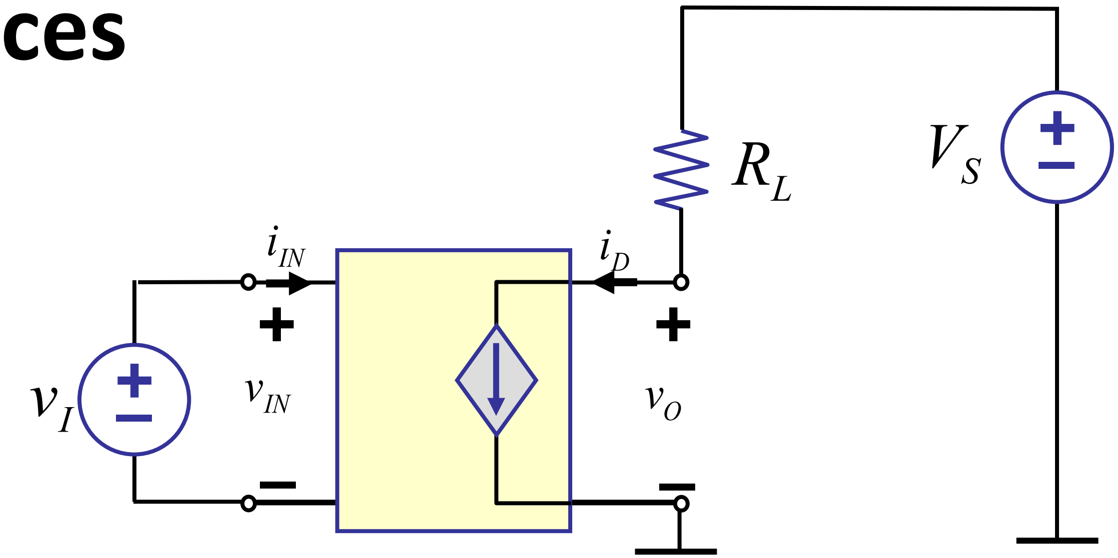
or $V = \sqrt{KR}$

$$= \sqrt{10^{-3} \cdot 10^{3}}$$

$$= 1\ Volt$$

# Dependent Sources

- Example 3




$$i_D = f(v_{IN})$$

**e.g.**

$$i_D = f(v_{IN})$$

$$= \frac{K}{2}(v_{IN} - 1)^2 \quad \text{for} \quad v_{IN} \geq 1$$

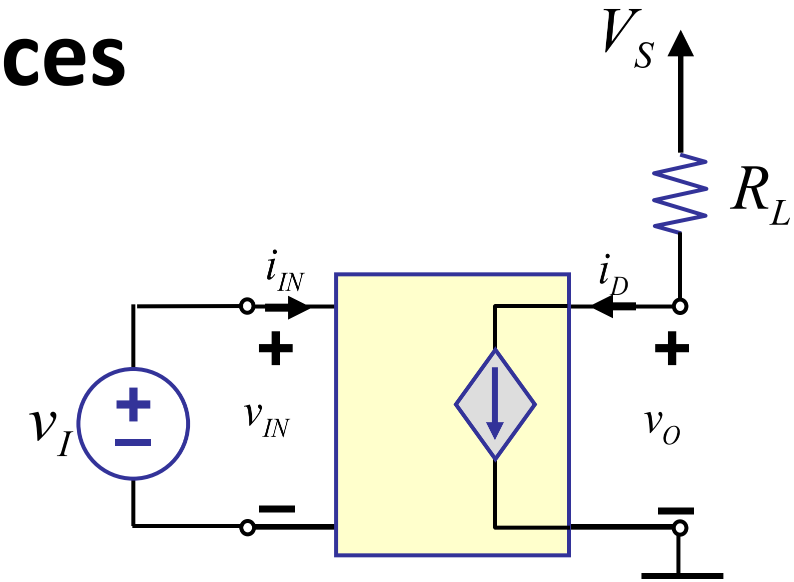
$$i_D = 0 \qquad \text{otherwise}$$

(This is MOSFET Switch-Current Source (SCS) model with $V_T$=1V…)

Find $v_O$ as a function of $v_I$.

# Dependent Sources

- Example 3




$$i_D = f(v_{IN})$$

e.g.

$$i_D = f(v_{IN}) = \frac{K}{2}(v_{IN} - 1)^2 \quad \text{for} \quad v_{IN} \geq 1$$

$$i_D = 0 \quad \text{otherwise}$$

(This is MOSFET Switch-Current Source (SCS) model with $V_T$=1V…)

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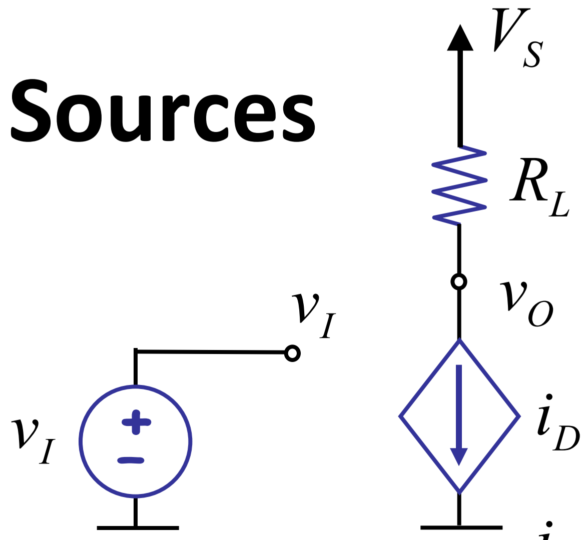
# Dependent Sources

- **Example 3**



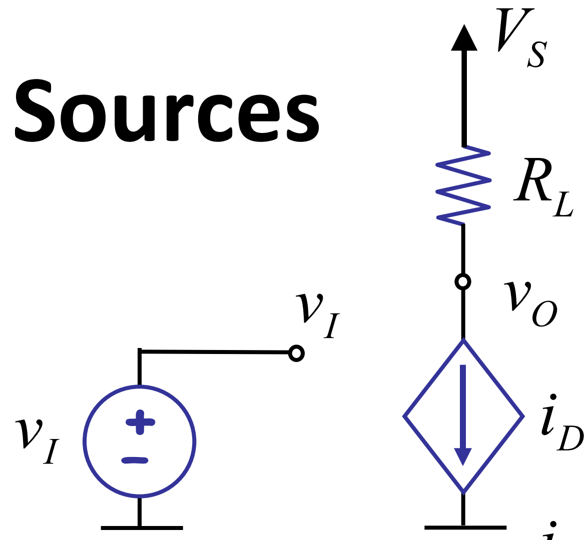

$$i_D = \frac{K}{2}(v_{IN} - 1)^2 \quad \text{for } v_{IN} \geq 1$$

$$i_D = 0 \quad \text{otherwise}$$

Find $v_O$ as a function of $v_I$.

# Dependent Sources

- Example 3




$i_D = \frac{K}{2}(v_{IN} - 1)^2$ for $v_{IN} \geq 1$

$i_D = 0$ otherwise

Find $v_O$ as a function of $v_I$.

KVL

$$-V_S + i_D R_L + v_O = 0$$

$$v_O = V_S - i_D R_L$$

$$\boxed{v_O = V_S - \frac{K}{2}(v_I - 1)^2 R_L \quad \text{for } v_I \geq 1}$$

Hold that thought

$$v_O = V_S \quad \text{for } v_I < 1$$

# Outline

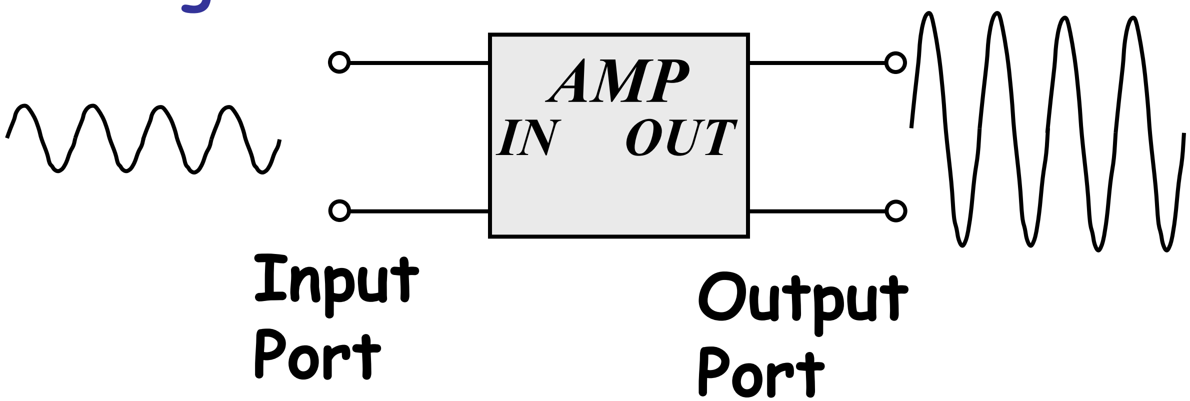
**Textbook: 7.1, 7.2, 7.3, 7.4**

- (Review of) Dependent Sources
- **Why Amplify?**
- **Signal Amplification**
- Actual MOSFET Characteristics
- MOSFET SCS Model

# Why Amplify?

Signal amplification key to both analog and digital processing.

Analog:

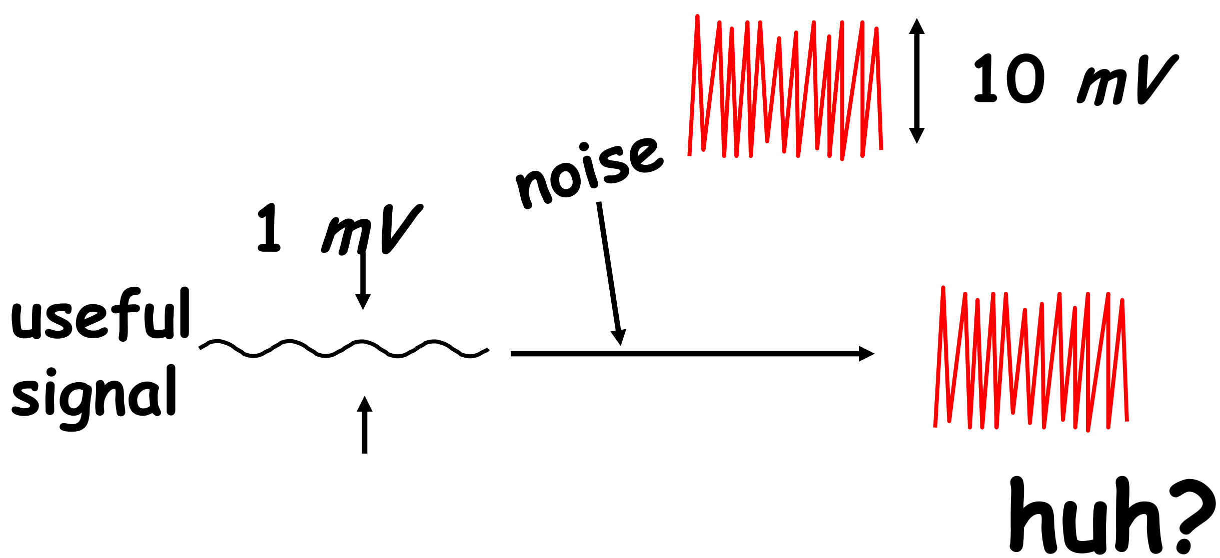



Besides the obvious advantages of being heard farther away, amplification is key to noise tolerance during communcation

# Why Amplify?

Amplification is key to noise tolerance during communcation

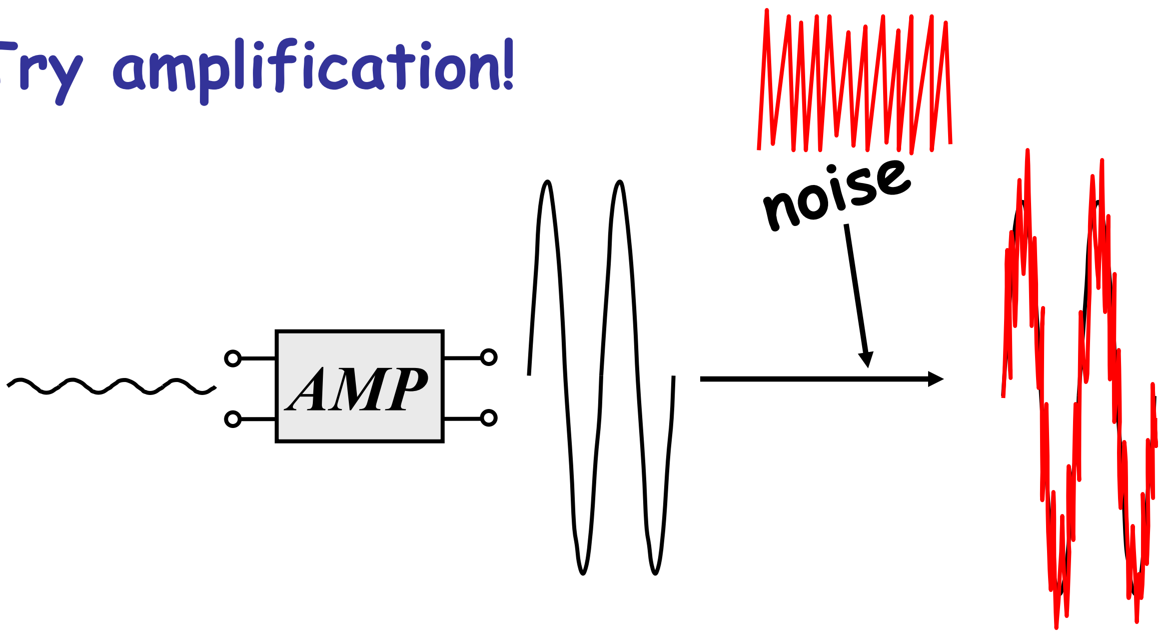
## No amplification



# Why Amplify?

Amplification is key to noise tolerance during communcation

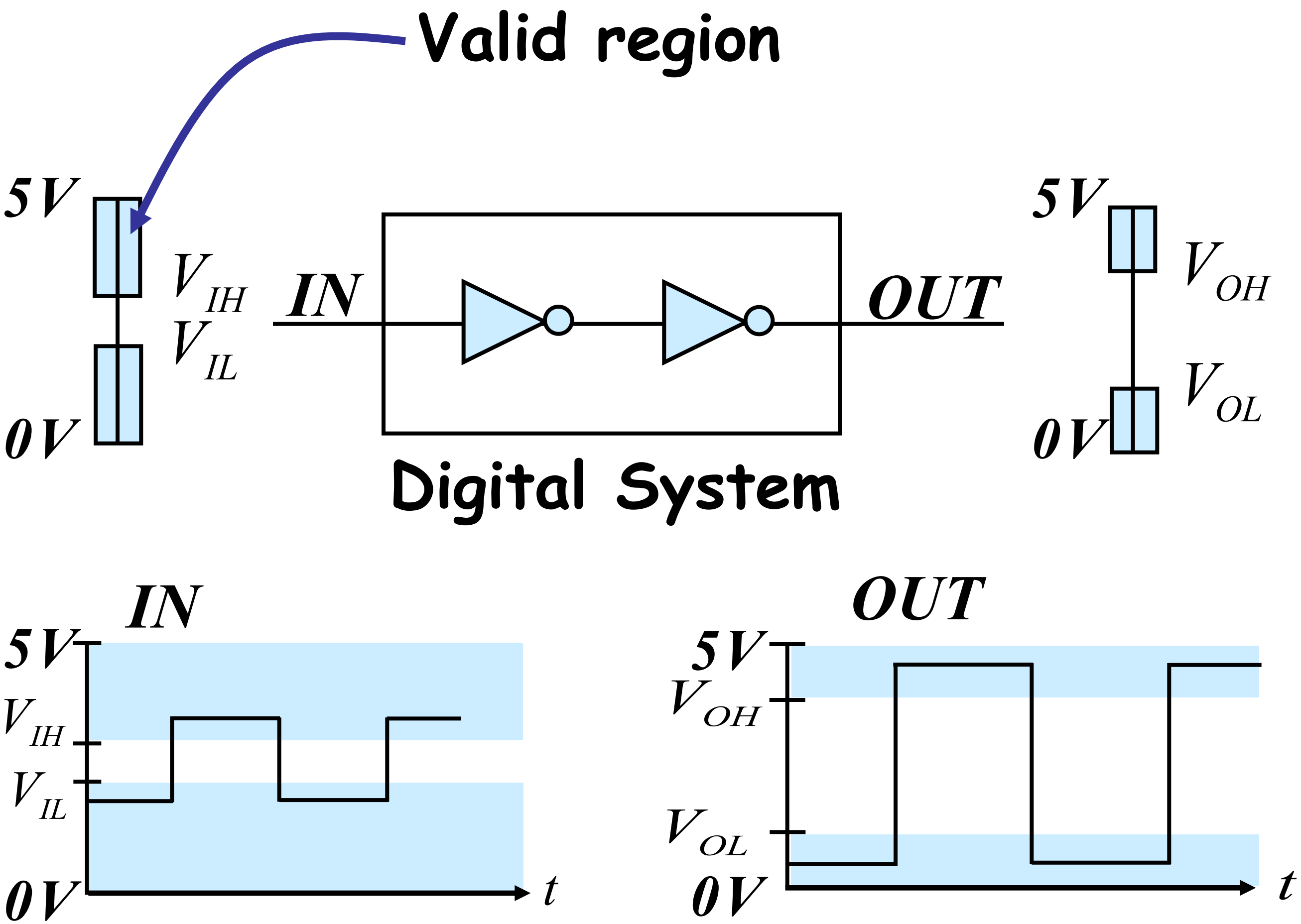
Try amplification!




not bad!

# Why Amplify?

## Digital:

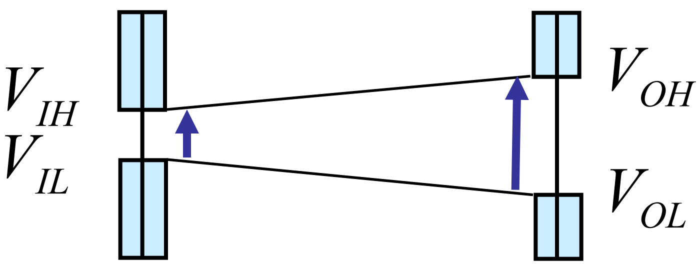


# Why Amplify?

## Digital:

**Static discipline requires amplification!**

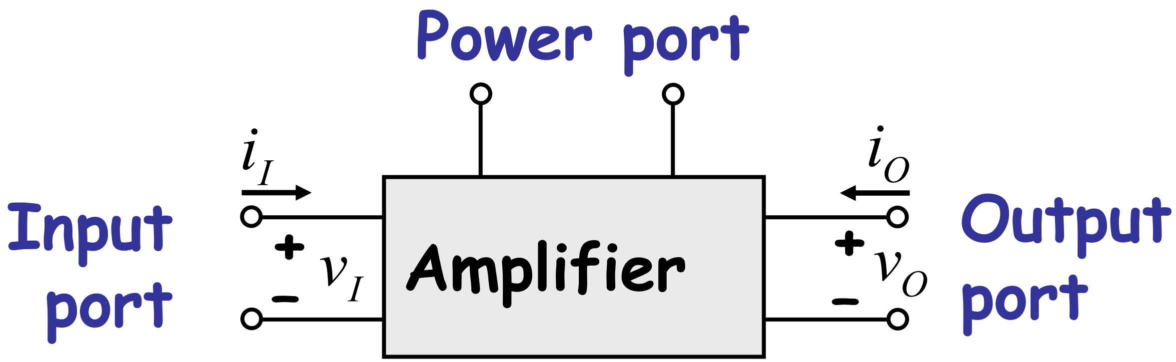
**Minimum amplification (gain) needed:**




$$\frac{V_{OH} - V_{OL}}{V_{IH} - V_{IL}}$$

# Signal Amplification

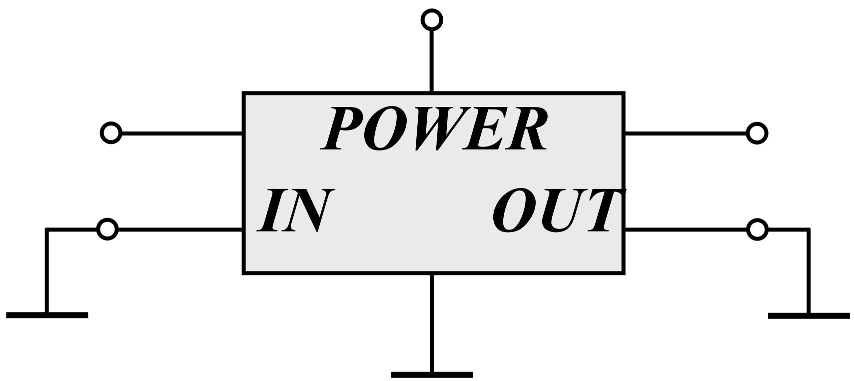
An amplifier is a 3-ported device, actually




We often don't show the power port.

# Signal Amplification

An amplifier is a 3-ported device, actually

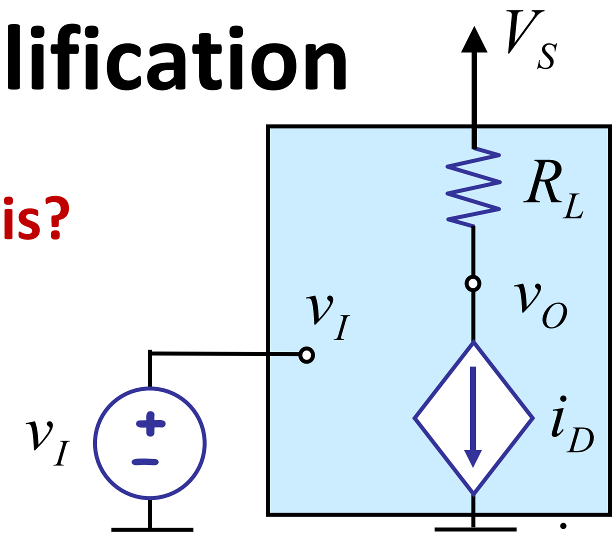



Also, for convenience we commonly observe "the common ground discipline."
In other words, all ports often share a common reference point called "ground."

How do we build one?

# Signal Amplification

- **Remember this?**




$$i_D = \frac{K}{2}(v_{IN} - 1)^2 \quad \text{for } v_{IN} \geq 1$$

$$i_D = 0 \quad \text{otherwise}$$

**Find $v_O$ as a function of $v_I$.**

**KVL**

**Claim:**
**This is an amplifier!**

$$-V_S + i_D R_L + v_O = 0$$

$$v_O = V_S - i_D R_L$$

$$\boxed{v_O = V_S - \frac{K}{2}(v_I - 1)^2 R_L \quad \text{for } v_I \geq 1}$$

$$v_O = V_S \quad \text{for } v_I < 1$$

# Signal Amplification

## So, where's the amplification?

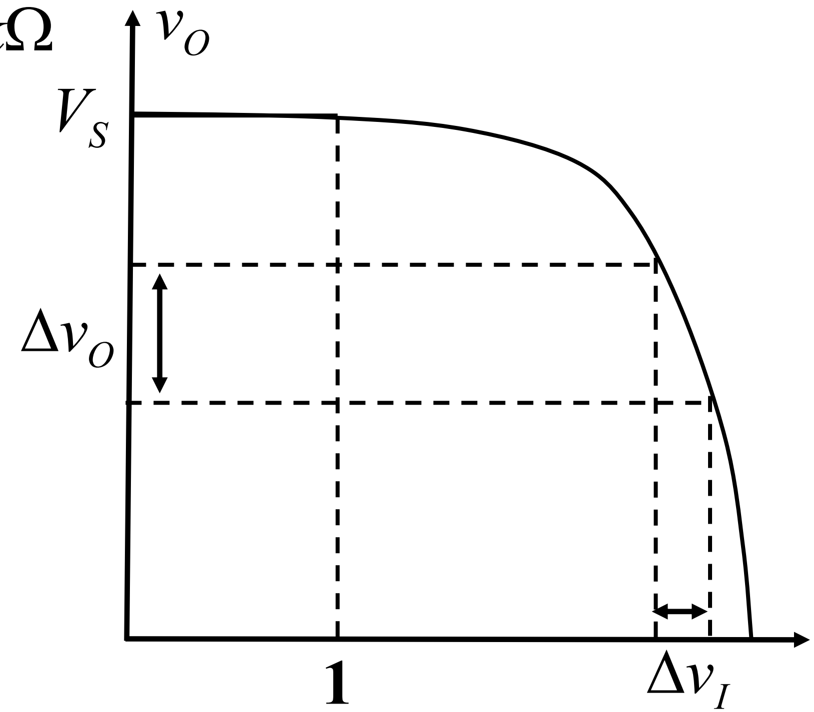
**Let's look at the $v_O$ versus $v_I$ curve.**

**e.g.** $V_S = 10V, \quad K = 2\frac{mA}{V^2}, \quad R_L = 5k\Omega$

$$v_O = V_S - \frac{K}{2} R_L (v_I - 1)^2$$

$$= 10 - \frac{\cancel{2}}{\cancel{2}} \cancel{\cdot 10^{-3}} \cdot 5 \cancel{\cdot 10^{3}} (v_I - 1)^2$$

$$v_O = 10 - 5(v_I - 1)^2$$




$$\frac{\Delta v_O}{\Delta v_I} > 1 \longrightarrow \text{amplification}$$

# Signal Amplification

**So, where's the amplification?**

**Plot $v_O$ versus $v_I$**

$$v_O = 10 - 5\left(v_I - 1\right)^2$$

| $v_I$ | $v_O$ |
|---|---|
| 0.0 | 10.00 |
| 1.0 | 10.00 |
| 1.5 | 8.75 |
| 2.0 | 5.00 |
| 2.1 | 4.00 |
| 2.2 | 2.80 |
| 2.3 | 1.50 |
| 2.4 | ~ 0.00 |

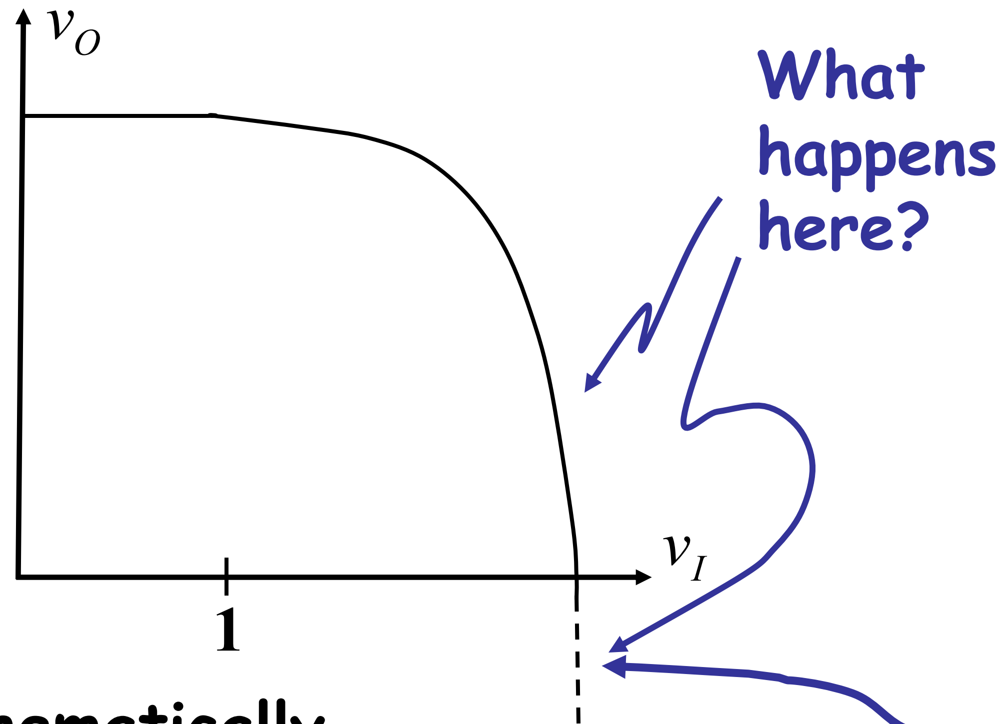
0.1 change in $v_I$

1V change in $v_O$

Gain!

# Signal Amplification

## One nit …




**Mathematically,**

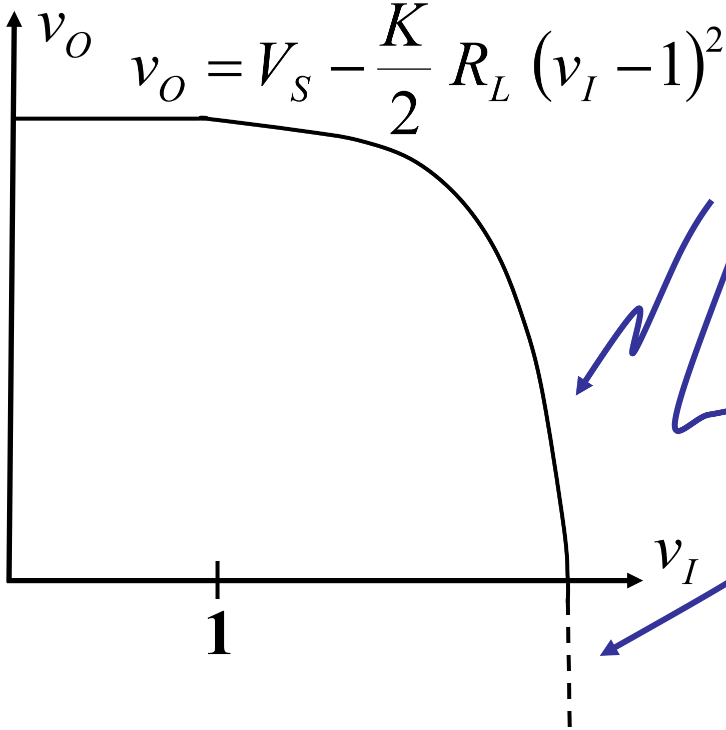
$$v_O = V_S - \frac{K}{2} R_L (v_I - 1)^2$$

**So is mathematically predicted behavior**

# Signal Amplification

## One nit …

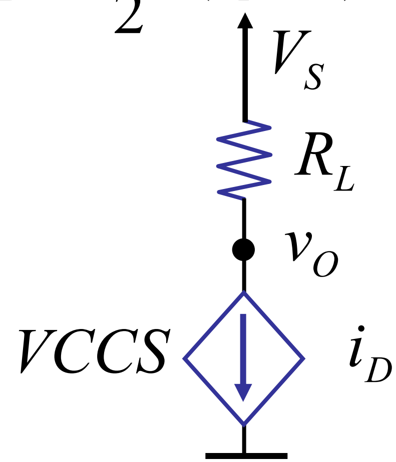
$$v_O = V_S - \frac{K}{2} R_L \left(v_I - 1\right)^2$$




What happens here?

However, from

$$i_D = \frac{K}{2} \left(v_I - 1\right)^2 \quad \text{for} \quad v_I \geq 1$$



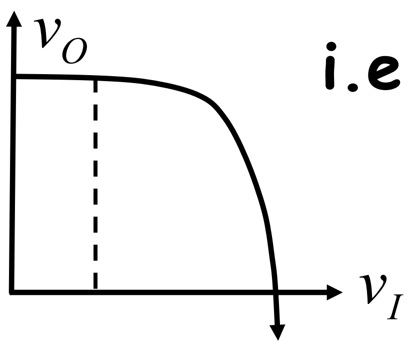

For $v_O > 0$, VCCS consumes power: $v_O i_D$

For $v_O < 0$, VCCS must supply power!

# Signal Amplification

## One nit …

**If VCCS were a device that can source power, then the mathematically predicted behavior could be observed —**




**i.e.** $v_O = V_S - \frac{K}{2} R_L \left(v_I - 1\right)^2$

**where $v_O$ goes *negative***

# Signal Amplification

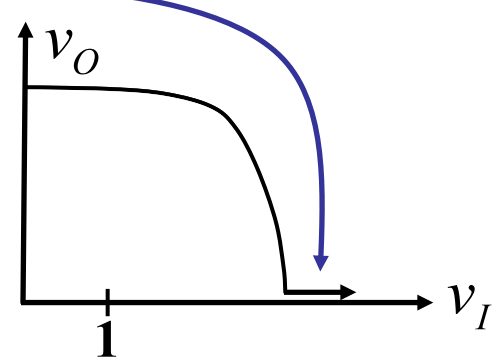
## One nit ...

If VCCS is a passive device,
then it cannot source power,
so $v_O$ cannot go negative.

Turns out, our model breaks down.

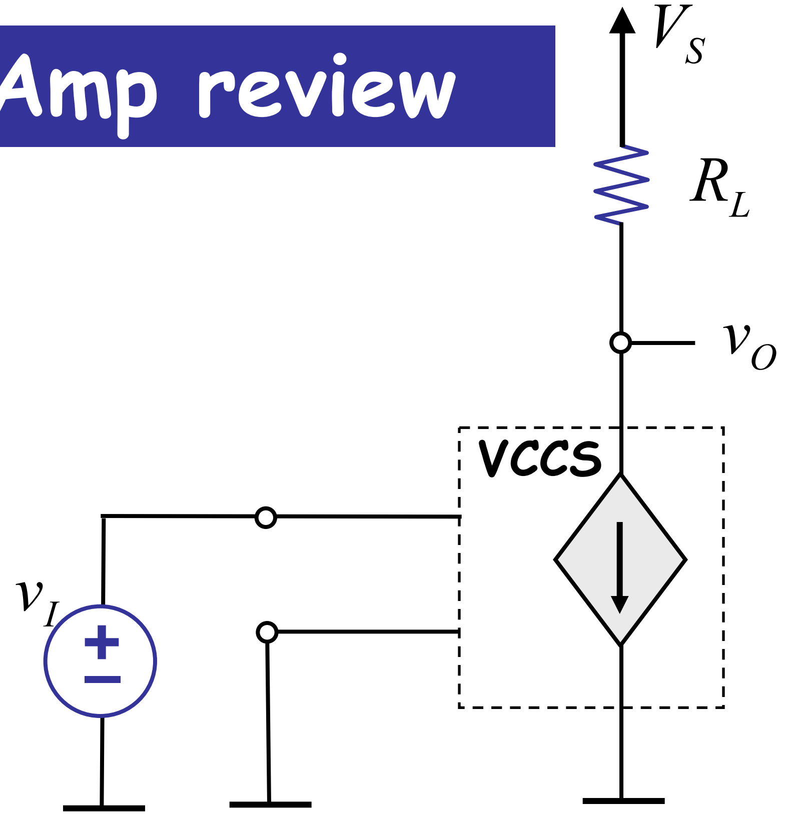
Commonly $i_D = \frac{K}{2}(v_I - 1)^2$

will no longer be valid when $v_O \leq 0$ .
e.g. $i_D$ saturates (stops increasing)
and we observe:



# Signal Amplification

## Amp review




$$i_D = \frac{K}{2}(v_I - 1)^2 \quad \textbf{for } v_I \geq 1V$$

$$= 0 \quad \textbf{otherwise}$$

$$v_O = V_S - i_D R_L$$

$$\frac{K}{2}(v_I - 1)^2$$

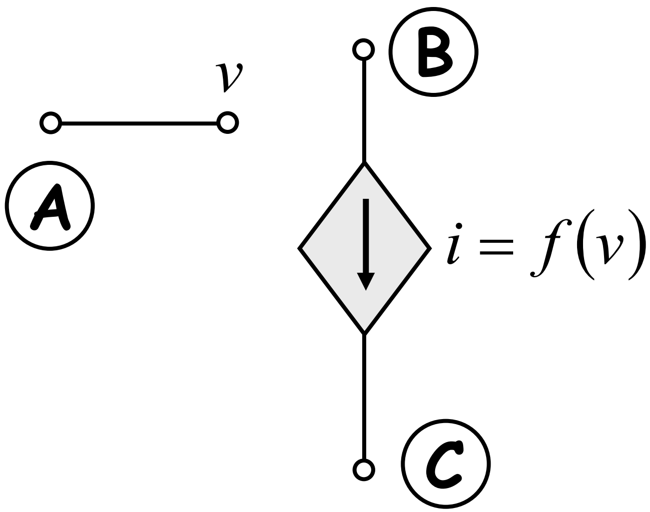
# Outline

**Textbook: 7.1, 7.2, 7.3, 7.4**

- (Review of) Dependent Sources
- Why Amplify?
- Signal Amplification
- **Actual MOSFET Characteristics**
- **MOSFET SCS Model**

# Actual MOSFET Characteristics

## Key device Needed:



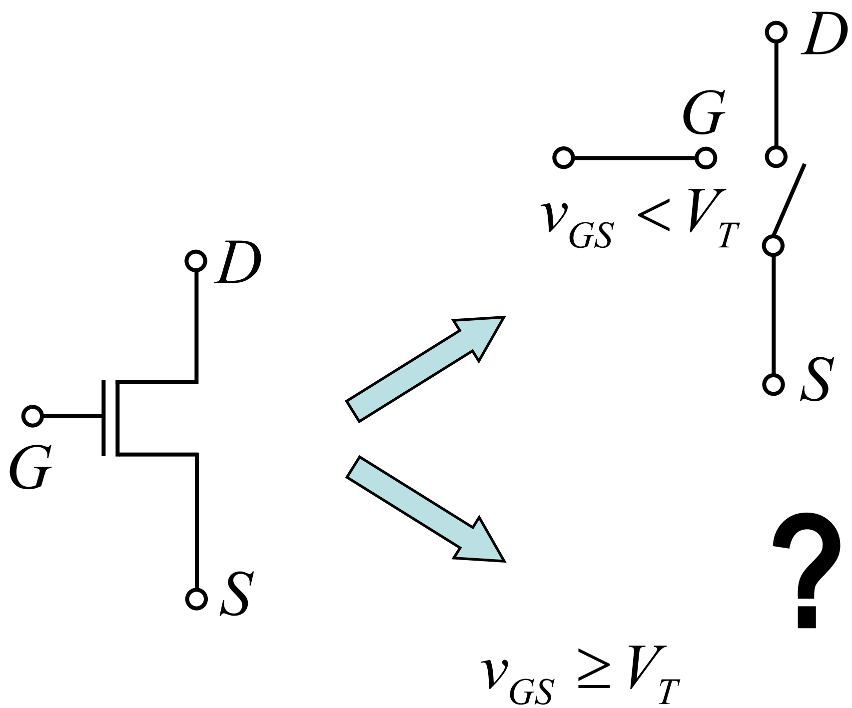

voltage controlled current source

Let's look at our old friend, the MOSFET …

# Actual MOSFET Characteristics

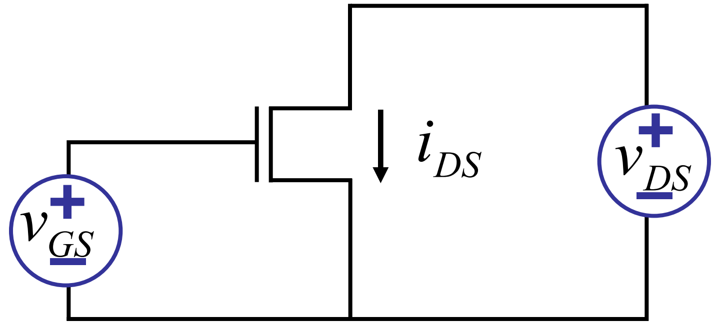
## Key device Needed:

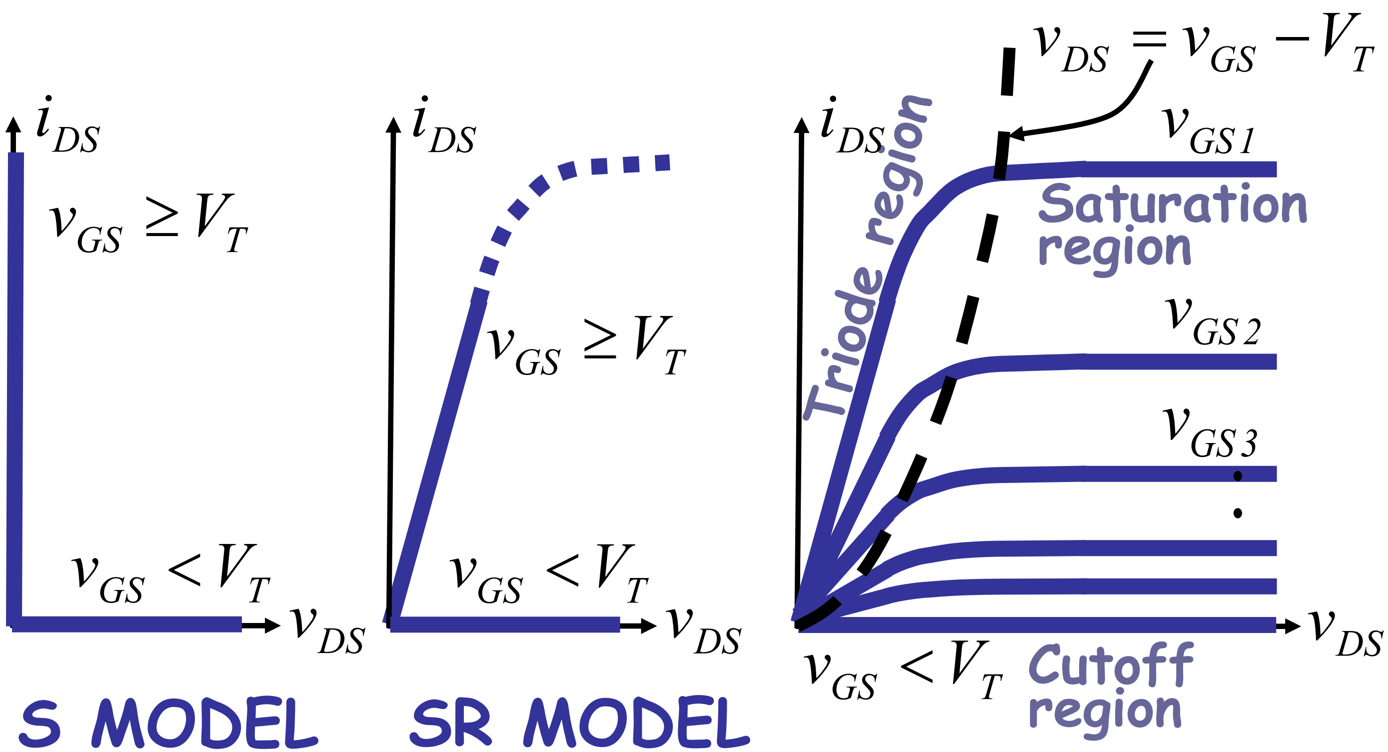
**Our old friend, the MOSFET …**
**First, we sort of lied. The on-state behavior of the MOSFET is quite a bit more complex than either the ideal switch (S) or the resistor (SR) model.**



# Actual MOSFET Characteristics

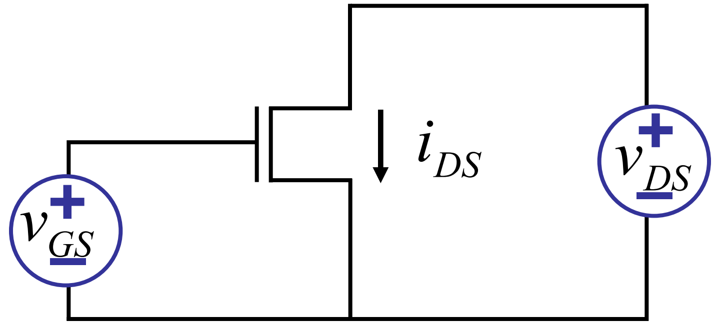
## Graphically



# Actual MOSFET Characteristics

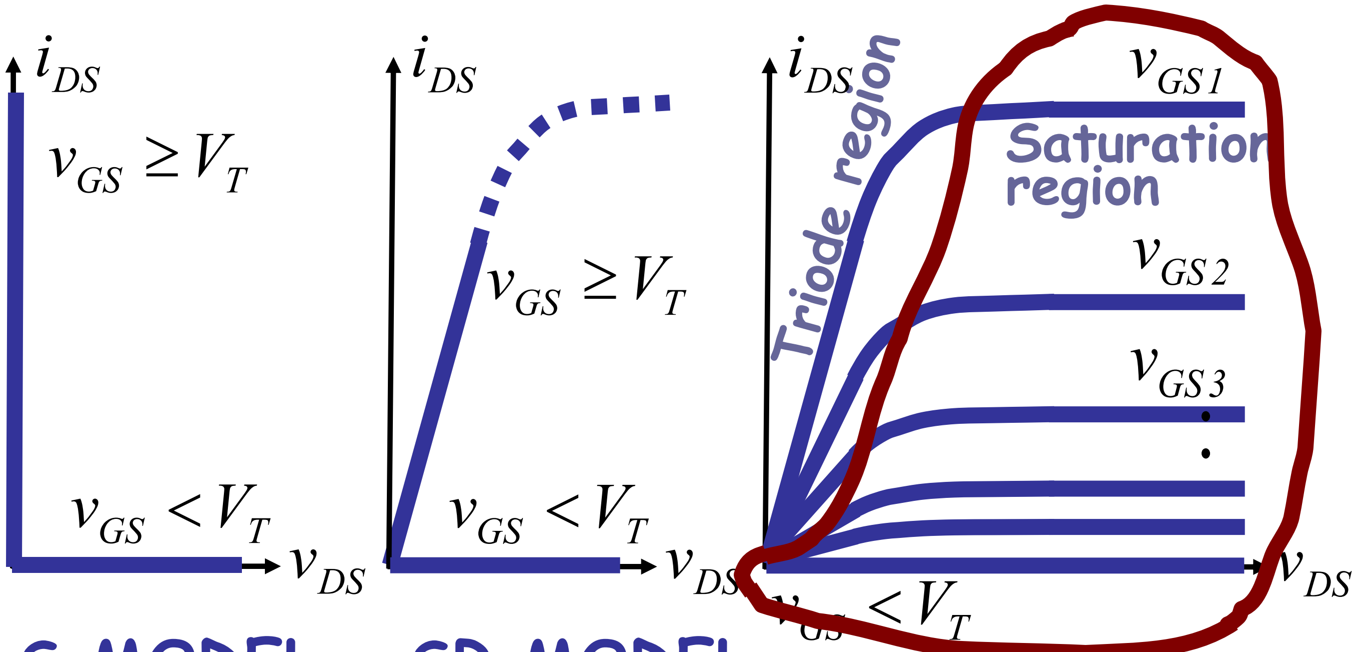
## Graphically




when

$v_{DS} \geq v_{GS} - V_T$

Notice that MOSFET behaves like a current source

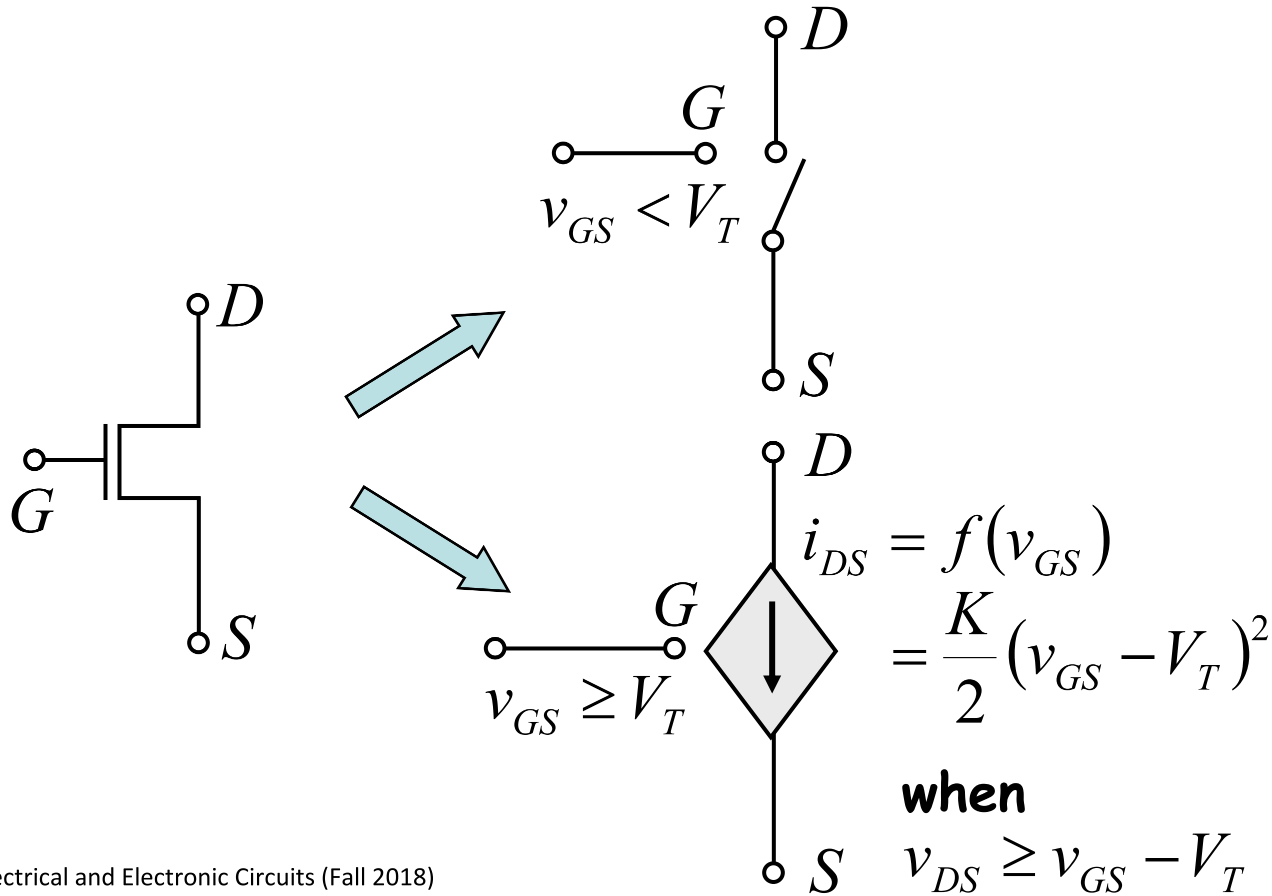



S MODEL SR MODEL

# MOSFET SCS Model

- **SCS Model: Switched Current Source Model**
  - Saturation region of operation: “saturation principle”

**When** $v_{DS} \geq v_{GS} - V_T$



# MOSFET SCS Model

- **Reconciling the models**