The MOSFET Switches
Key Devices Inside the Digital Gate

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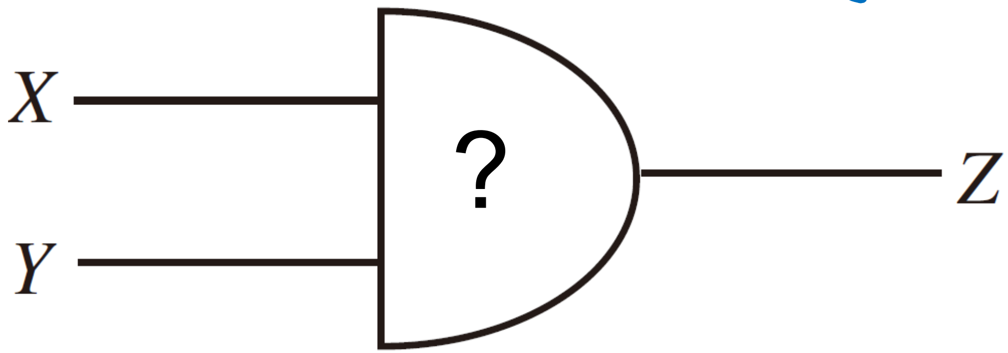
Inside the Digital Gate

- What kinds of elements and the circuits are inside the digital gate?

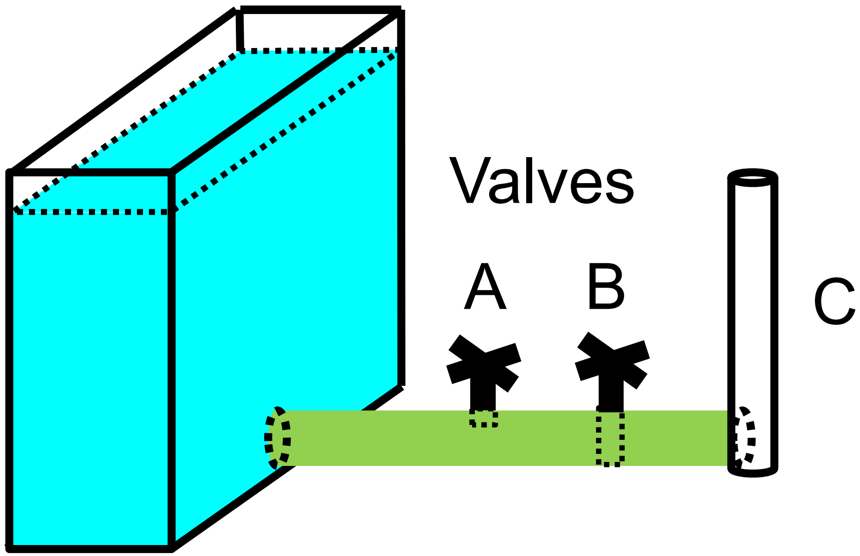
$Z = X \cdot Y$



How to build an AND gate

- Water Analogy

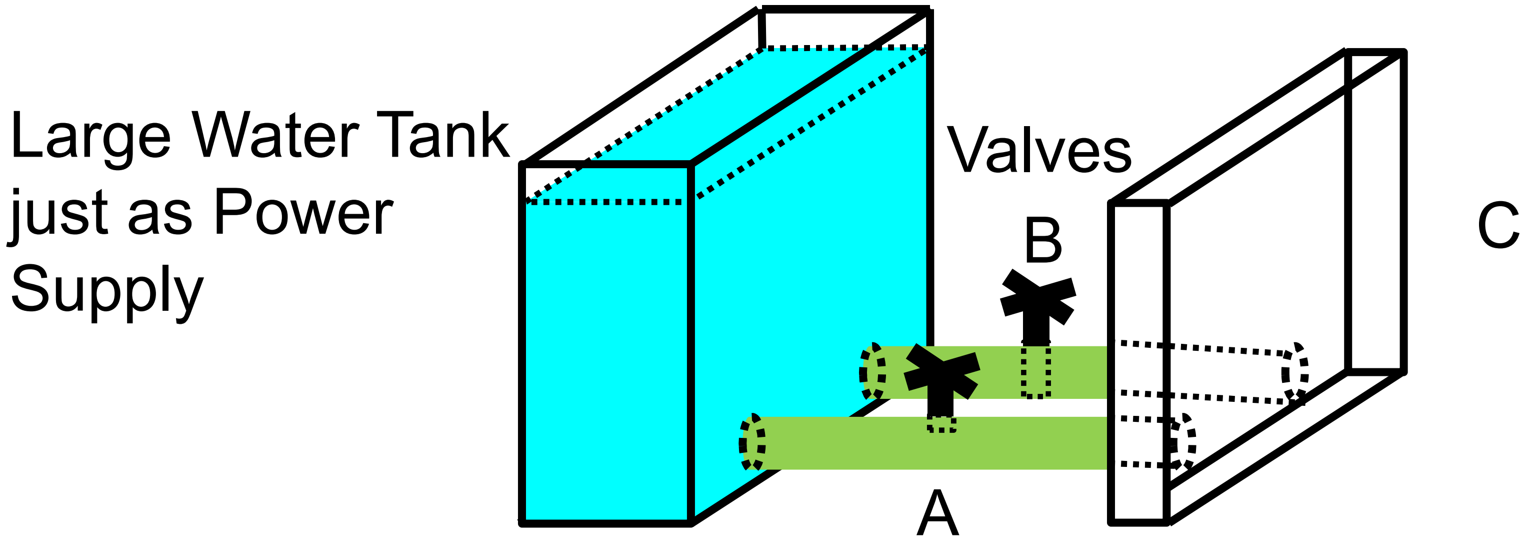
Large Water Tank just as Power Supply



- If A is open AND B is open, then C has water else C has no Water.
- Similarly, we can use this insight to build an AND gate.

How to build an OR gate

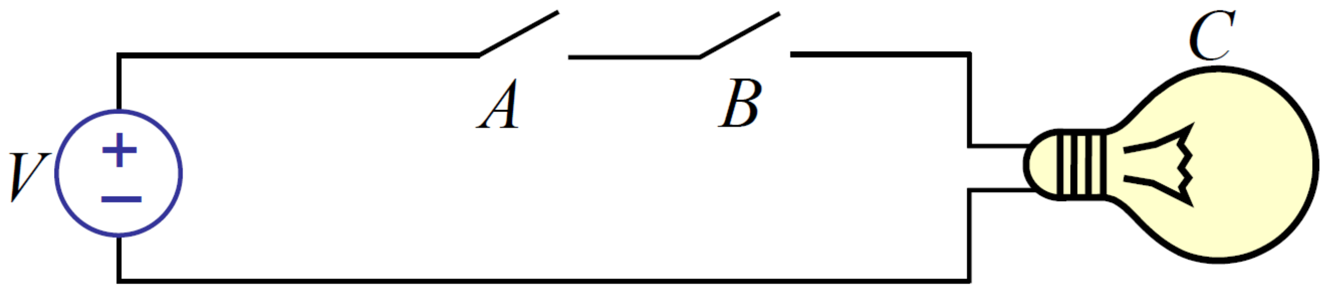
- Water Analogy



- If A is open OR B is open, then C has water else C has no Water.
- Similarly, we can use this insight to build an OR gate.

How to build an AND gate

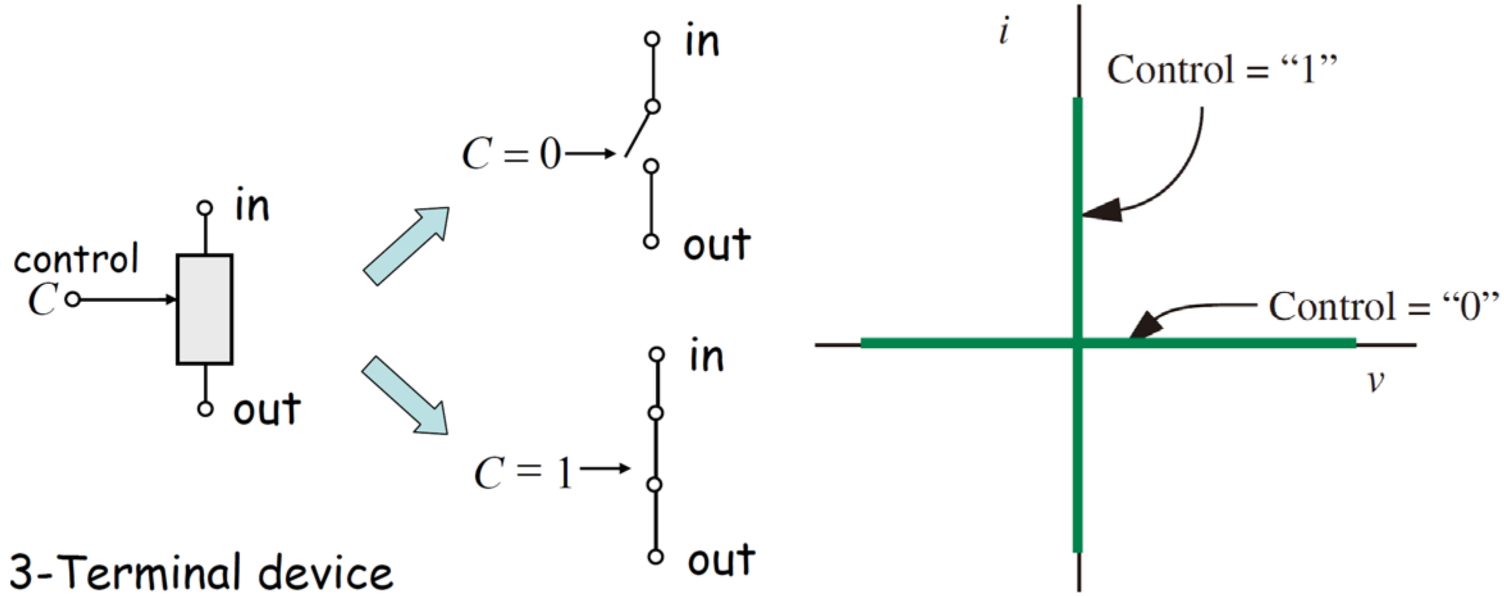
- Electrical Analogy



- If A is closed AND B is closed, then C is lighted else C is darken.
- ***Switch*** is the ***Key device***.

The Three-terminal Switch

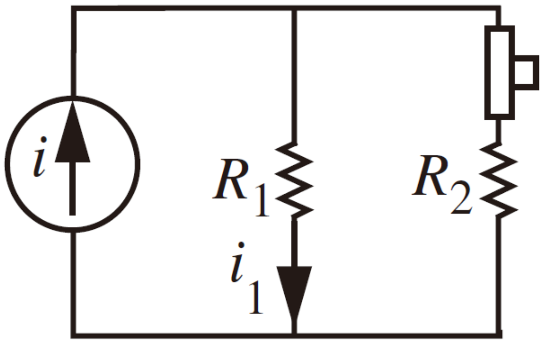
- Three-terminal switch model.



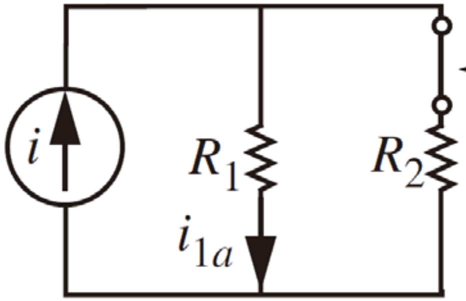
- If **C = 1, *short circuit*** between in and out, else **(C = 0) *open circuit*** between in and out.
- For mechanical switch, Control (C) means the mechanical pressure.

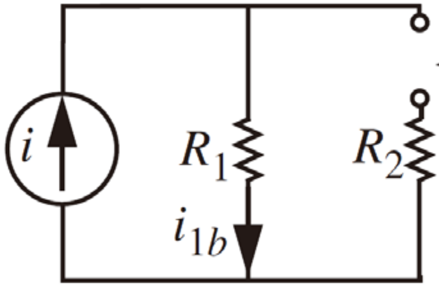
Example

- Find the current through R_1.



- If **C = 1,** R_2 is connected to the circuit. If **C = 0**, R_2 is disconnected from the circuit.



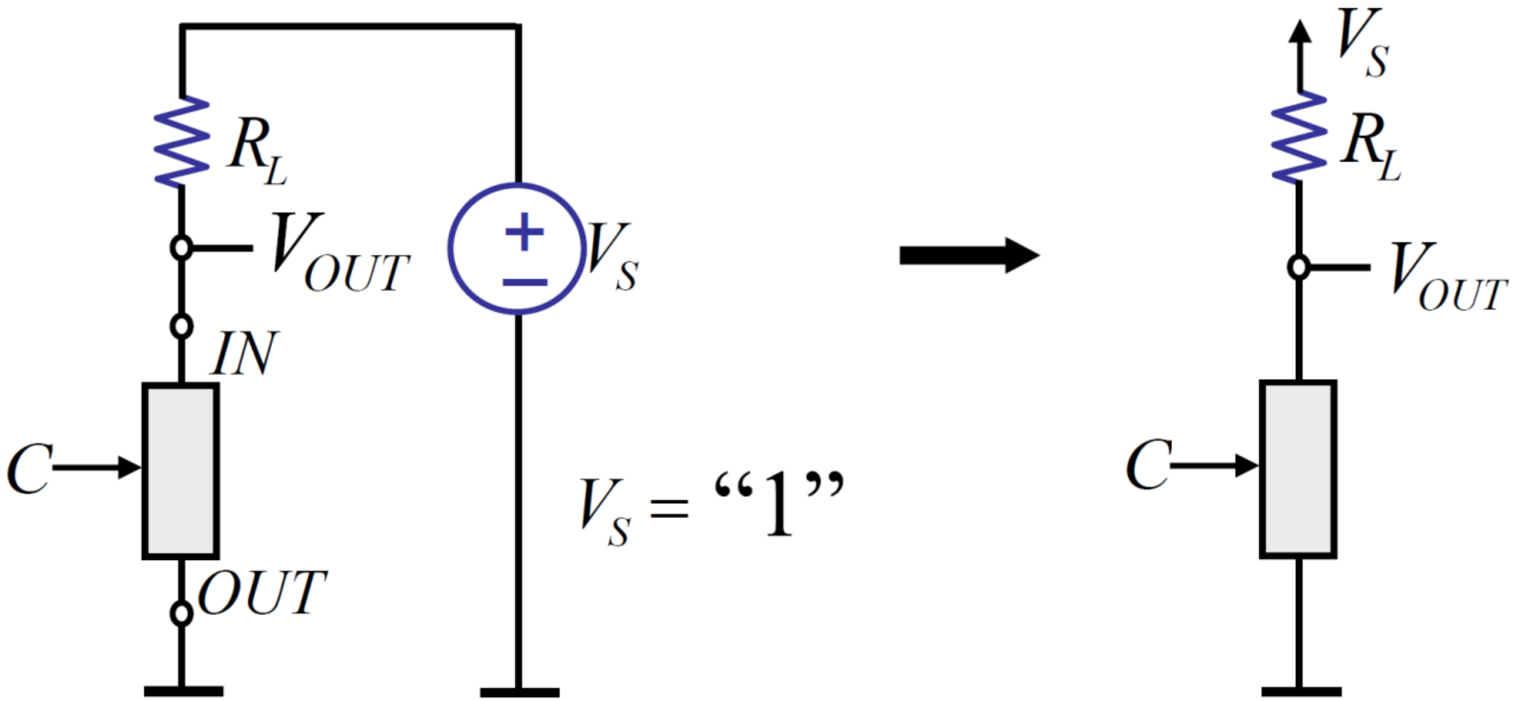


- $i_{1a} = \frac{R_2}{R_1 + R_2} I$

$i_{1b} = I$

Logic Function Using Switches

- The Inverter Circuit.
- This is a very common circuit topography which we will encounter over and over again. We have a special short hand for this kind of circuit.



The Inverter

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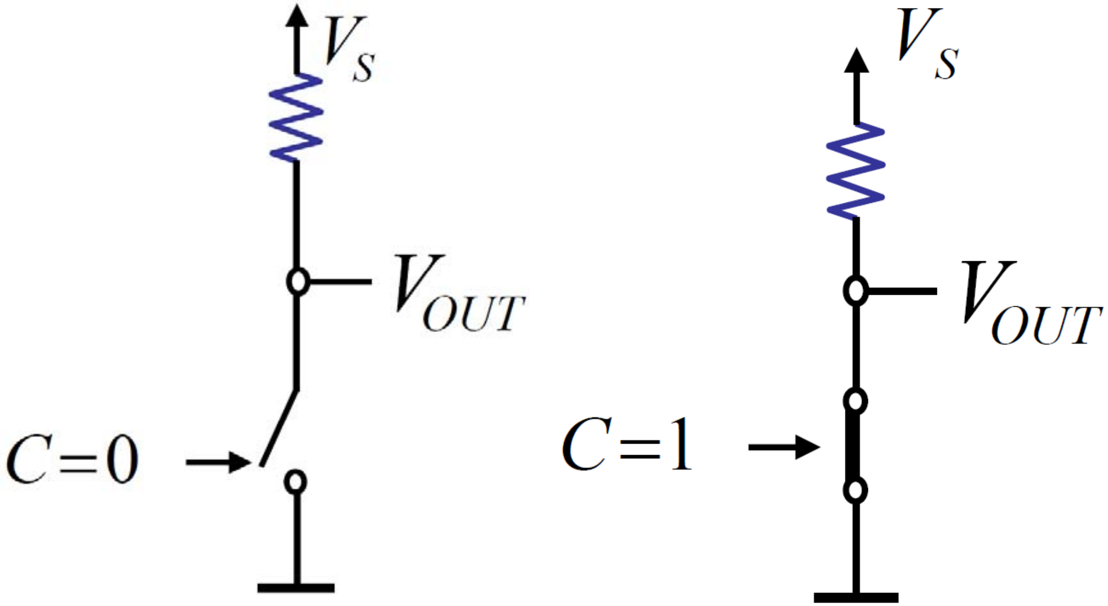
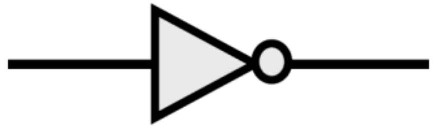
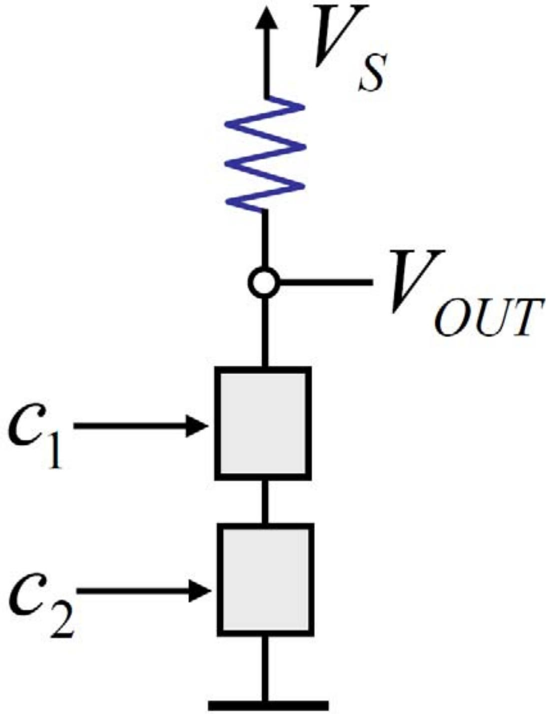


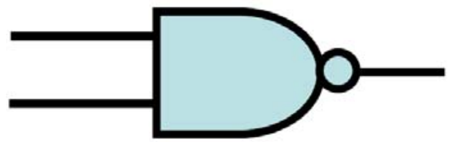


C	V_{OUT}
0	1
1	0

If C = 0, then V_{out} = 1
else (C = 1) V_{out} = 0.

The NAND Gate

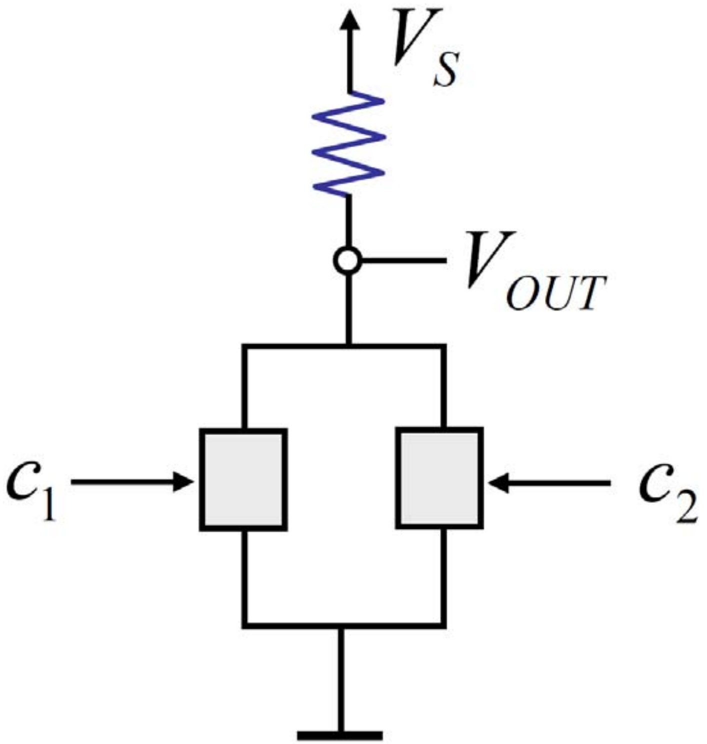


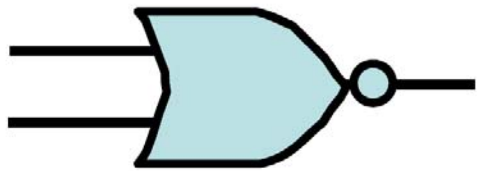


c_1	c_2	V_O
0	0	1
0	1	1
1	0	1
1	1	0

If c_1 = 1 AND c_2 = 1 , then V_{out} = 0
Else V_{out} = 1.

The NOR Gate

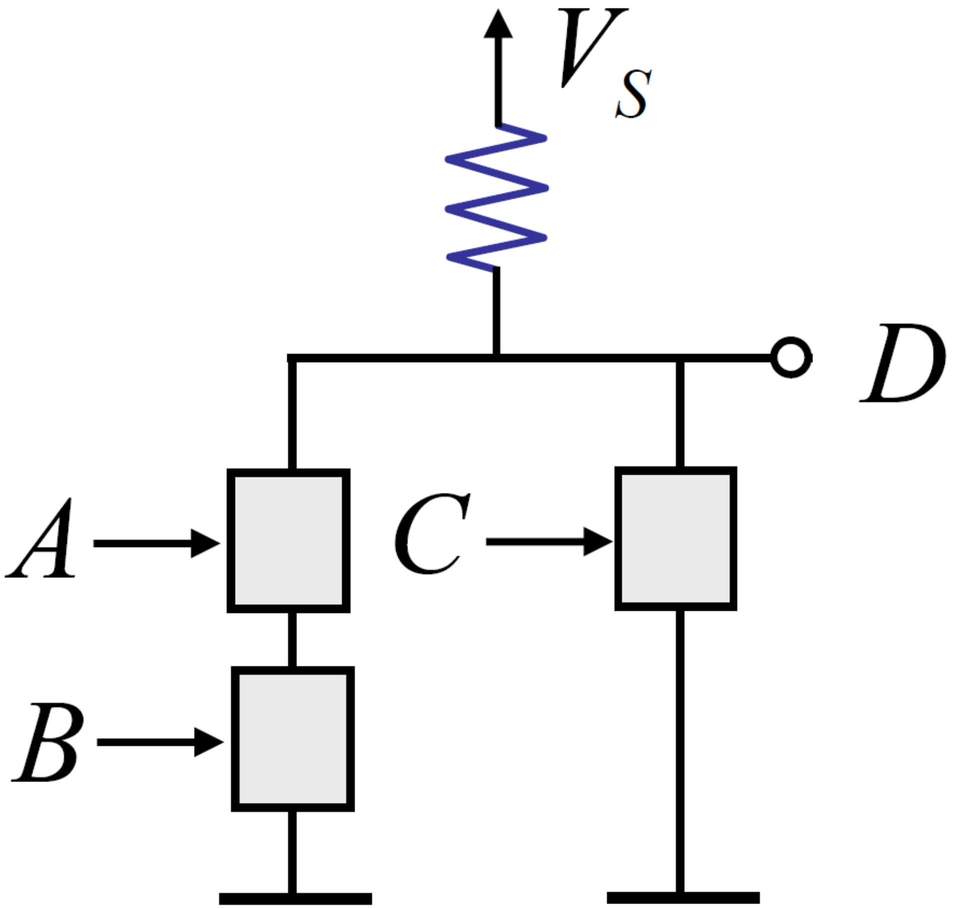




c_1	c_2	V_O
0	0	1
0	1	0
1	0	0
1	1	0

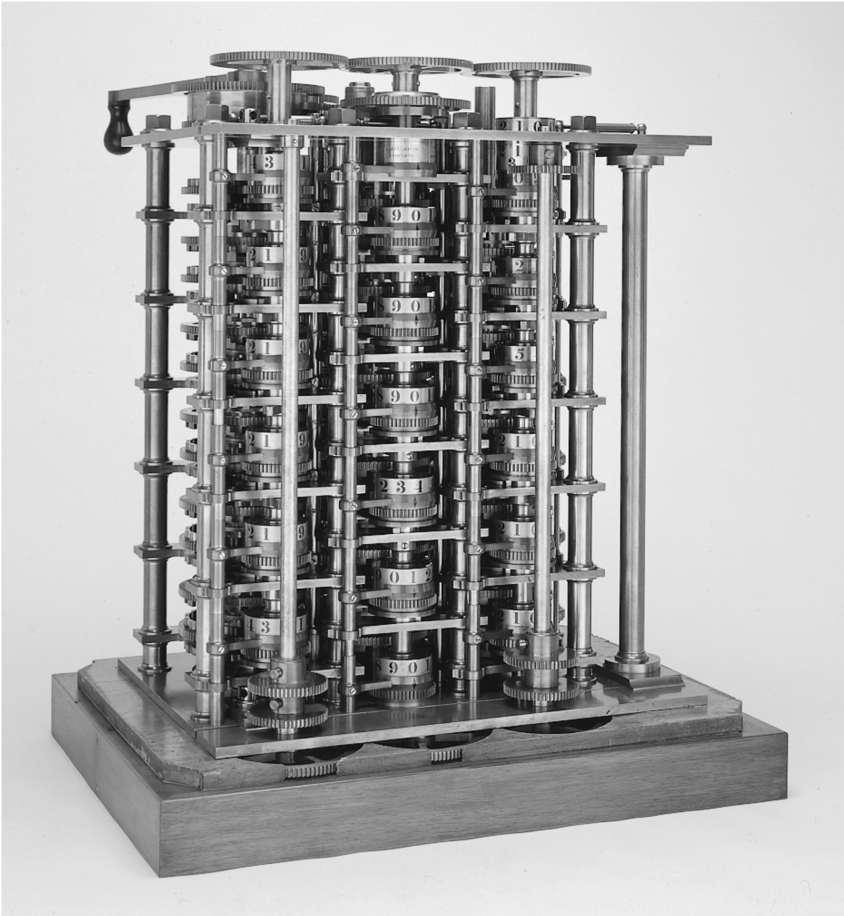
If c_1 = 0 AND c_2 = 0 , then V_{out} = 1
Else V_{out} = 0.

A Complex Gate



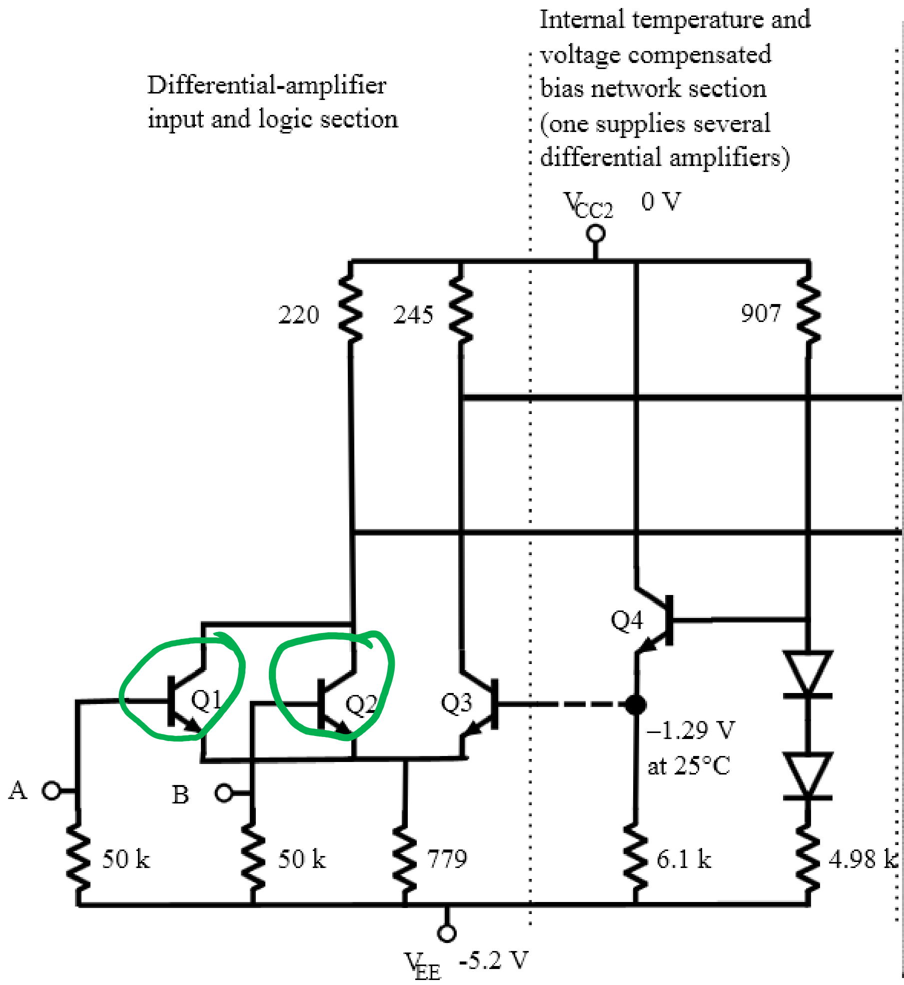
$$D = \overline{(A \cdot B) + C}$$

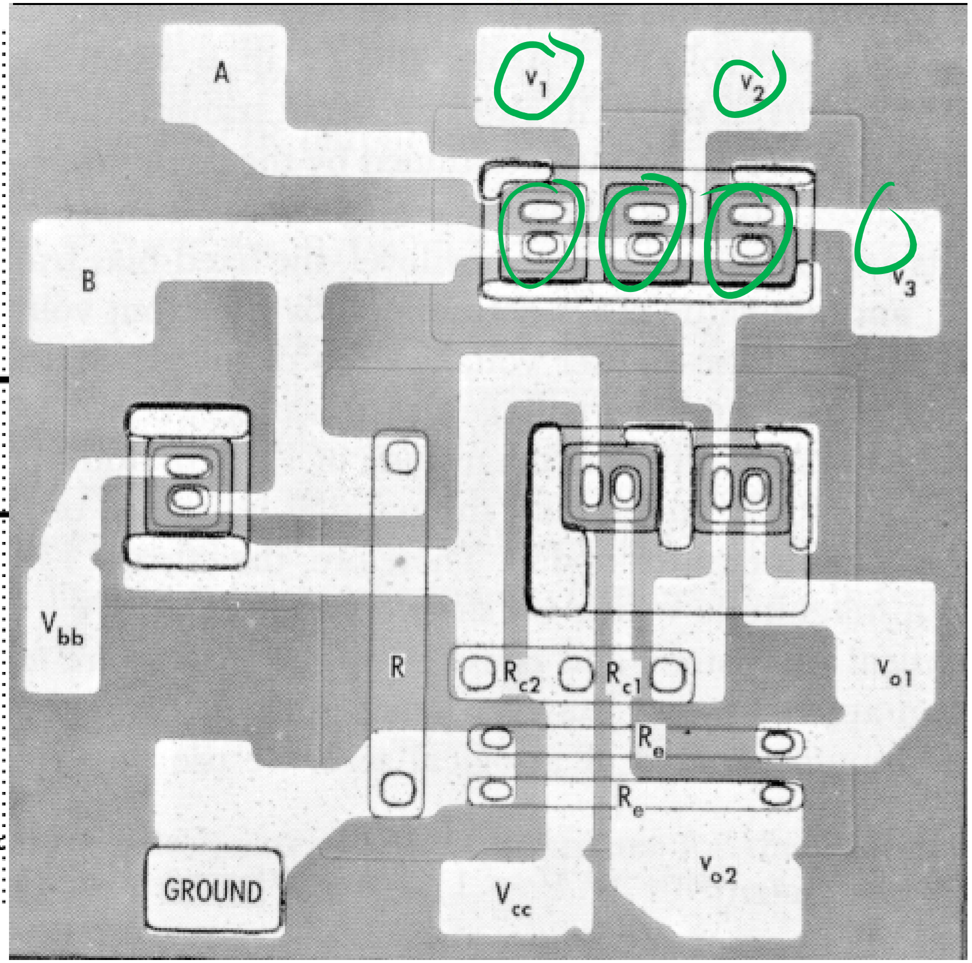
The Babbage Difference Engine



- 25,000 parts, cost: £17,470

3 Input NOR Gate





- Bipolar logic, 1960's, ECL 3-input NOR Gate, Motorola 1966

3 Input NOR Gate

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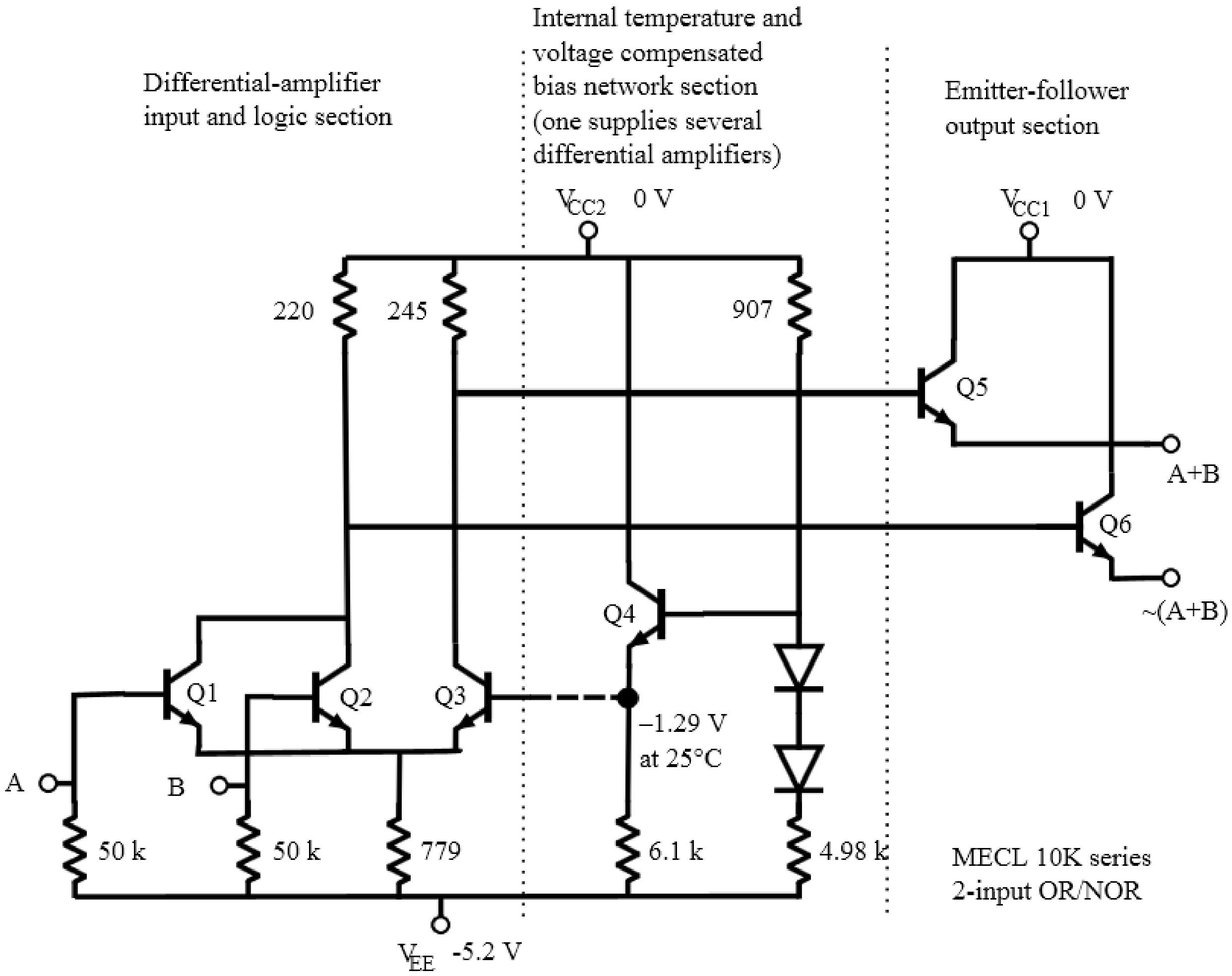
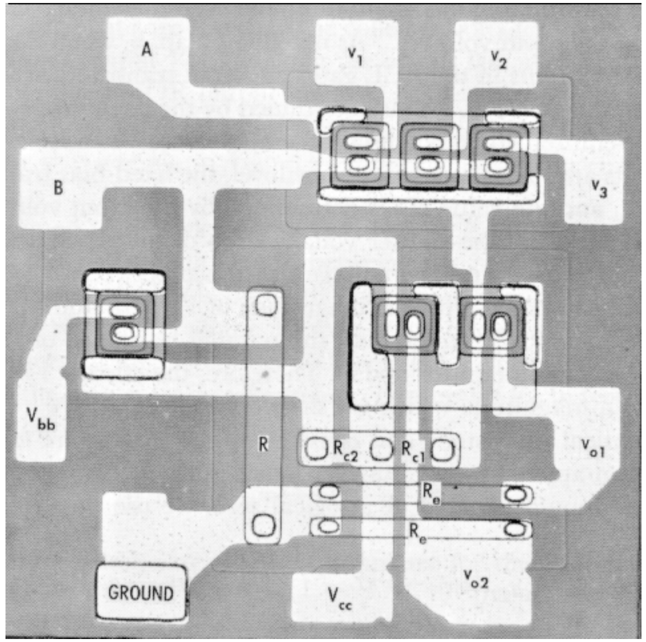
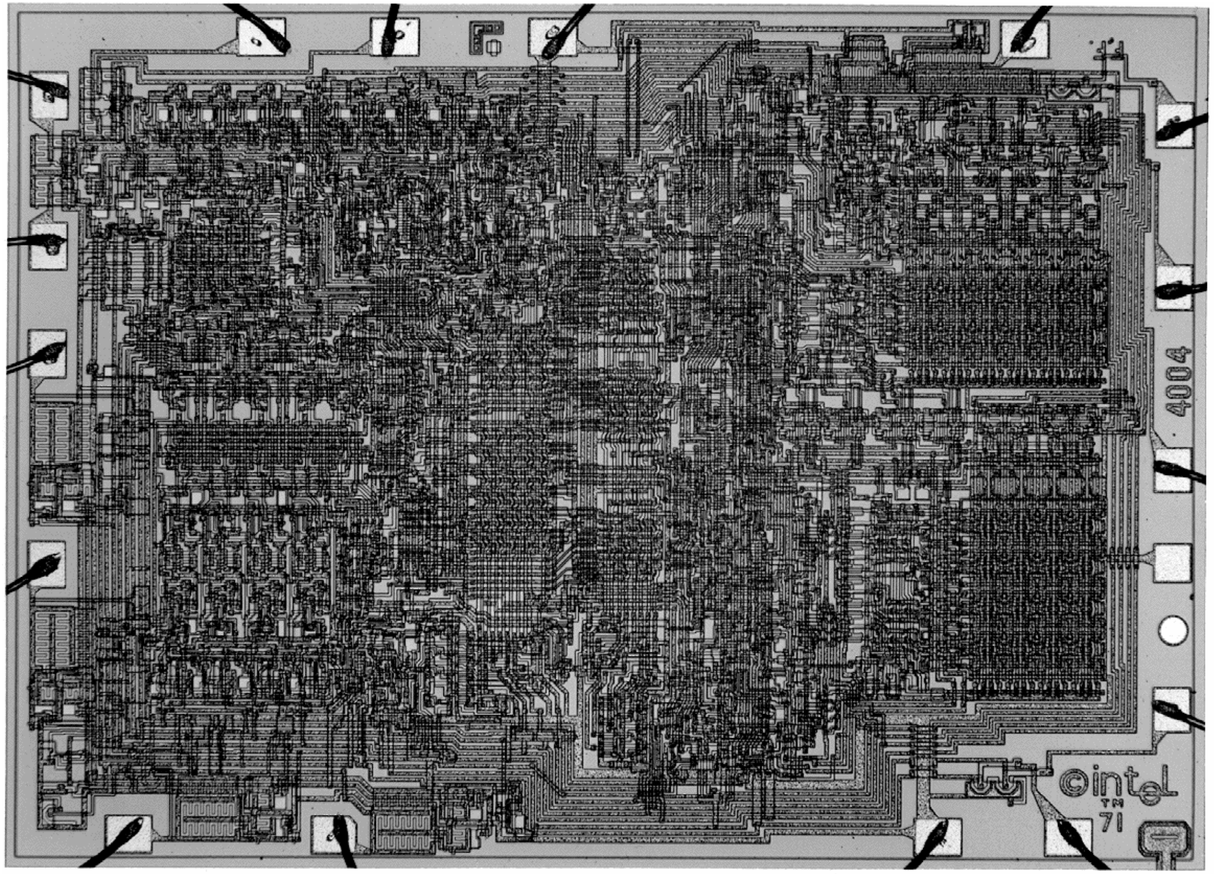




- Bipolar logic, 1960's, ECL 3-input NOR Gate, Motorola 1966

Intel 4004 Microprocessor



- Intel, 1971, 2,300 transistors (12mm^2), 740 KHz operation, (10μm PMOS technology)

Intel Core 2 Microprocessor

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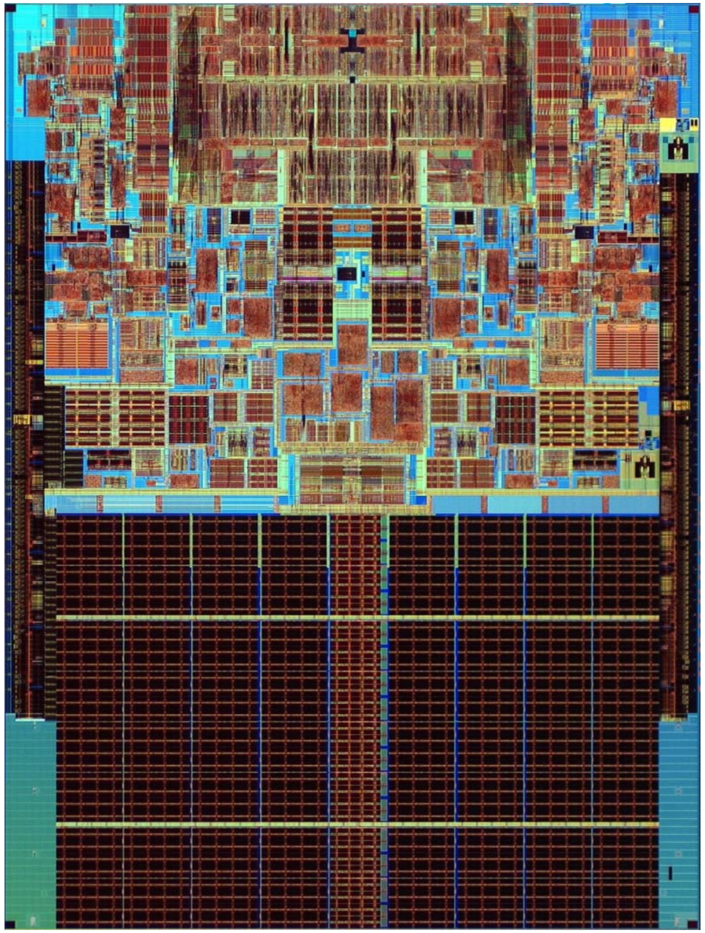
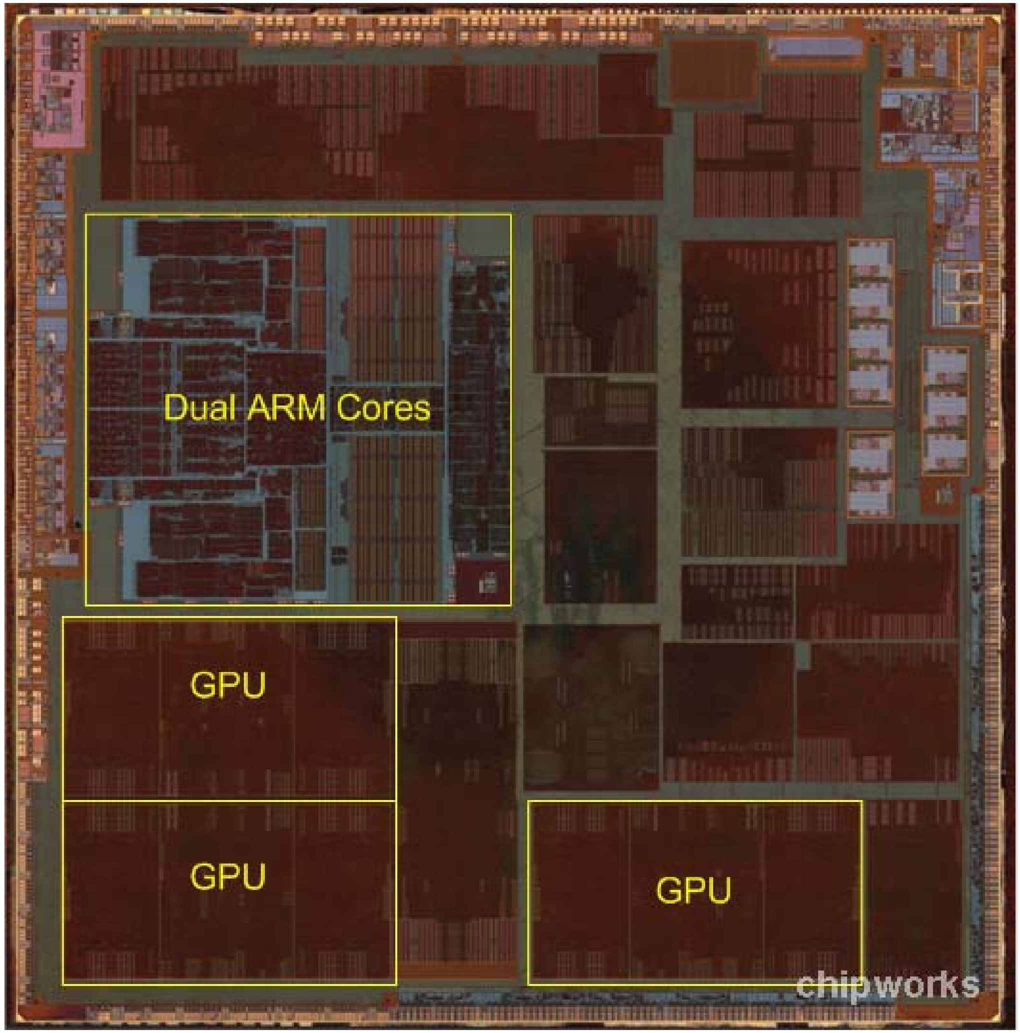


- Intel, 2006, 291,000,000 transistors, ($143mm^2$), 3 GHz operation, (65nm CMOS technology)

Apple A6 Microprocessor



- Apple, 2012, (96.7mm^2), (32nm CMOS technology)

Apple A10 Microprocessor

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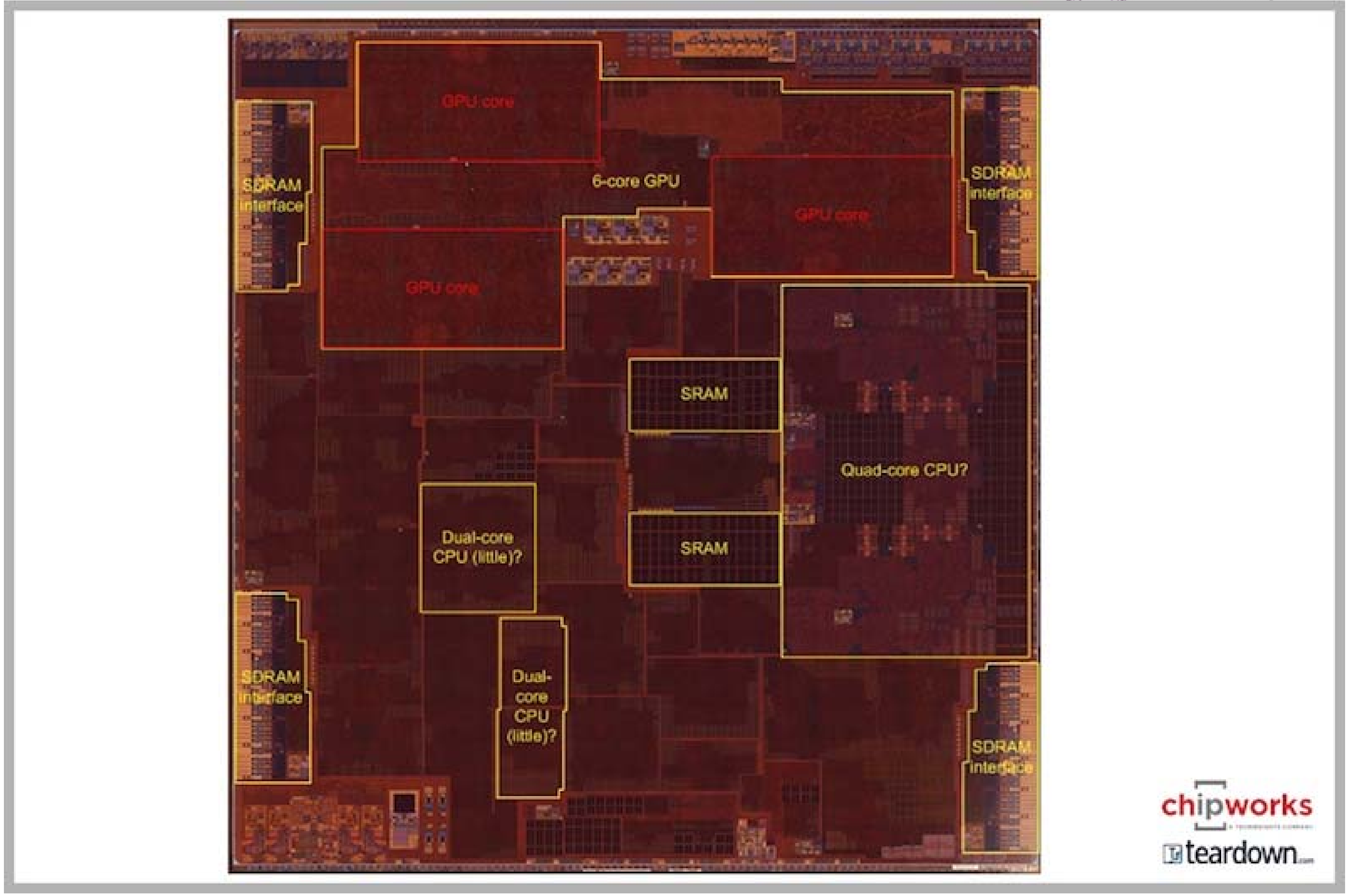
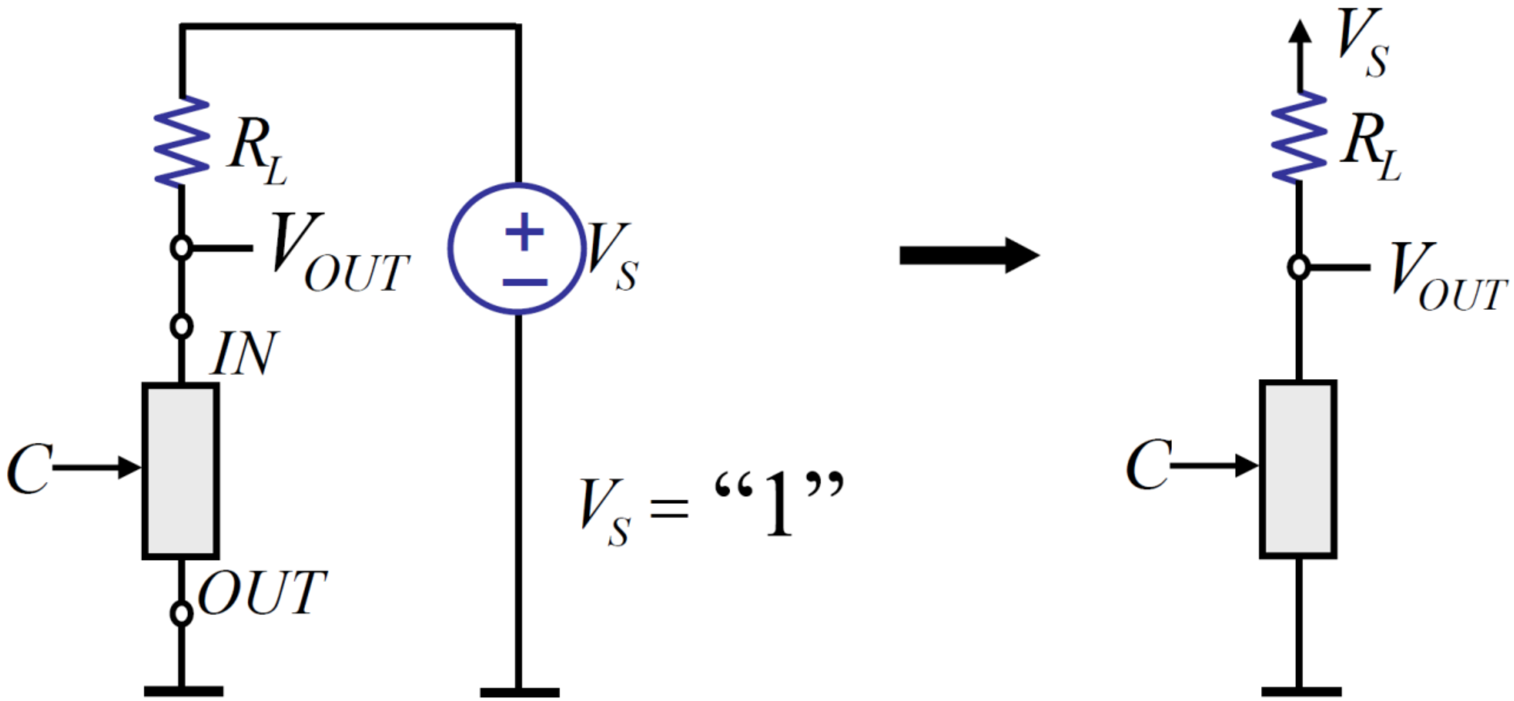


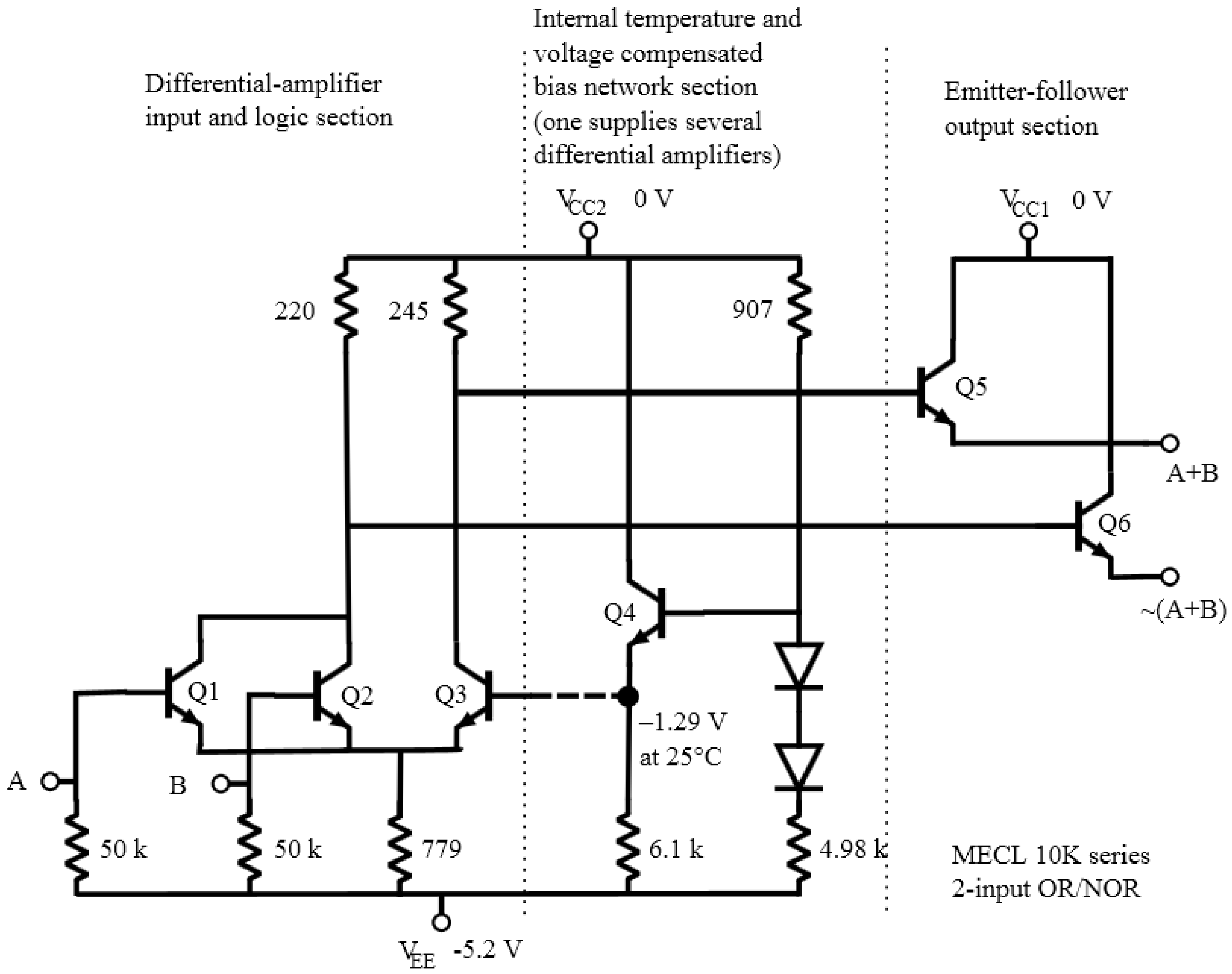
- Apple, 2016, (125 mm^2), (16nm FinFET CMOS technology)

Logic Function Using Switches

- The Inverter Circuit.
- This is a very common circuit topography which we will encounter over and over again. We have a special short hand for this kind of circuit.



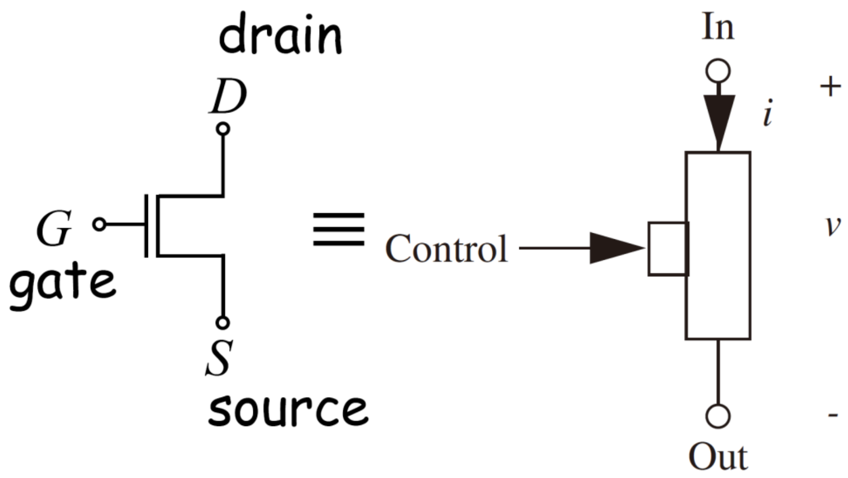
3 Input NOR Gate

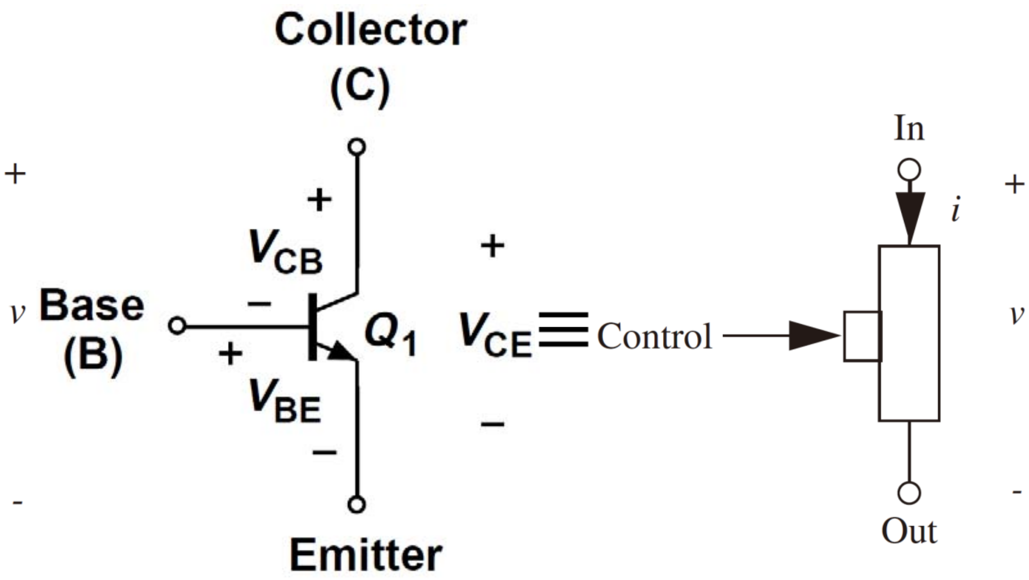


- iBpolar logic, 1960's, ECL 3-input NOR Gate, Motorola 1966

The Semiconductor Switches

- Two kinds of semiconductor switches: MOSFET and BJT
- Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)
- Bipolar Junction Transistor (BJT)





MOSFET BJT

- 3 terminal lumped element behaves like a switch with Gate (G) or Base (B) as control terminal and Drain (D) to Source (S) or Collector (C) to Emitter (E) as in and out port.

The BJT and MOSFET

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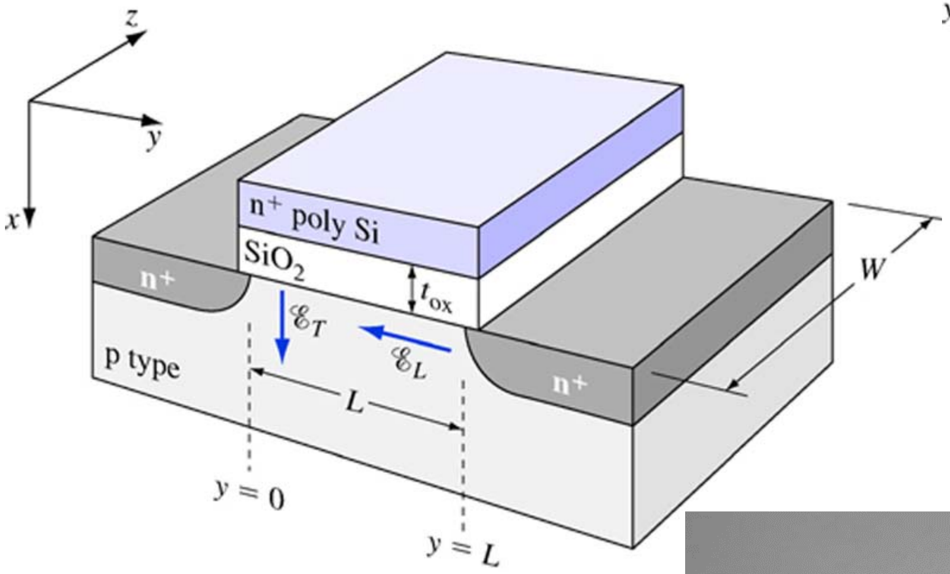
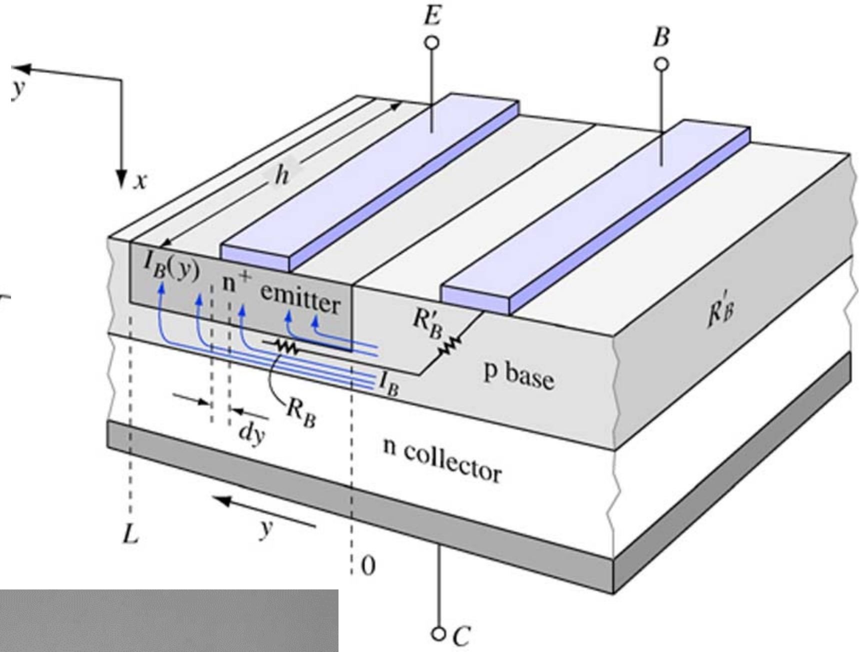
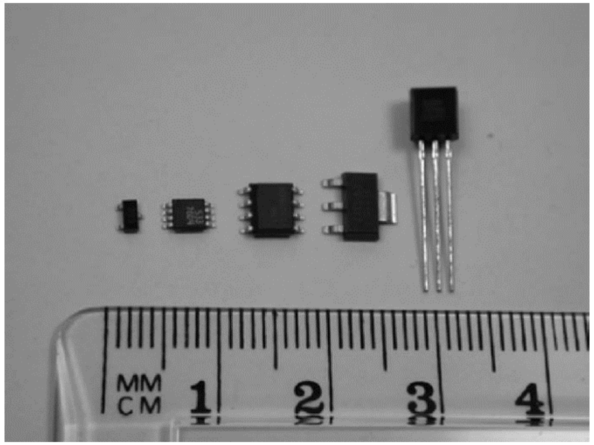
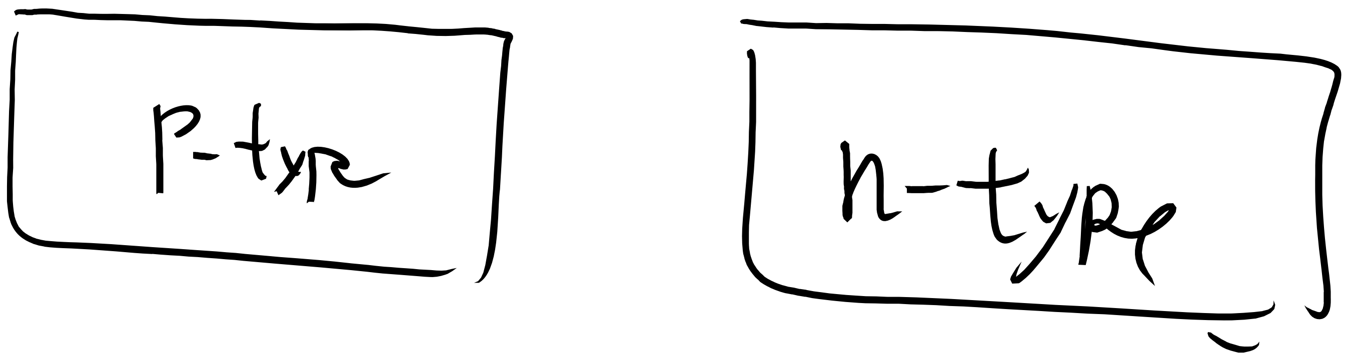


MOSFET





BJT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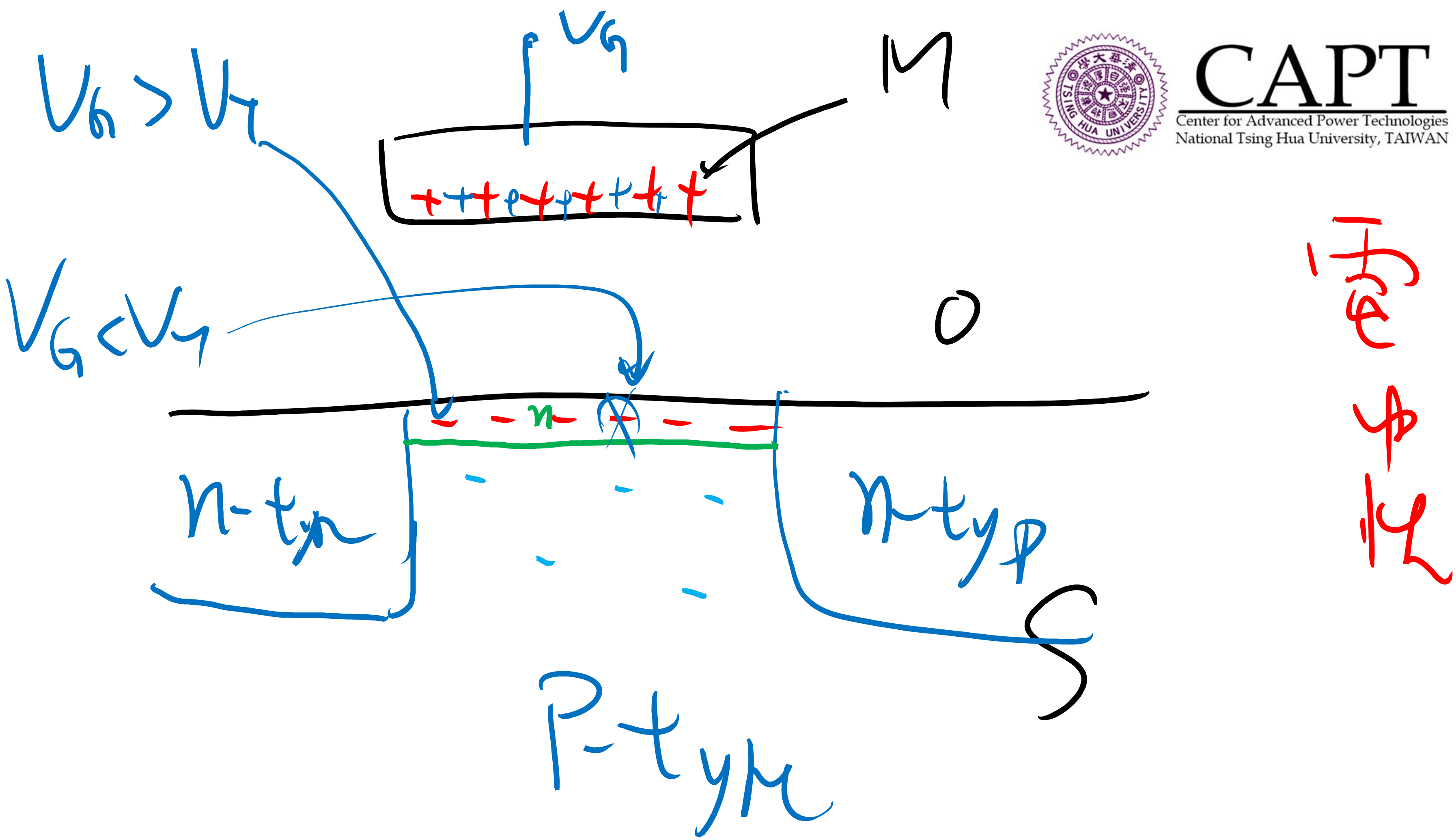
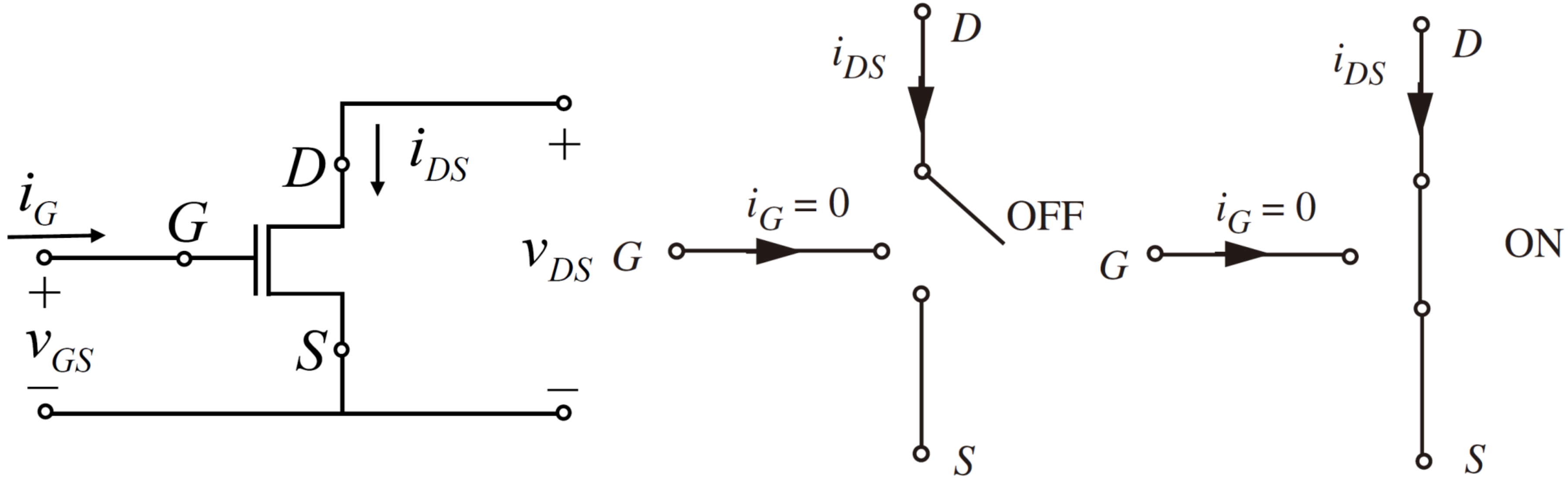


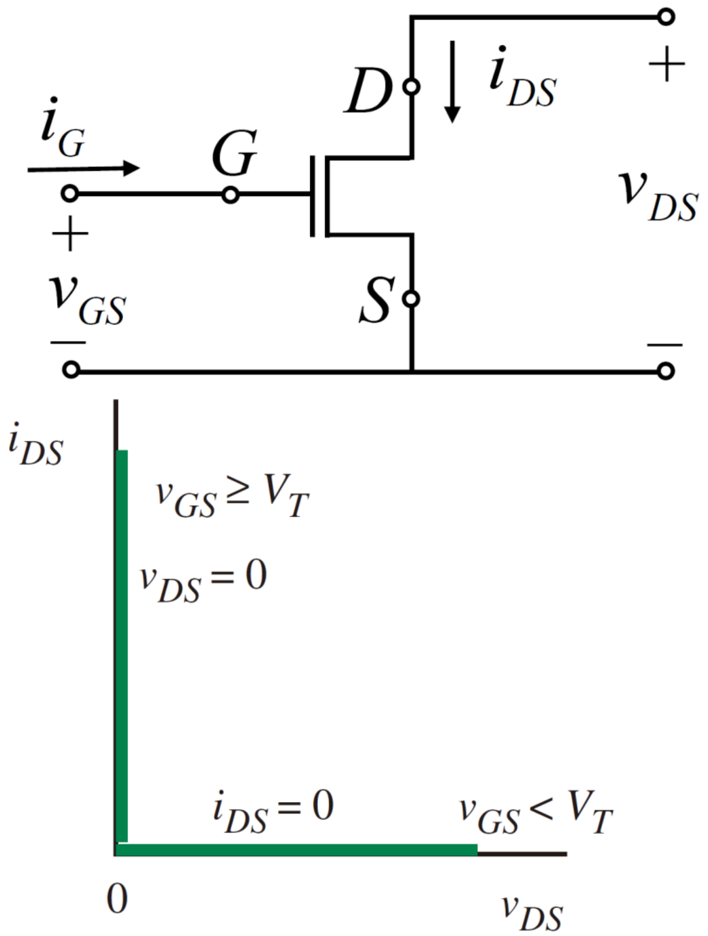
Switch model (S model) of the MOSFET

- Port Representation: Understand the operation of MOSFET by viewing it as a two-port element.

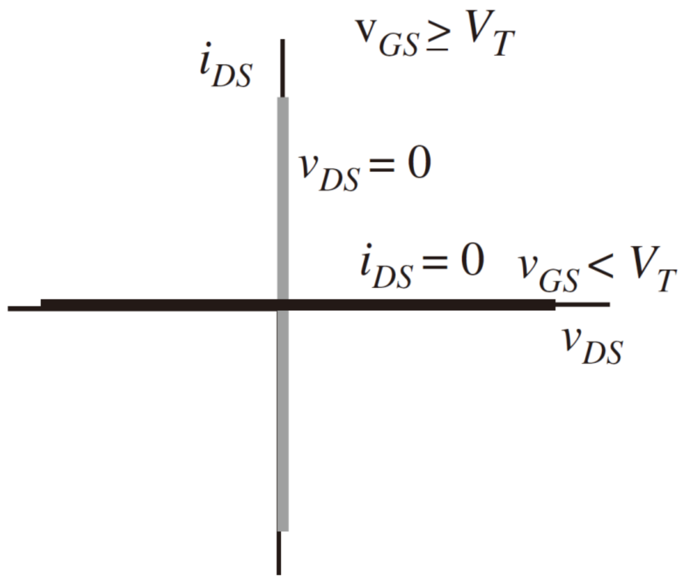


Two port device $\quad$ $v_{GS} < V_T$ $\quad$ $v_{GS} \geq V_T$

Switch model (S model) of the MOSFET



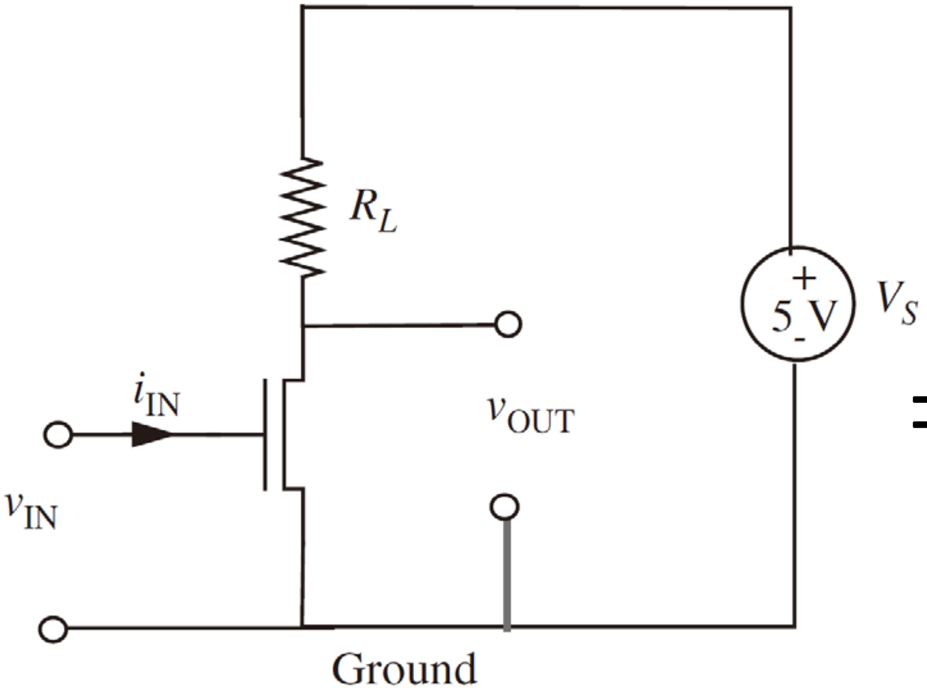
MOSFET *i*-*v* characteristics



For $\boldsymbol{v_{GS} < V_T,\ i_{DS} = 0}$
and
For $\boldsymbol{v_{GS} \geq V_T,\ v_{DS} = 0}$

The MOSFET inverter

- The MOSFET Inverter Circuit.



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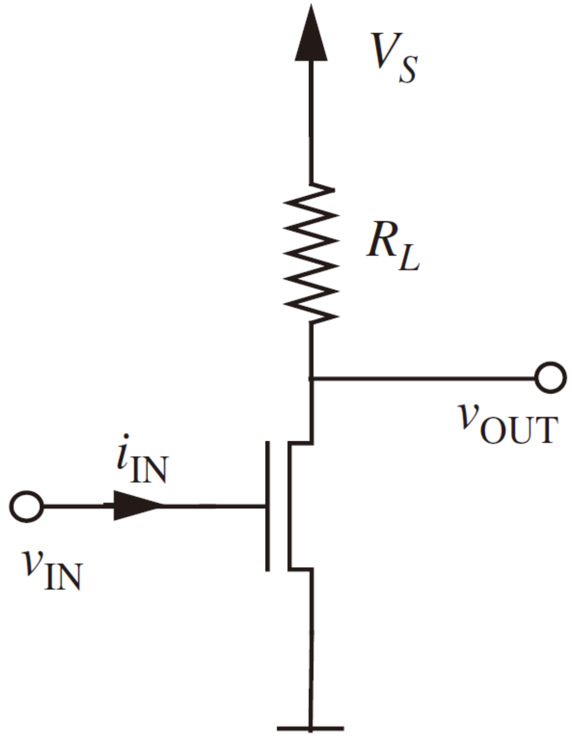
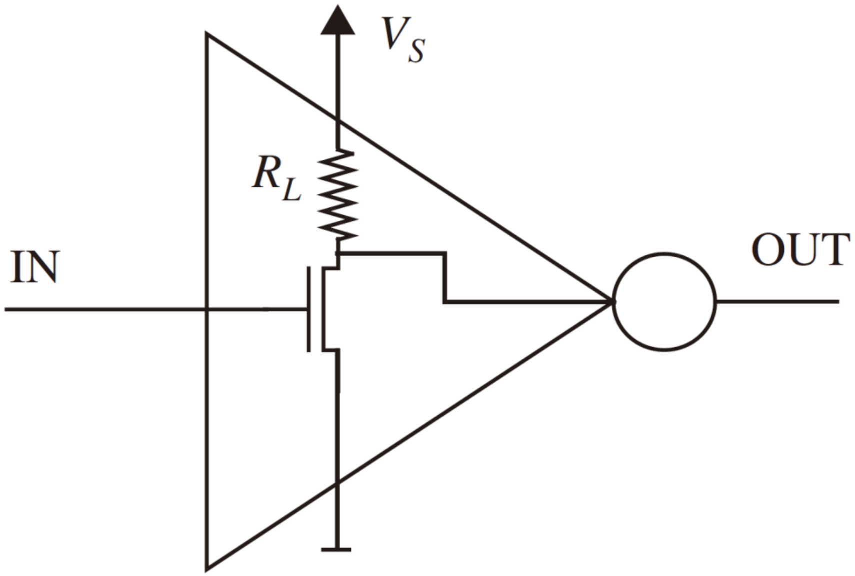


MOSFET Inverter Circuit

Shorthand notation for power and ground

The inverter abstraction



The inverter abstraction and its internal circuit

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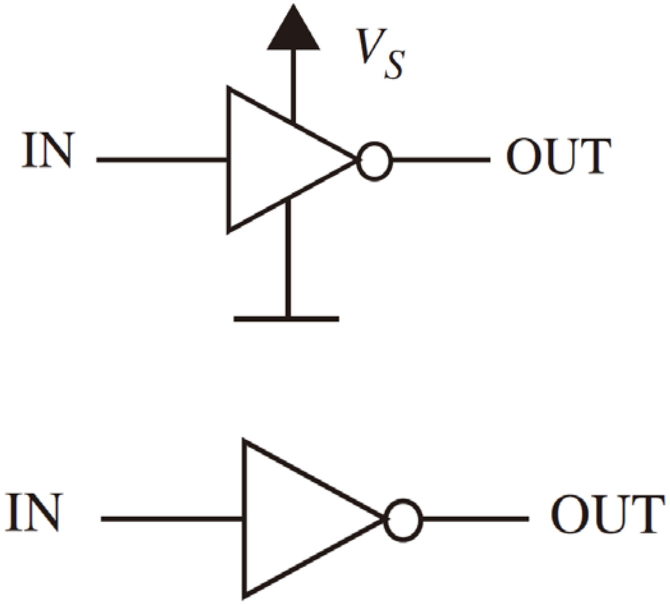
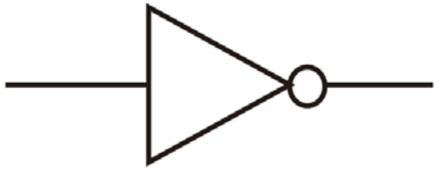
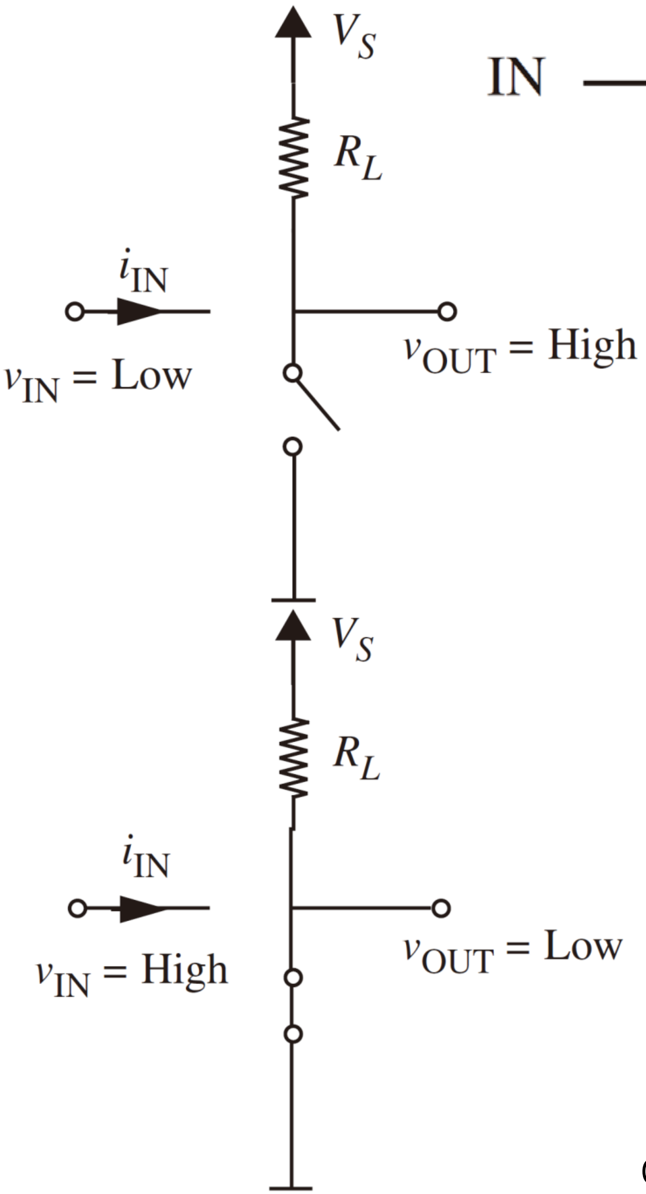


The inverter abstraction

Note the power of abstraction: The ***inverter abstraction*** hides the internal details such as power supply, transistor, ground connections.

Voltage Transfer Characteristics





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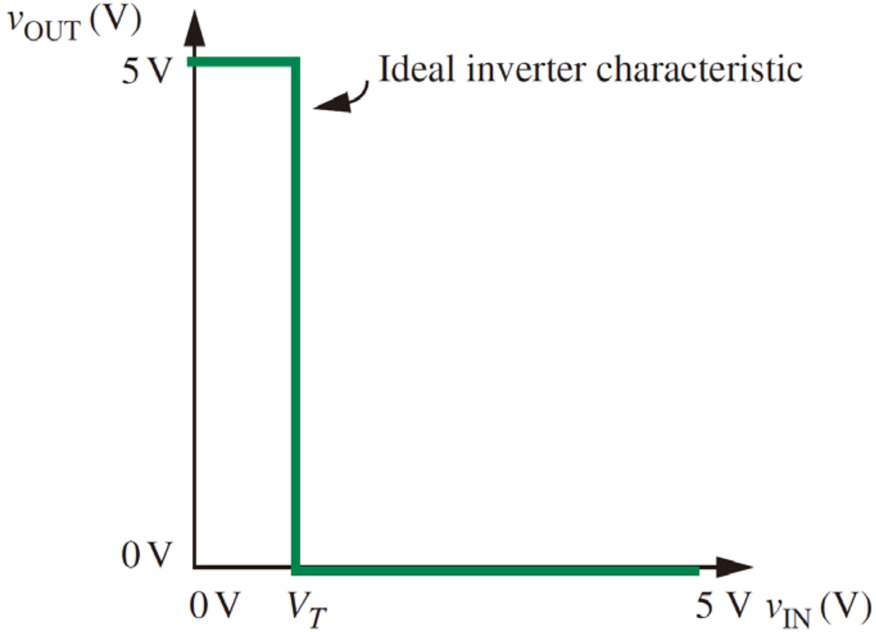


The voltage transfer characteristics of the inverter

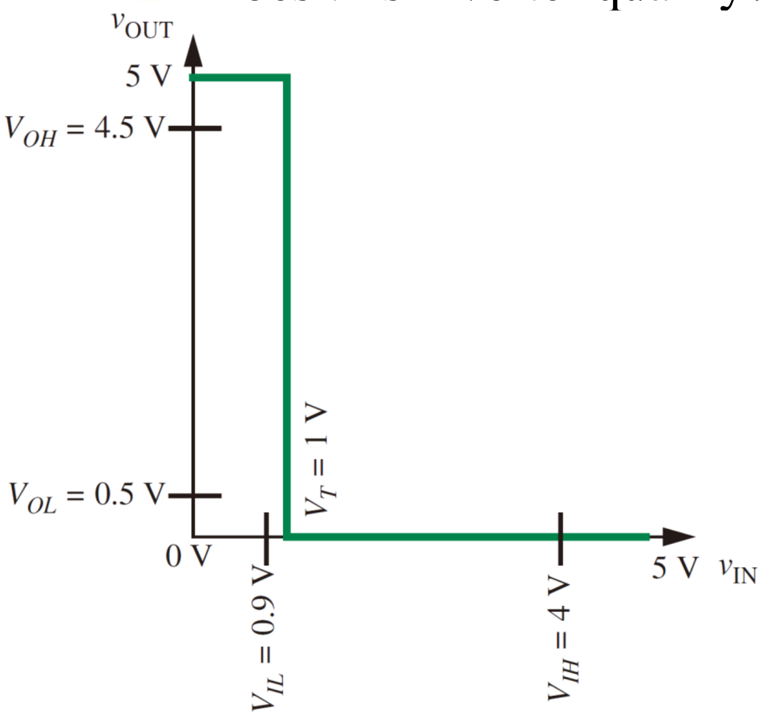
Static Analysis Using S Model

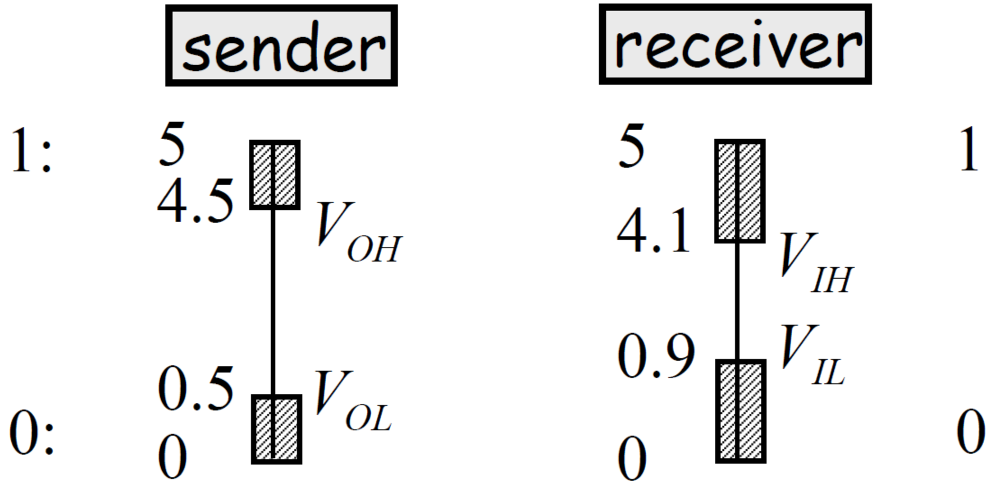
- Suppose gates should satisfy the following static discipline.

$$V_{OL} = 0.5 \text{ V}, \qquad V_{OH} = 4.5 \text{ V}$$

$$V_{IL} = 0.9 \text{ V}, \qquad V_{IH} = 4.1 \text{ V}$$

- Does this inverter qualify?





- This inverter satisfies the above static discipline.

Static Analysis Using S Model

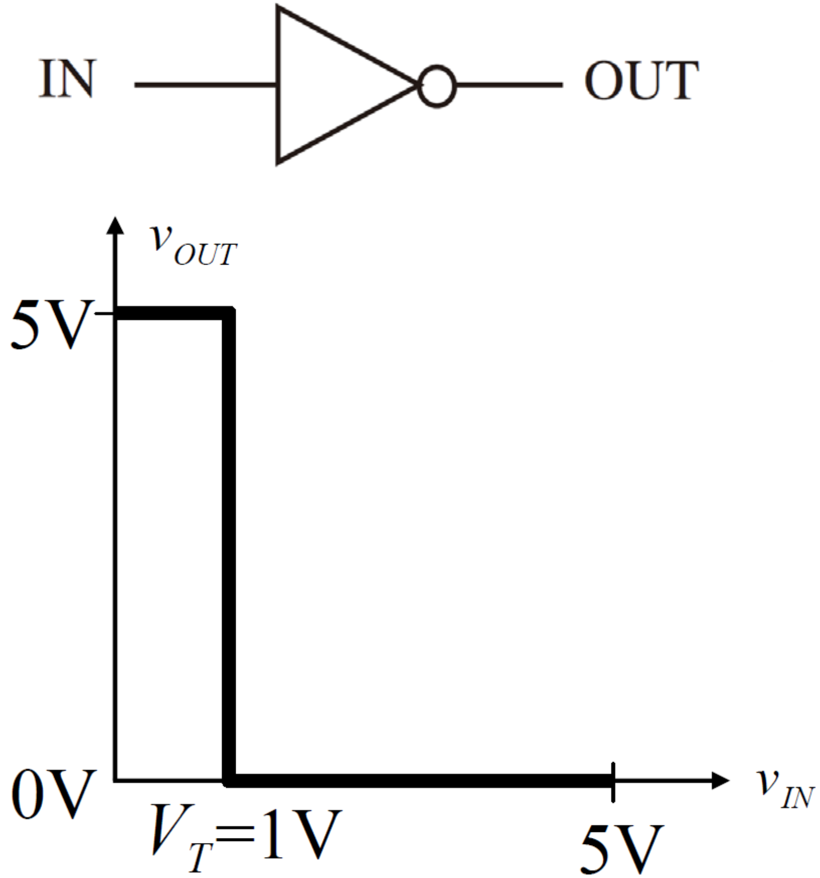
- Does this inverter satisfy the following two static disciplines A and B:

- Static disciplines A

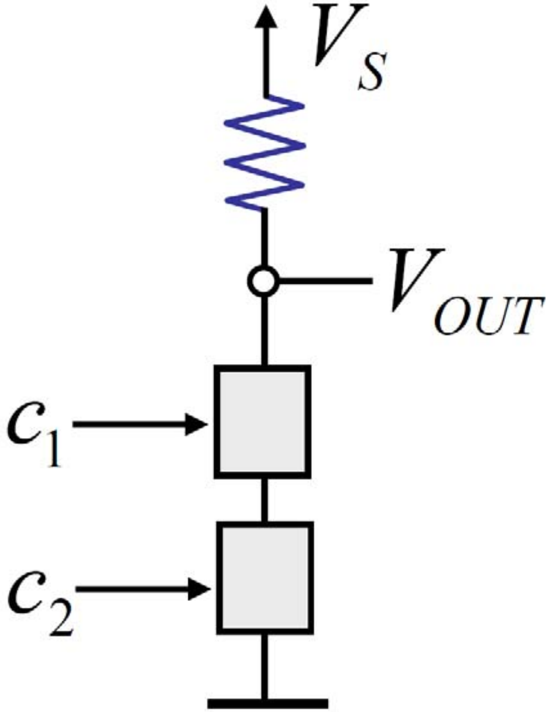
$V_{OL} = 0.2$ V, $V_{OH} = 4.8$ V
$V_{IL} = 0.5$ V, $V_{IH} = 4.5$ V
Yes, for Static disciplines A.

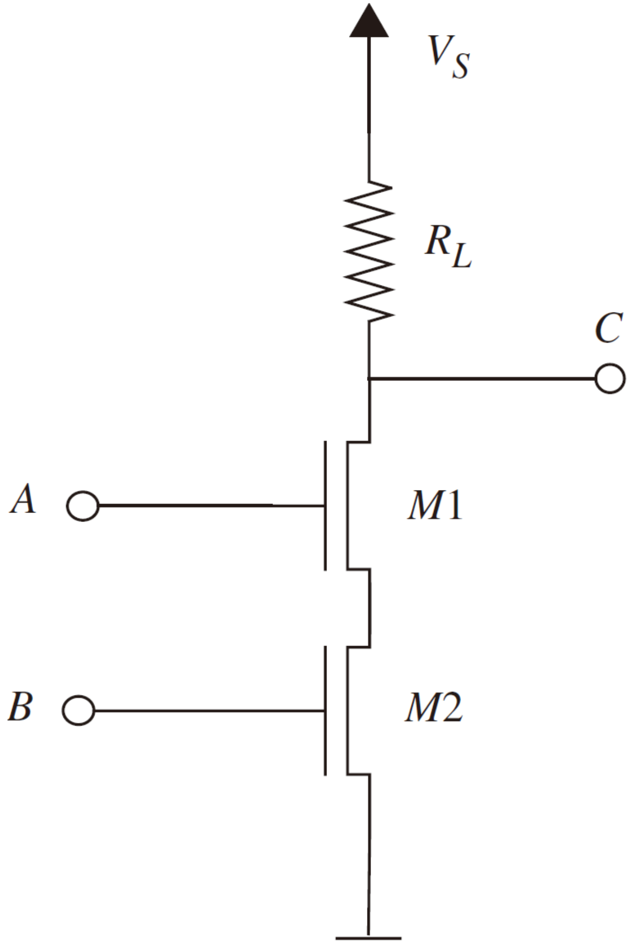
- Static disciplines B

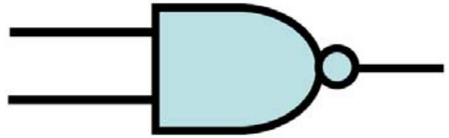
$V_{OL} = 0.5$ V, $V_{OH} = 4.5$ V
$V_{IL} = 1.5$ V, $V_{IH} = 3.5$ V
No, for Static disciplines A



The NAND Gate



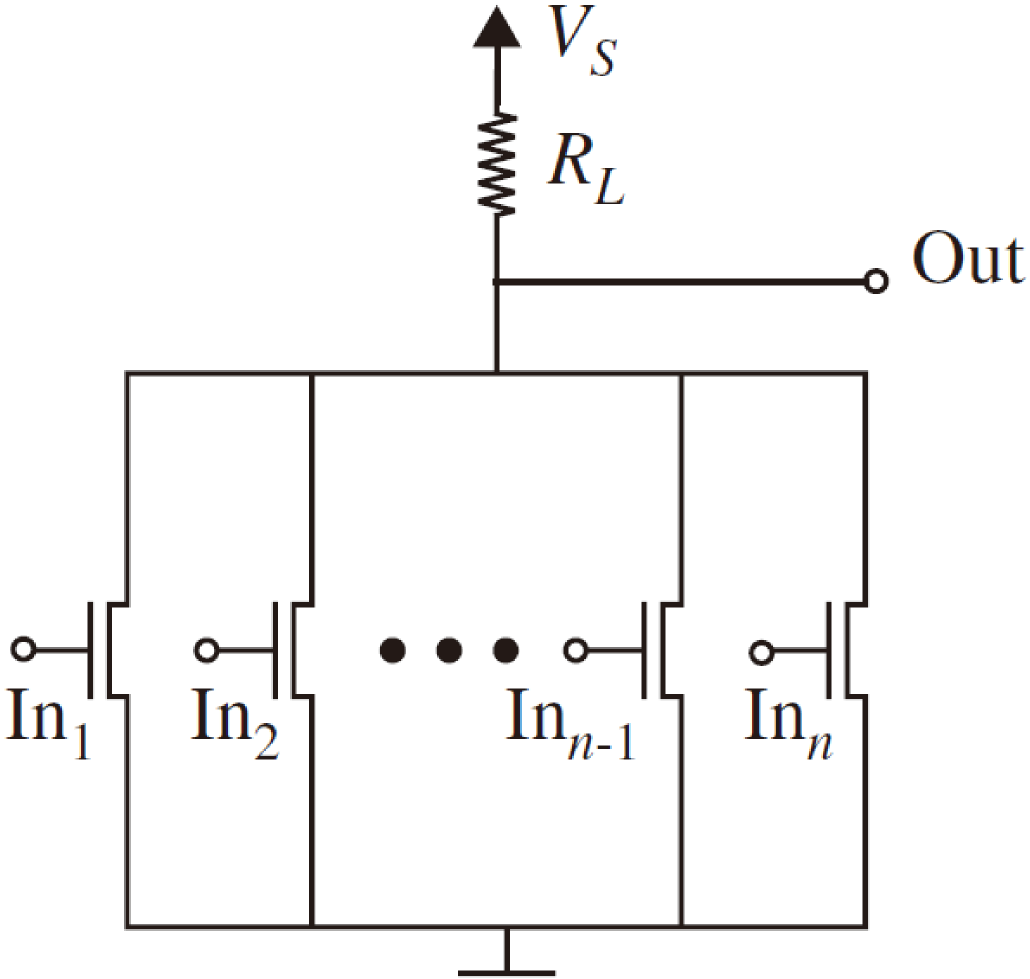


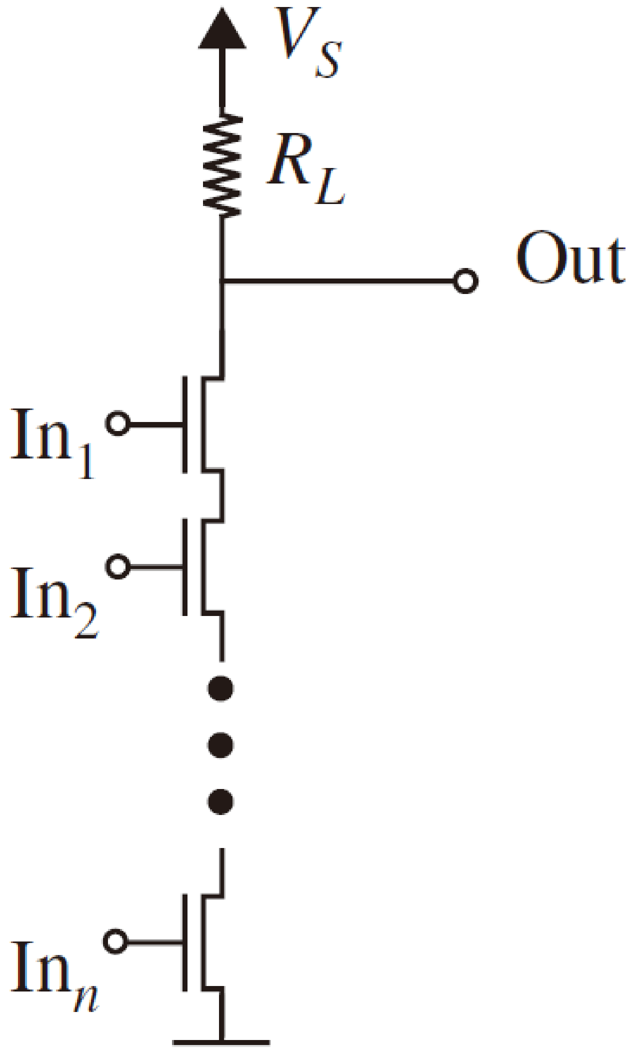


c_1	c_2	V_O
0	0	1
0	1	1
1	0	1
1	1	0

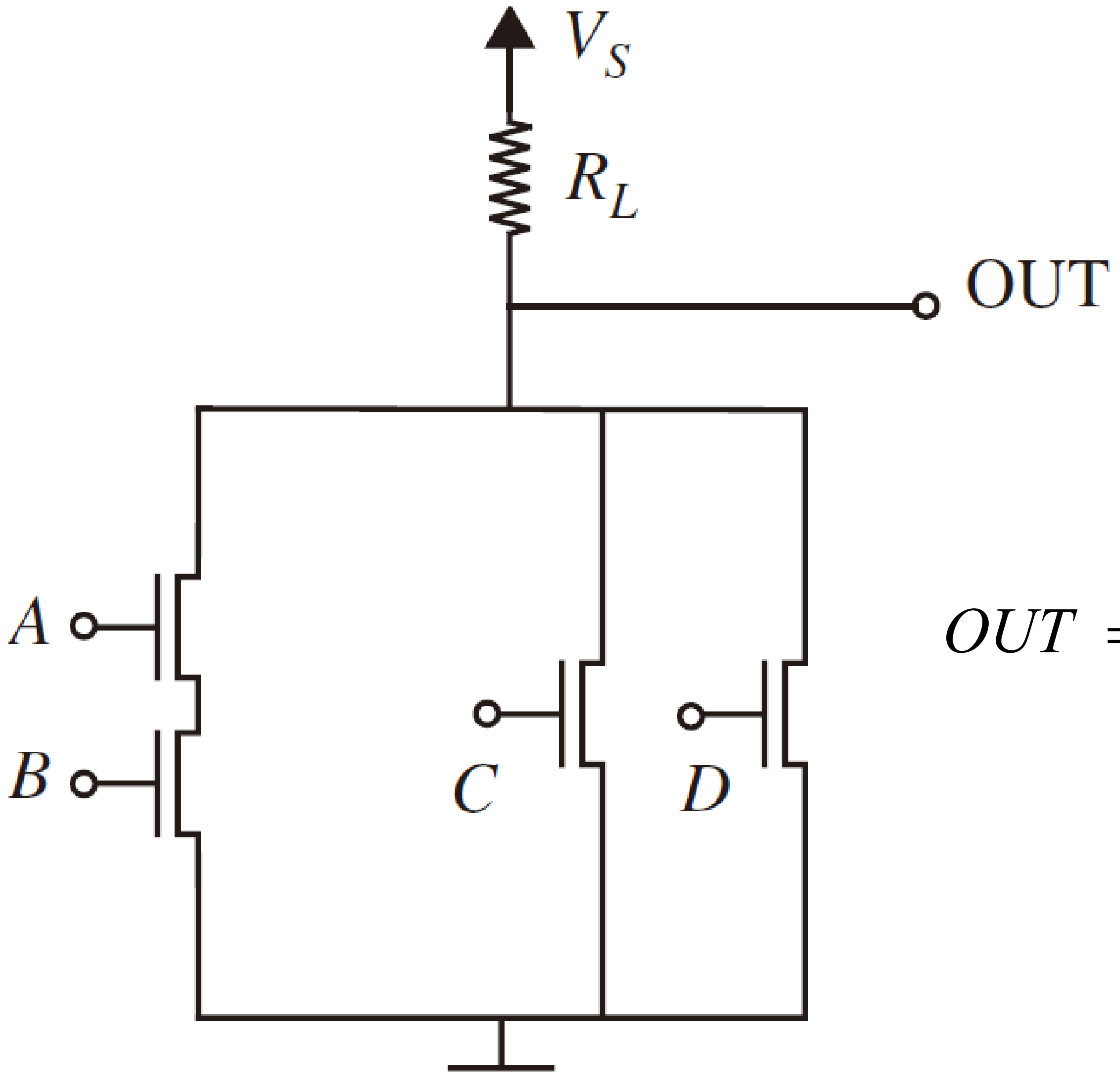
If $V_A \geqq V_T$ AND $V_B \geqq V_T$, then $V_{out} = 0$ Else $V_{out} = V_S$.

Multiple-input NOR and NAND gates



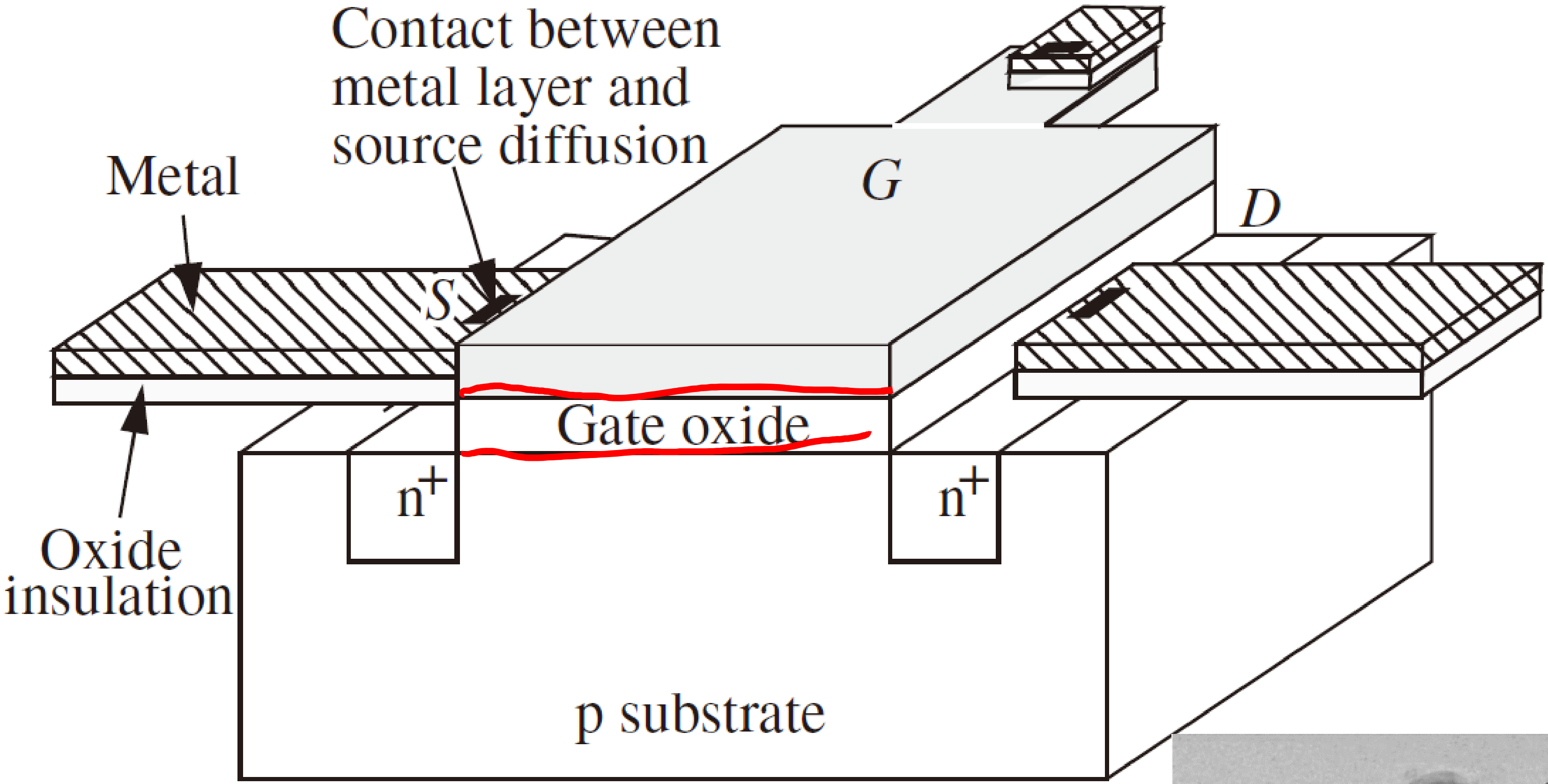


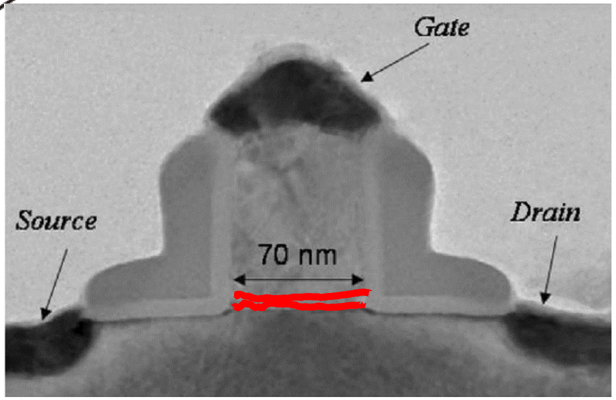
A Complex Gate



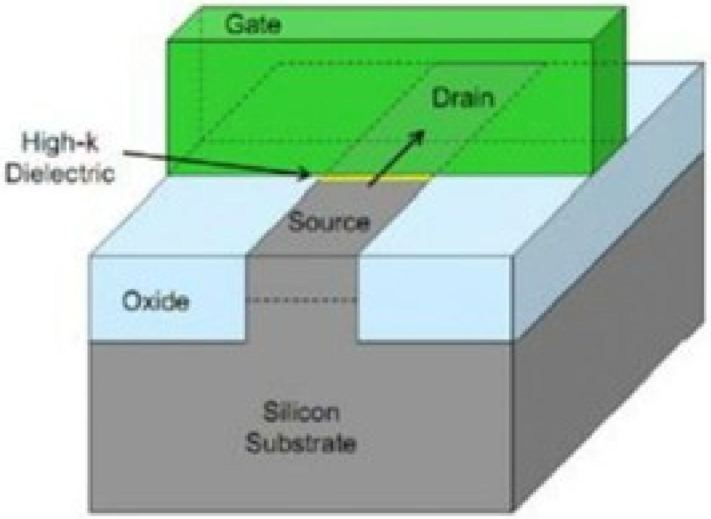
$$OUT = \overline{A \cdot B + C + D}$$

The Physical Structure of MOSFET



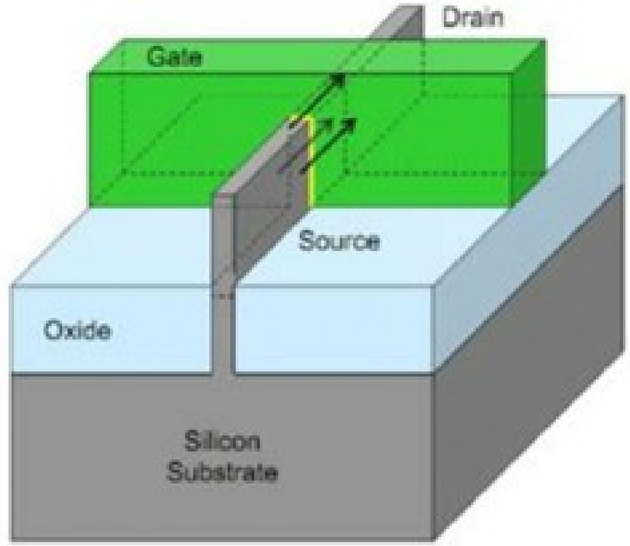


Traditional Planar

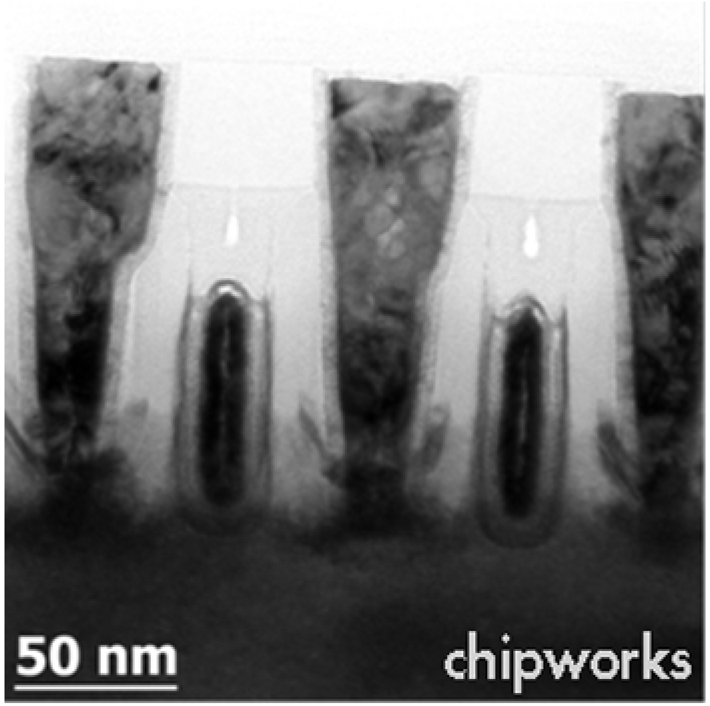


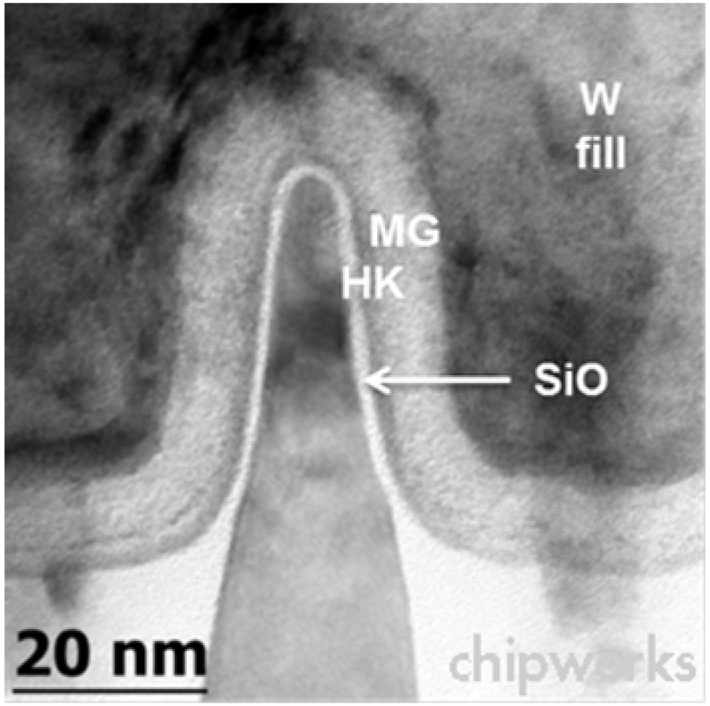
Traditional 2-D planar transistor form a conducting channel in the silicon region under the gate electrode when in the "on" state

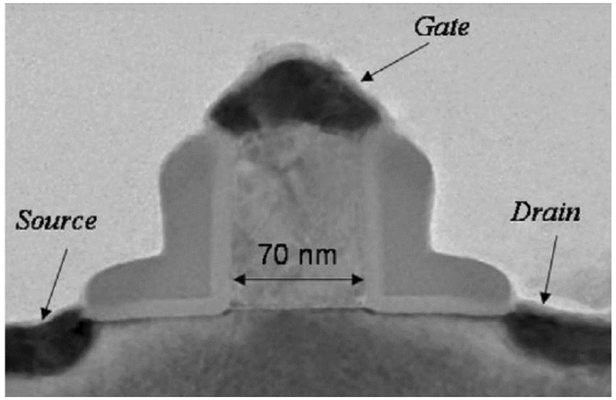
3D FinFET

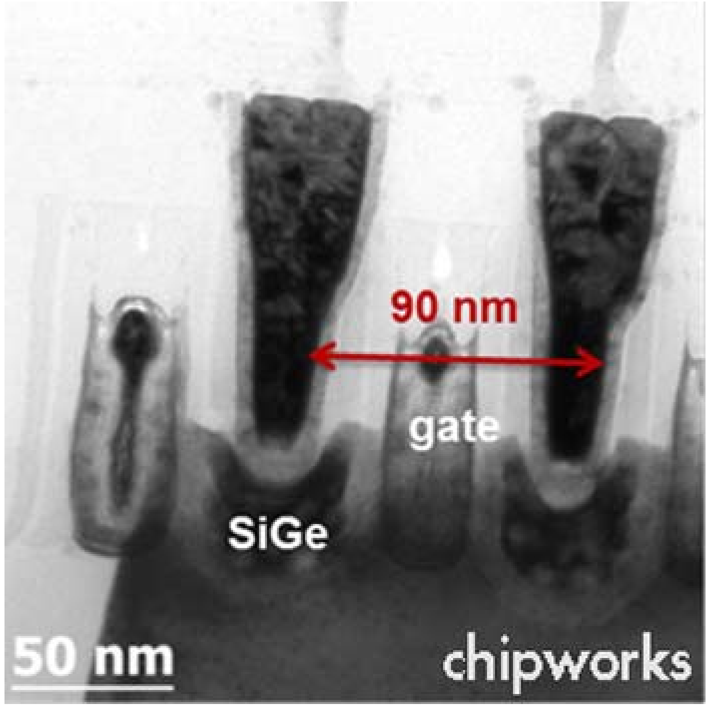


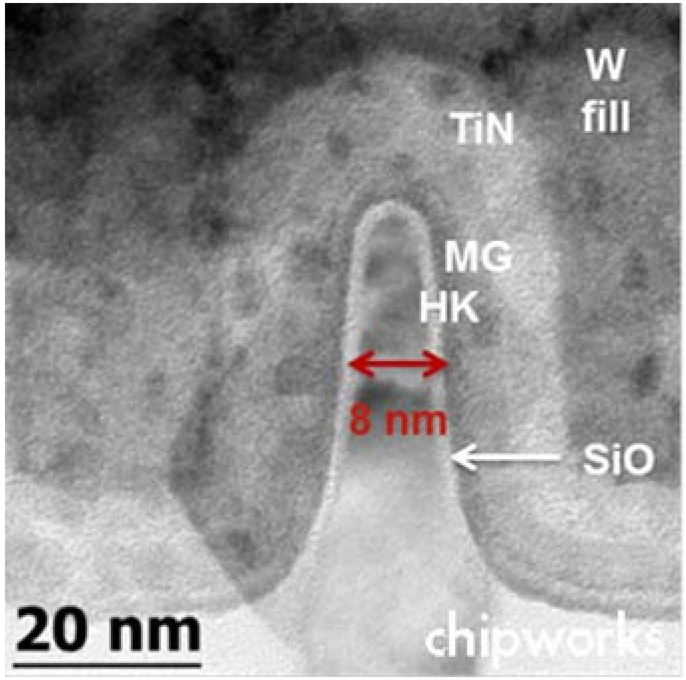
3-D Tri-Gate transistor form conducting channels on three sides of a vertical fin structure, providing "fully depleted" operation


50 nm
chipworks


W
fill
MG
HK
SiO
20 nm
chipworks


Gate
Source
Drain
70 nm


90 nm
gate
SiGe
50 nm
chipworks


W
fill
TiN
MG
HK
8 nm
SiO
20 nm
chipworks

The Physical Structure of MOSFET

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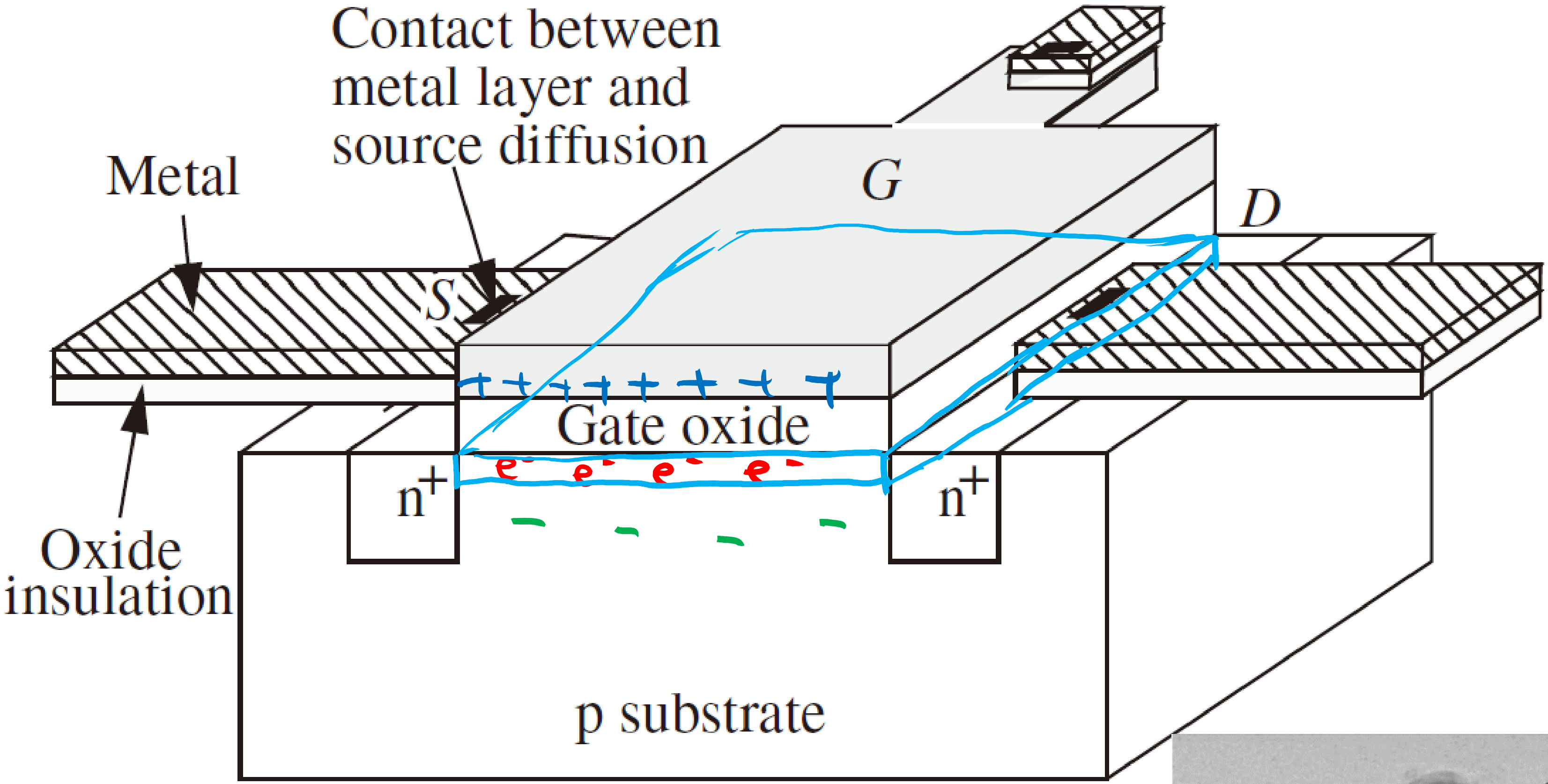
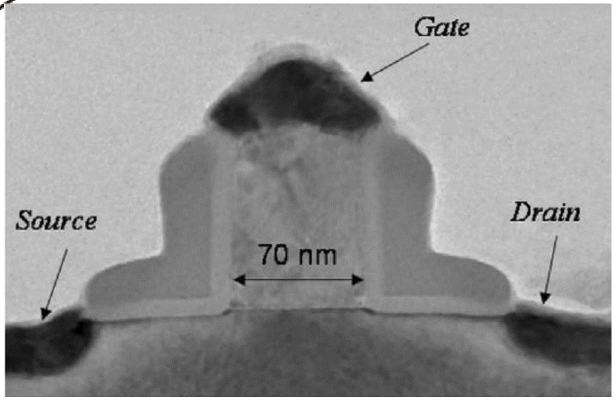
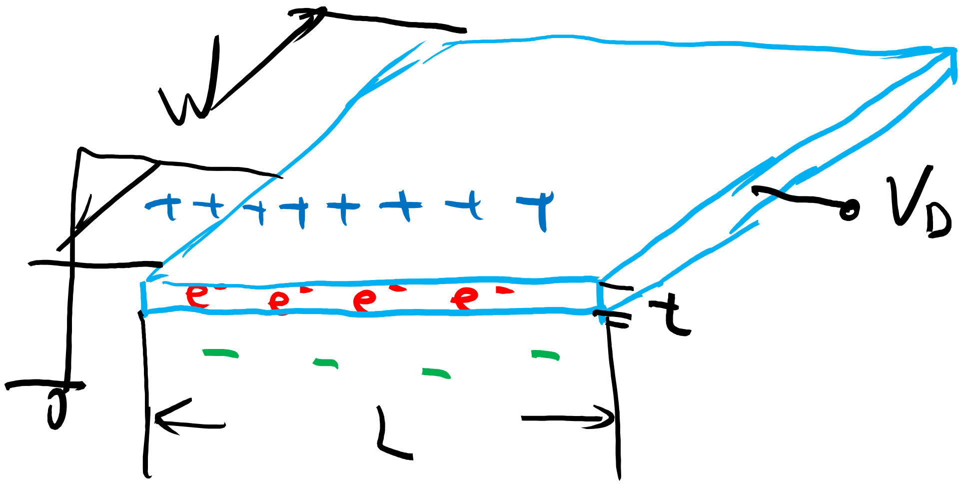




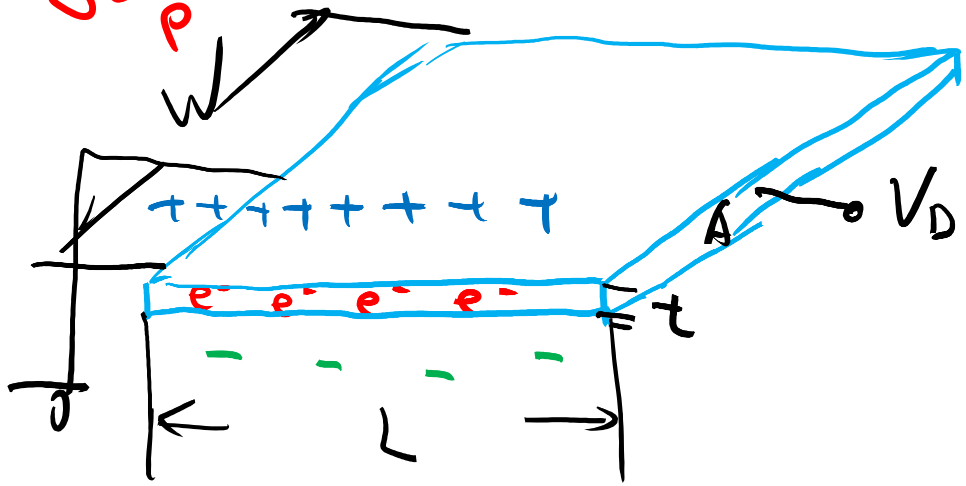

W
V_D
t
L

$$R = \rho \frac{L}{A} = \rho \frac{L}{Wt}$$

$$\sigma = \frac{1}{\rho}$$

$$\vec{J} = \sigma \vec{E}$$

$$\vec{J} = \rho \vec{v}$$



$$I = \vec{J} \cdot A = \vec{J} \cdot W \cdot t$$

$$\rho = q \cdot n$$

$$q = 1.6 \times 10^{-19} C$$

n: 電子濃度 $\frac{\#}{cm^3}$

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$$\vec{v} = \mu \vec{E} \qquad \vec{E} = \frac{V_D}{L} \qquad I \text{ vs } V_D$$

$$\vec{J} = \rho \vec{v} \qquad I = \frac{V}{R}$$

$$I = \vec{J} \cdot Wt = \rho \vec{v} \cdot Wt = qn \mu \vec{E} \cdot W \cdot t$$

$$= qn\mu \frac{V_D}{L} \cdot Wt$$

$$R = \frac{1}{qnt\mu} \frac{L}{W} \qquad = \frac{V_D}{R}$$

$$C_{ox}(V_G - V_t)$$

$$R = R_n \frac{L}{W}, \quad R_n = \frac{1}{\mu C_{ox}(V_G - V_t)}$$

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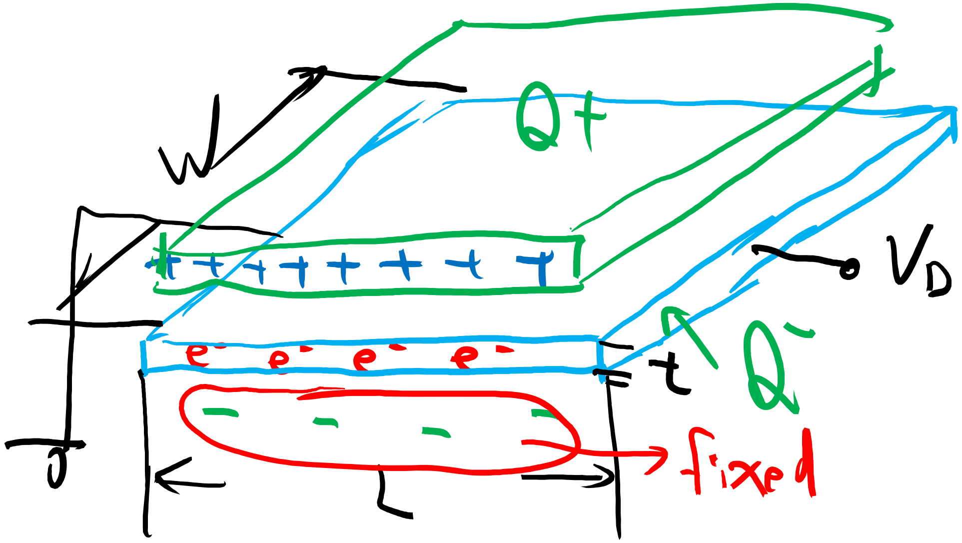


$$Q = CV - Q_{fixed} = C\left(V - \frac{Q_{fixed}}{C}\right)$$

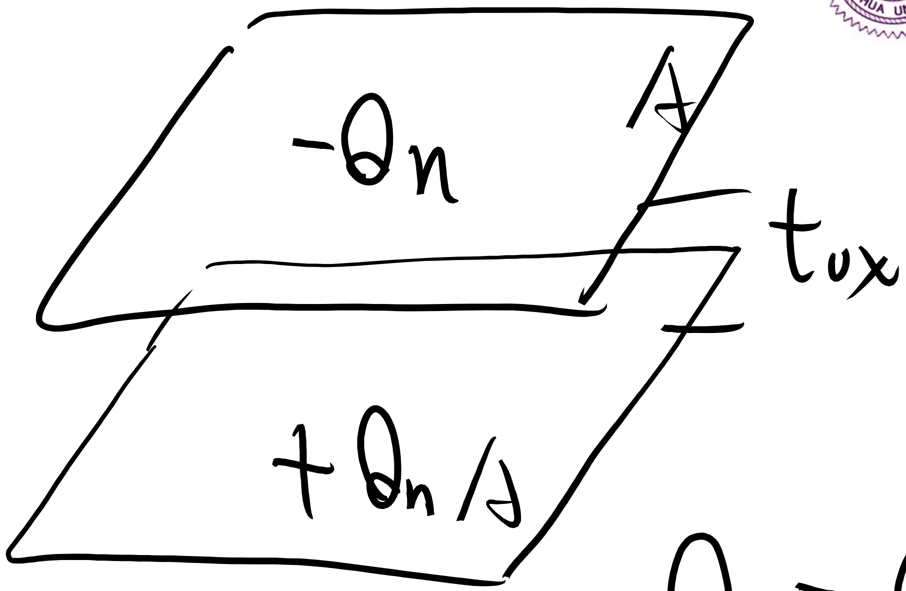
$$\rho_n t = C(V_G - V_T)$$

$$q n t = \rho_n \cdot t = \frac{C}{A}(V_G - V_T) = C'(V_G - V_T)$$

$$\frac{C}{cm^3}\cdot cm \qquad \frac{C}{cm^2}$$

$$q n = \rho_n$$

電子電荷密度



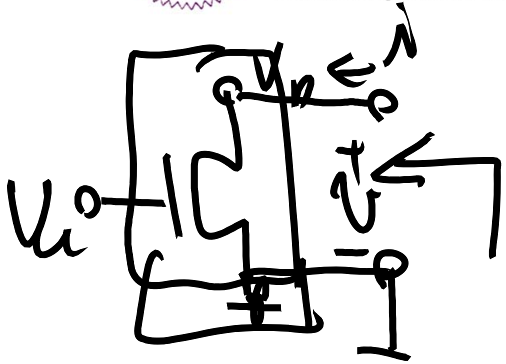
$$C = \epsilon_{SiO_2} \cdot \frac{A}{t_{ox}}$$

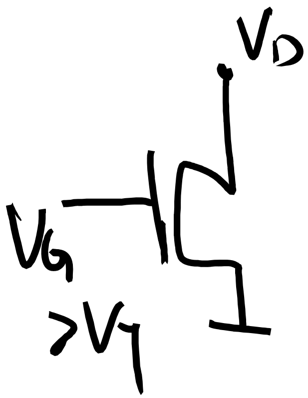
$$Q_n = -C(V_G - V_T)$$

$$\frac{Q_n}{A} = -\frac{C}{A}(V_G - V_T)$$

$$R = R_n \frac{L}{W}$$

$$R_n = \frac{1}{\mu C_{ox} (V_G - V_T)}$$

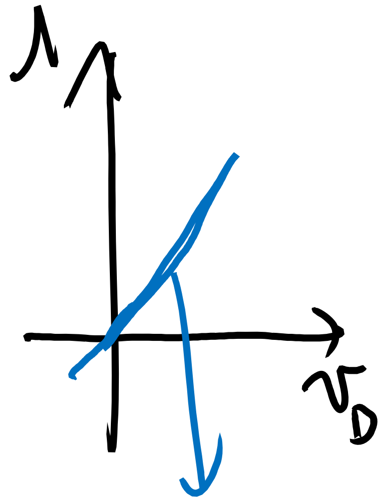




$V_G > V_T$

$\Longrightarrow$

$R = R_n \frac{L}{W}$



$$\text{slope} = \frac{1}{R_n} \frac{W}{L}$$

The MOSFET with Gate Bias

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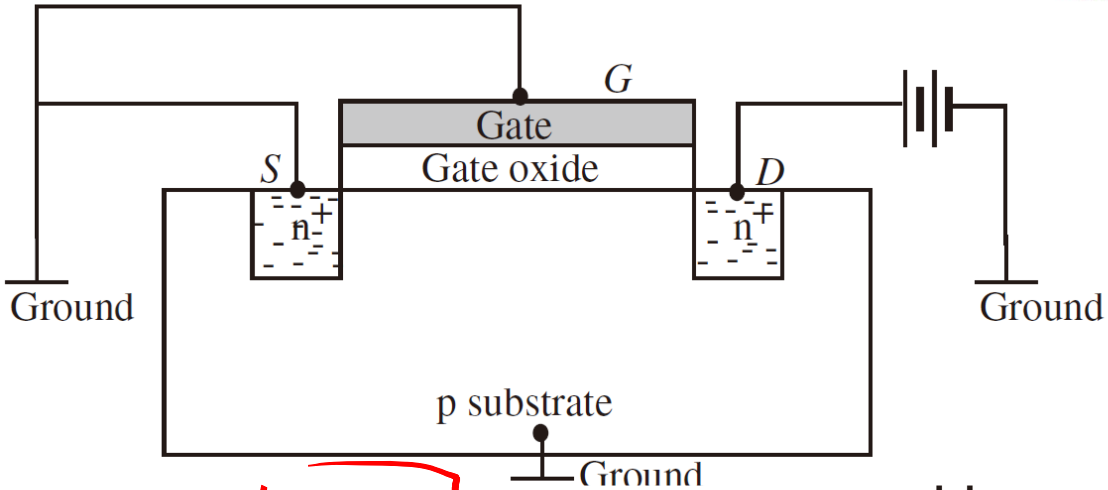
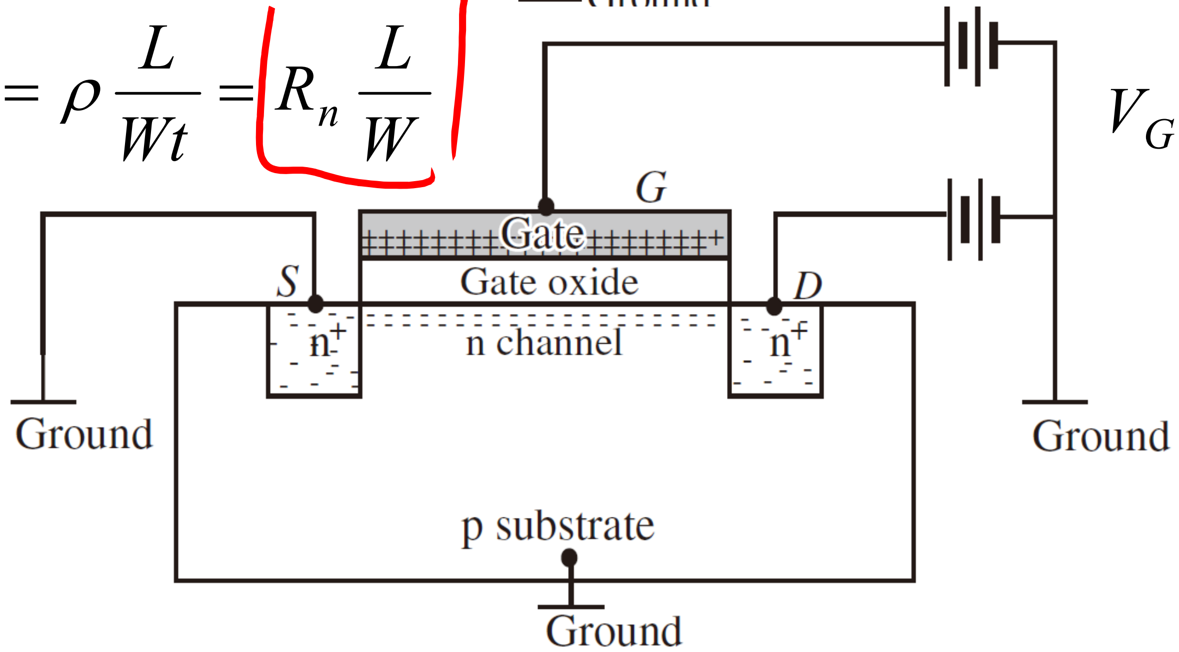
$V_G = 0\,V$



$$R_{on} = \rho \frac{L}{A} = \rho \frac{L}{Wt} = R_n \frac{L}{W}$$

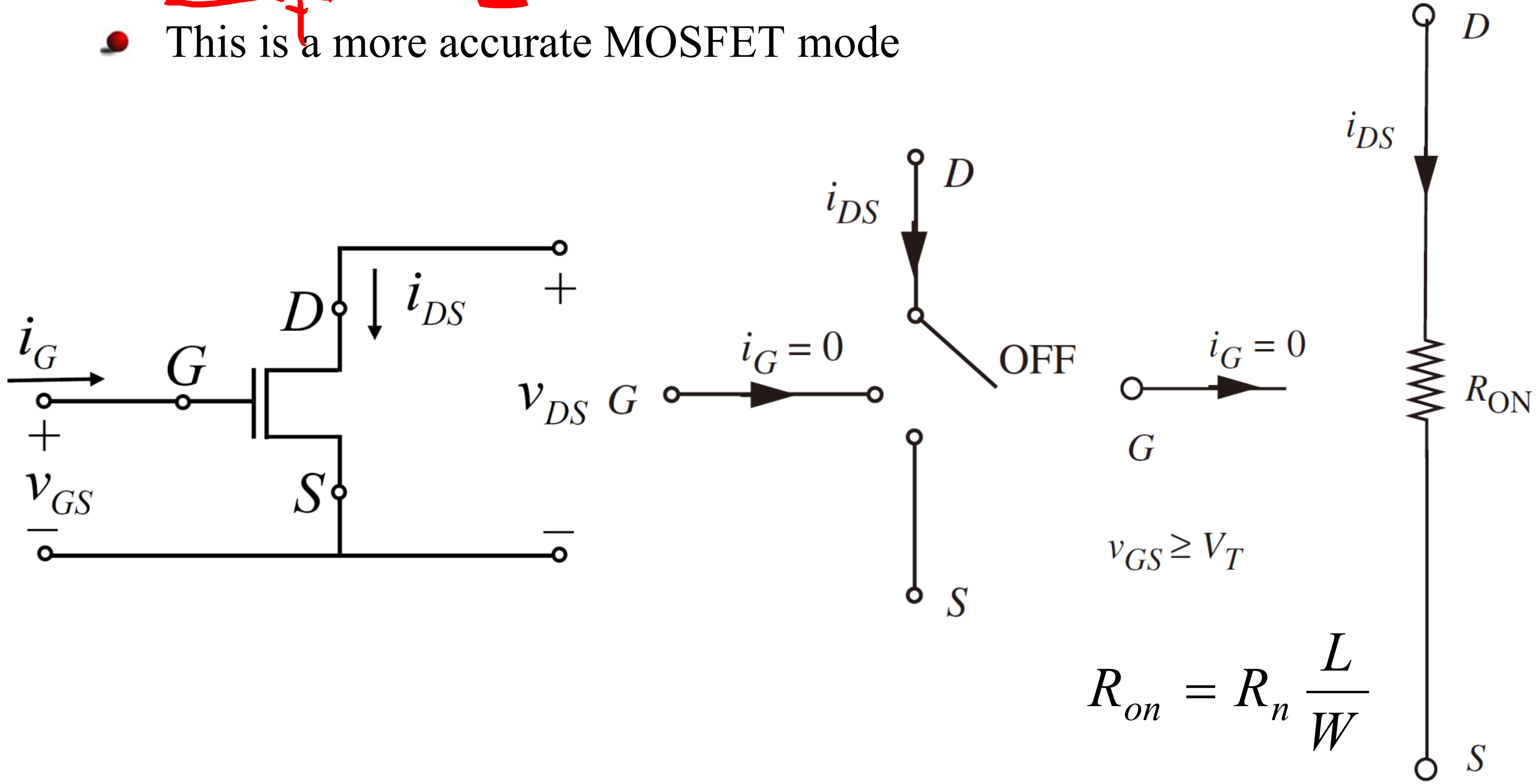
$V_G = 5\,V > V_T$

$R_{on} \neq 0\,\Omega$



SR model of MOSFET

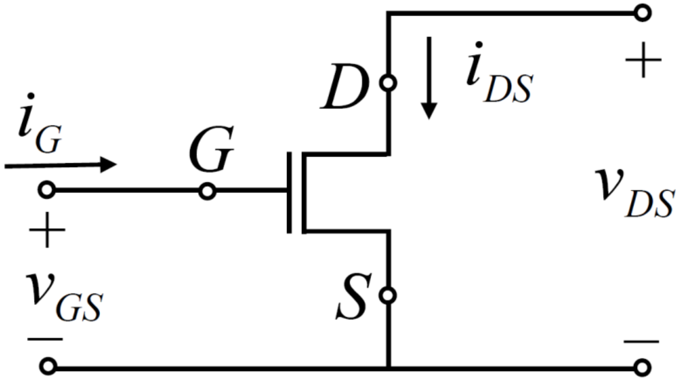
- Switch resistor (SR) model of MOSFET.
- This is a more accurate MOSFET mode

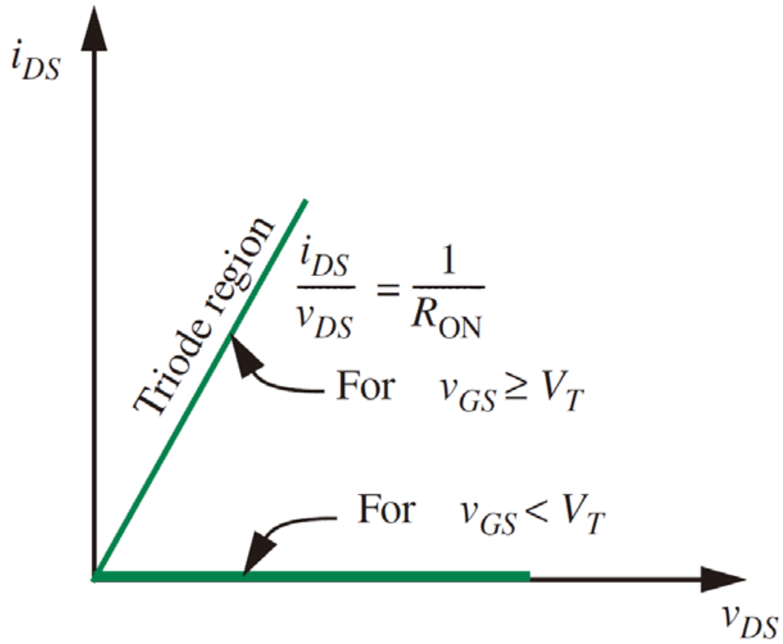


$$R_{on} = R_n \frac{L}{W}$$

Two port device **$v_{GS} < V_T$** **$v_{GS} \geq V_T$**

SR model of the MOSFET





MOSFET *i*-*v* characteristics

$$R_{on} = R_n \frac{L}{W}$$

For $\boldsymbol{v_{GS} < V_T,\ i_{DS} = 0}$

and

For $\boldsymbol{v_{GS} \geq V_T,\ i_{DS} = v_{DS} / R_{on}}$

Voltage Transfer Characteristics

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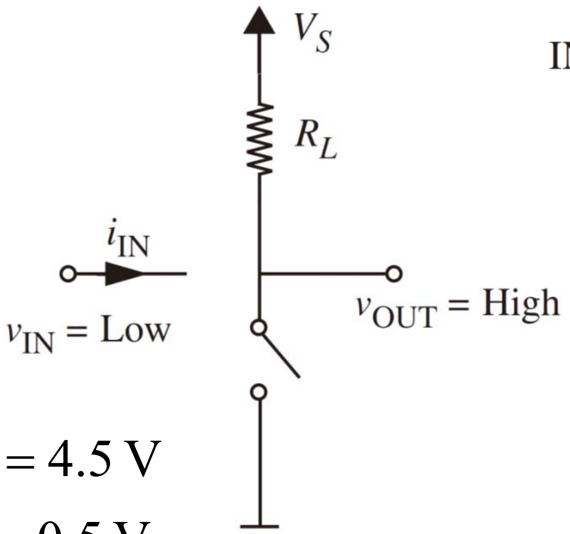
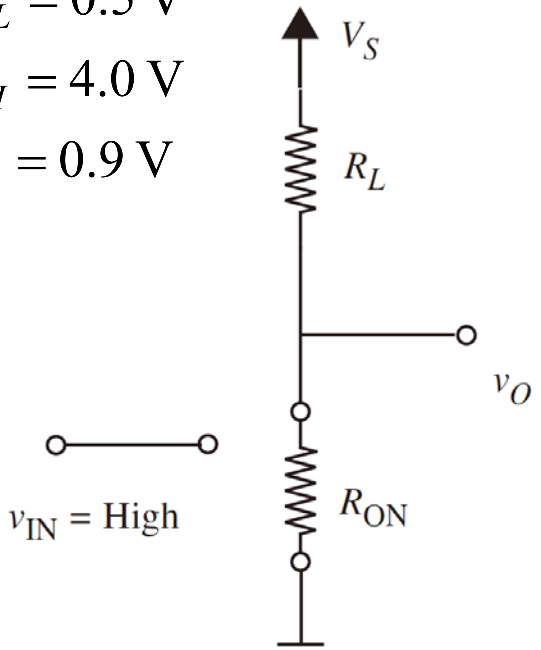


$V_{OH} = 4.5\ \text{V}$

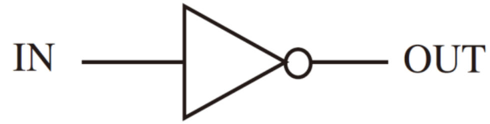
$V_{OL} = 0.5\ \text{V}$

$V_{IH} = 4.0\ \text{V}$

$V_{IL} = 0.9\ \text{V}$



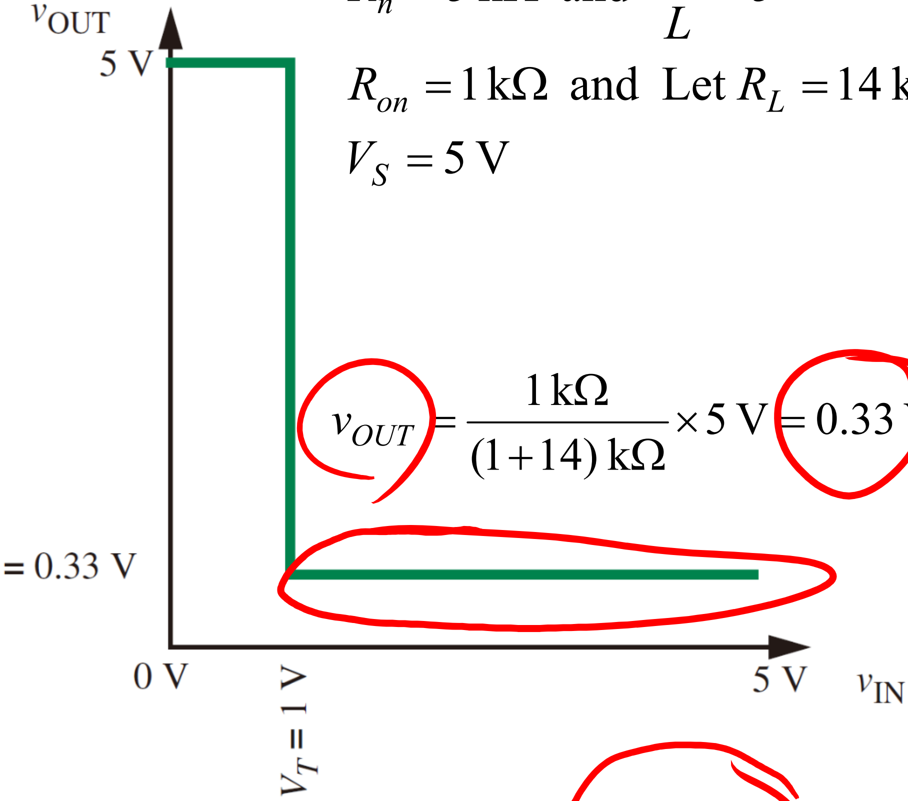
$\Rightarrow$



$R_n = 5\ \text{k}\Omega$ and $\dfrac{W}{L} = 5$

$R_{on} = 1\ \text{k}\Omega$ and Let $R_L = 14\ \text{k}\Omega$

$V_S = 5\ \text{V}$



$$v_{OUT} = \frac{1\ \text{k}\Omega}{(1+14)\ \text{k}\Omega} \times 5\ \text{V} = 0.33\ \text{V}$$

$$\frac{V_S R_{ON}}{R_{ON} + R_L} = 0.33\ \text{V}$$

$v_{OUT} \neq 0\ \text{V}$

Choose R_L, V_S and R_{ON} such that $v_{OUT} = \dfrac{R_{ON}}{R_{ON} + R_L} V_S \leq V_{OL}$

The NAND Gate

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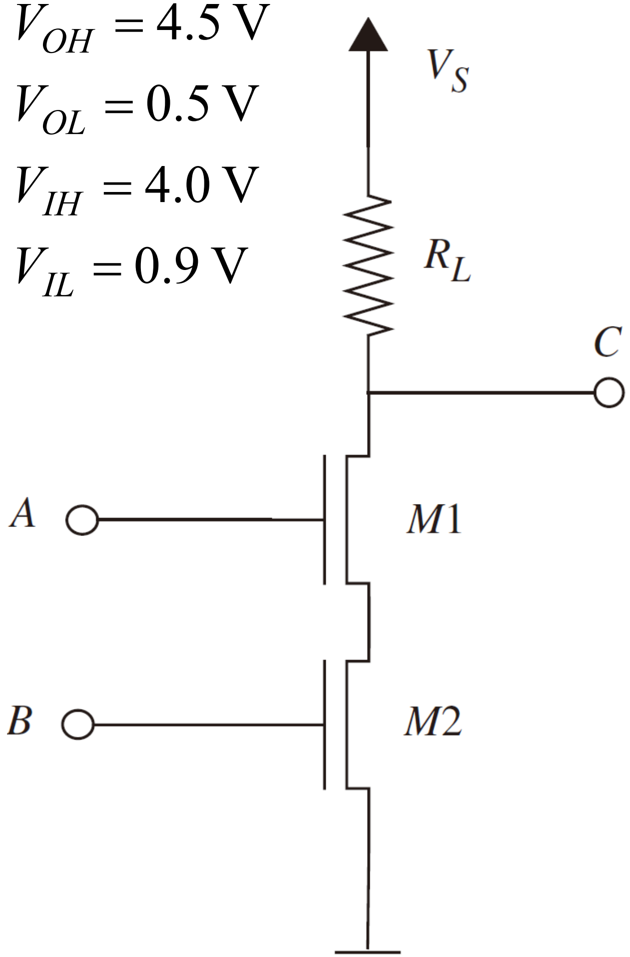
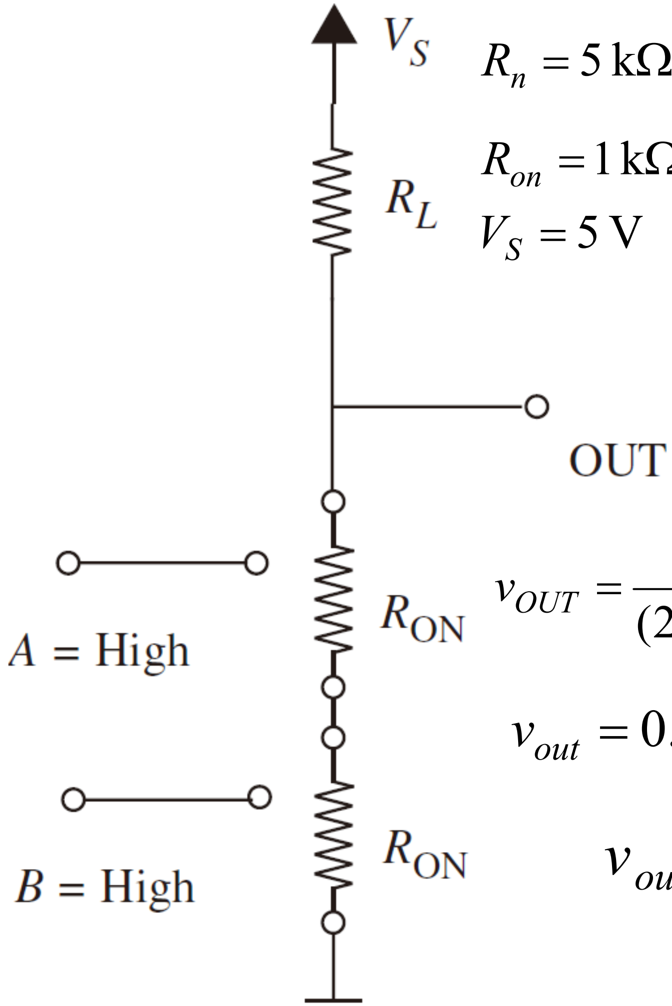
$V_{OH} = 4.5\text{ V}$

$V_{OL} = 0.5\text{ V}$

$V_{IH} = 4.0\text{ V}$

$V_{IL} = 0.9\text{ V}$





$R_n = 5\text{ k}\Omega$ and $\dfrac{W}{L} = 5$

$R_{on} = 1\text{ k}\Omega$ and Let $R_L = 14\text{ k}\Omega$

$V_S = 5\text{ V}$

$$v_{OUT} = \frac{2\text{ k}\Omega}{(2+14)\text{ k}\Omega} \times 5\text{ V} = 0.625\text{ V}$$

$$v_{out} = 0.625V > 0.5\text{ V} = V_{OL}$$

$$v_{out} > V_{OL}$$

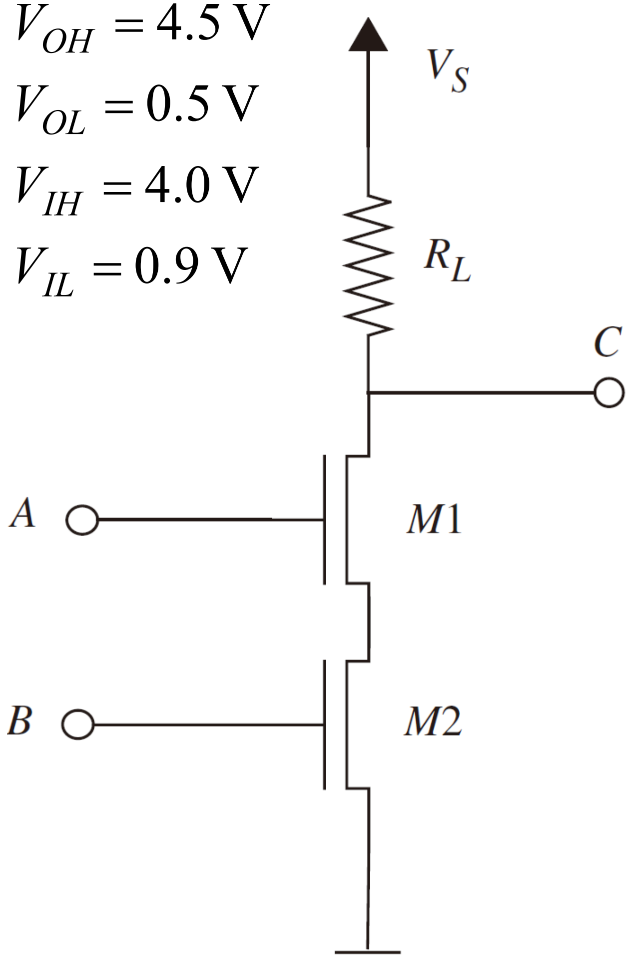
The NAND Gate

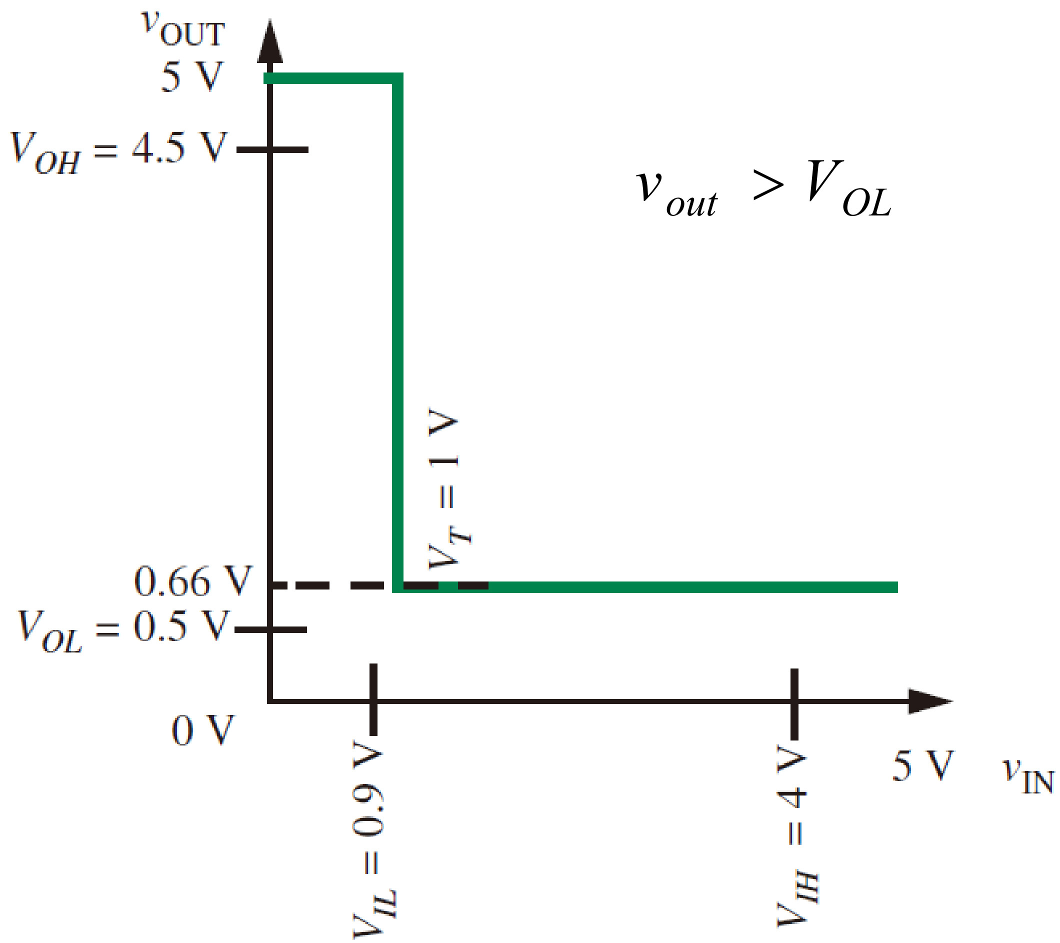
$V_{OH} = 4.5\text{ V}$

$V_{OL} = 0.5\text{ V}$

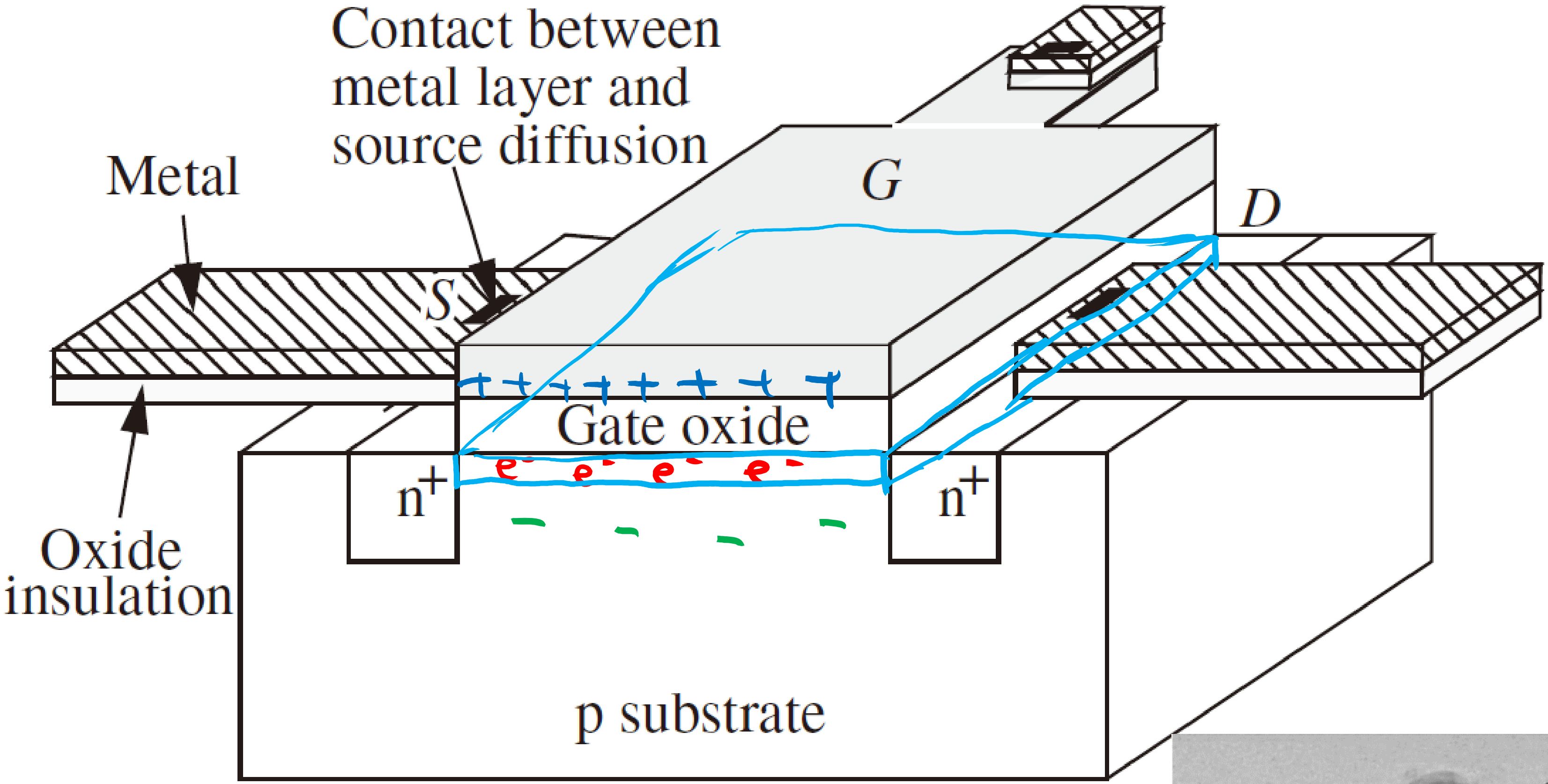
$V_{IH} = 4.0\text{ V}$

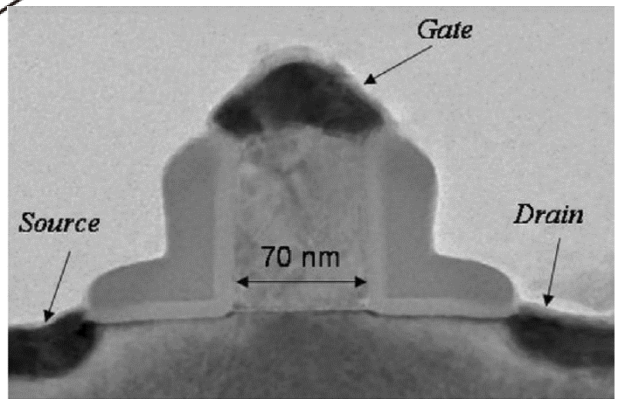
$V_{IL} = 0.9\text{ V}$





The Physical Structure of MOSFET





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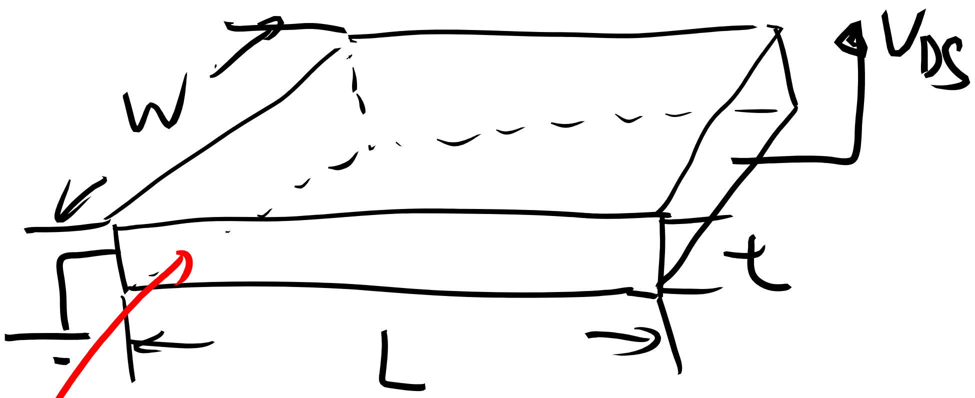
①



$$\vec{E} \simeq \frac{V_{DS}}{L}$$

V_{DS} 很小

$I_D = W Q_n v$

$$\vec{J} = \rho \vec{v} = (qn)(\mu \vec{E}) = qn\mu \frac{V_{DS}}{L}$$

qp

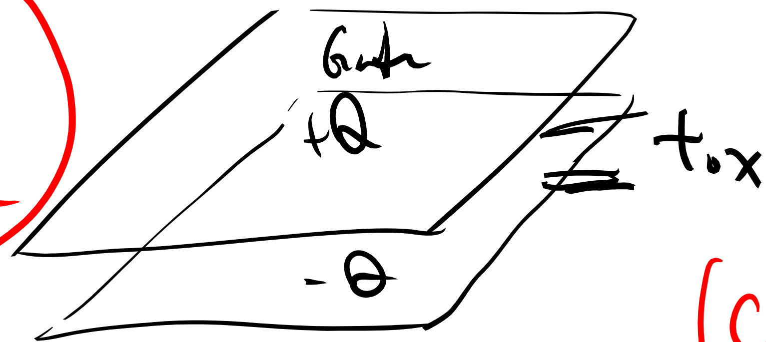
$$I = \vec{J} \cdot A = \vec{J} \cdot Wt = qn\mu \frac{V_{DS}}{L} \cdot Wt$$

$$= \mu \frac{W}{L} (qnt) V_{DS}$$

$$\left(\frac{C}{m^3}\right)(m) = \left(\frac{C}{m^2}\right)$$

$$qnt = \rho \cdot t$$

① $W \quad Q \quad \mu \frac{V_D}{L}$



$$I_D = \mu \frac{W}{L} C_{ox}(V_G - V_T) V_D$$

(C) (F)(V)

$$C = \epsilon_{ox} \cdot \frac{A}{t_{ox}} \qquad Q = CV = \epsilon_{ox}\frac{A}{t_{ox}} V$$

$$I = \mu \frac{W}{L} Q_n V_{DS}$$

$$Q_n = \frac{Q}{A} = \frac{\epsilon_{ox}}{t_{ox}} V$$

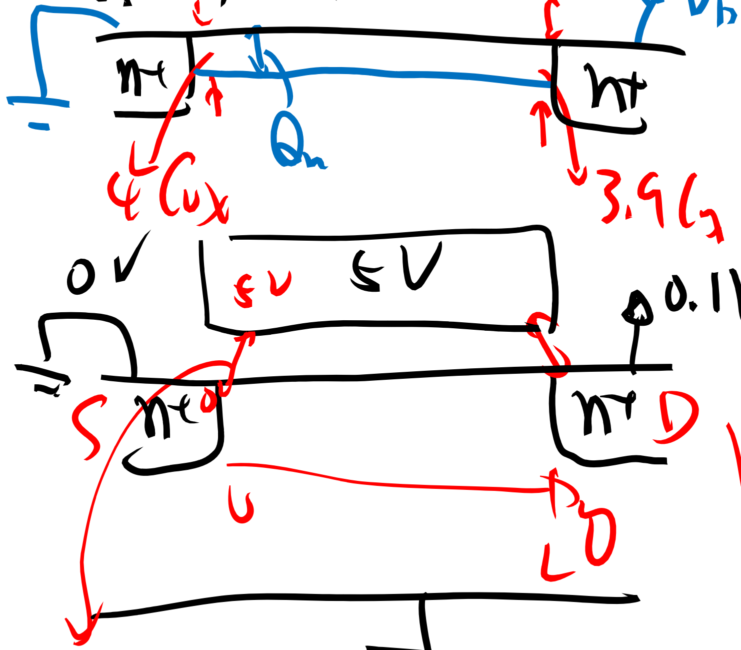
$\left(\frac{C}{m^2}\right)$ $\quad C_{ox}$

~~$Q_n = C_{ox} V$~~

$$Q_n = -C_{ox}(V_{GS} - V_T)$$

① $V_{GS} > V_T \Rightarrow |Q_n| > 0$

0.1V V_{DS} 很小 $< 0.1V$



$V_T = 1V$

$V_{GS} = 5V$

$V_{GD} = V_G - V_D = 5 - 0.1 = 4.9V$

$V_{GS} = 5 - 0 = 5V$

$Q_n(y=L) = -C_{ox}(5 - 0.1 - 1V)$

$= -C_{ox}(5 - 0.1 - 1V)$

$Q_n(y=0) = -C_{ox}(5 - 0 - 1V)$

$I_n = \frac{?}{?} \mu \frac{W}{L} C_{ox}(V_{GS} - V_T) \cdot 0.1V$

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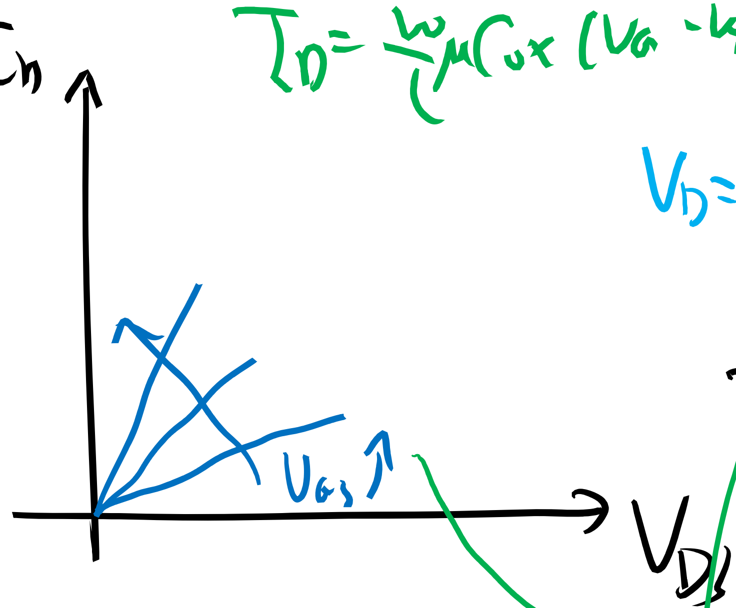


$$I_D = \frac{W}{L}\mu C_{ox}(V_G - V_T)V_D$$

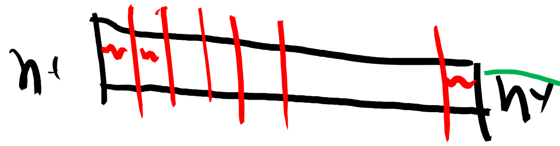
$$V_D = V_G - V_T$$

$$I_D = \mu \frac{W}{L} C_{ox}(V_{GS} - V_T)$$

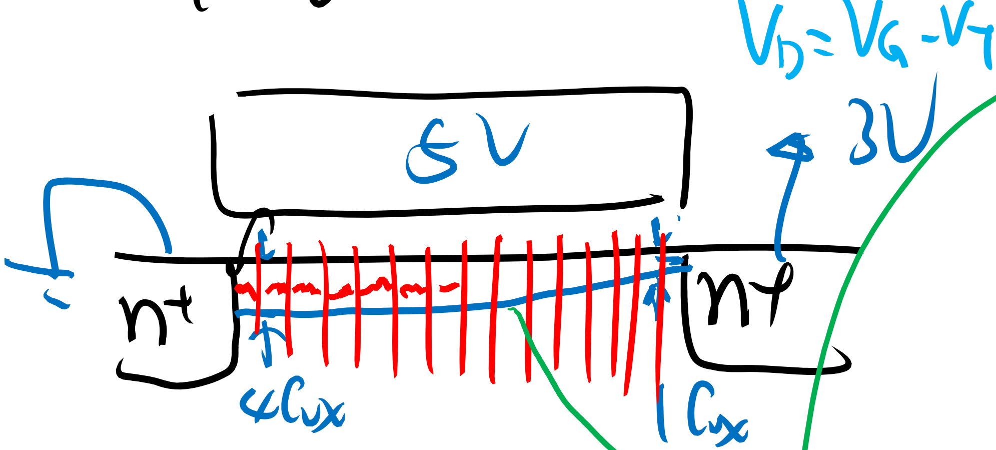
$$I_D = \mu \frac{W}{L} C_{ox}(V_{GS} - V_T)\cdot V_{DS}$$

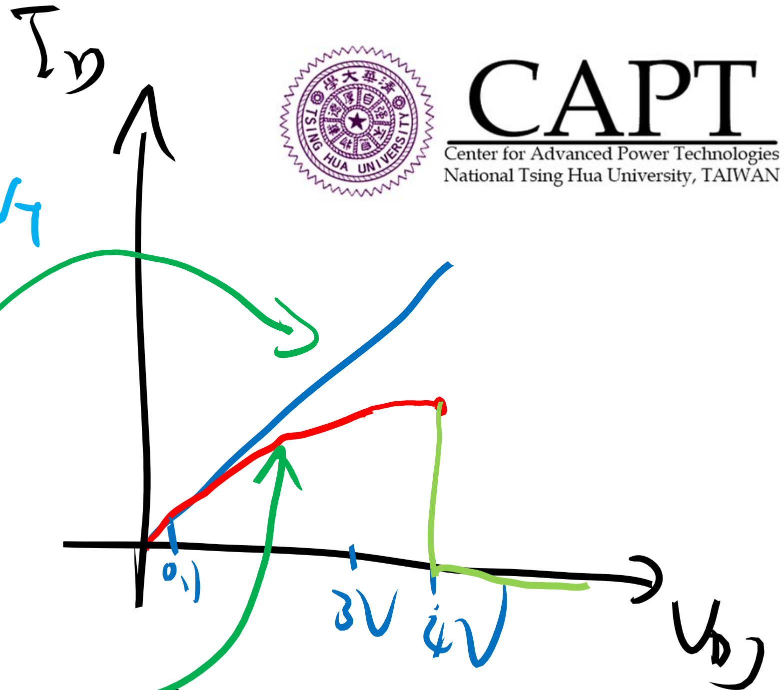
$$R_{on} = \frac{V_{DS}}{I_D} = \frac{1}{\mu \frac{W}{L} C_{ox}(V_{GS} - V_T)}$$

$$R_{on} = \frac{L}{W}\frac{1}{\mu C_{ox}(V_G - V_T)} = \frac{L}{W}R_n = R_n\frac{L}{W}$$



② $V_G = 5V$, $V_{DS} = 3V$
$V_T = 1V$

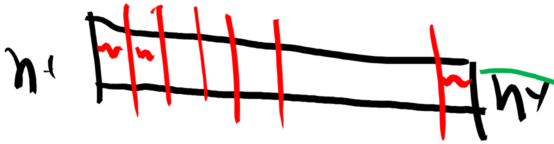


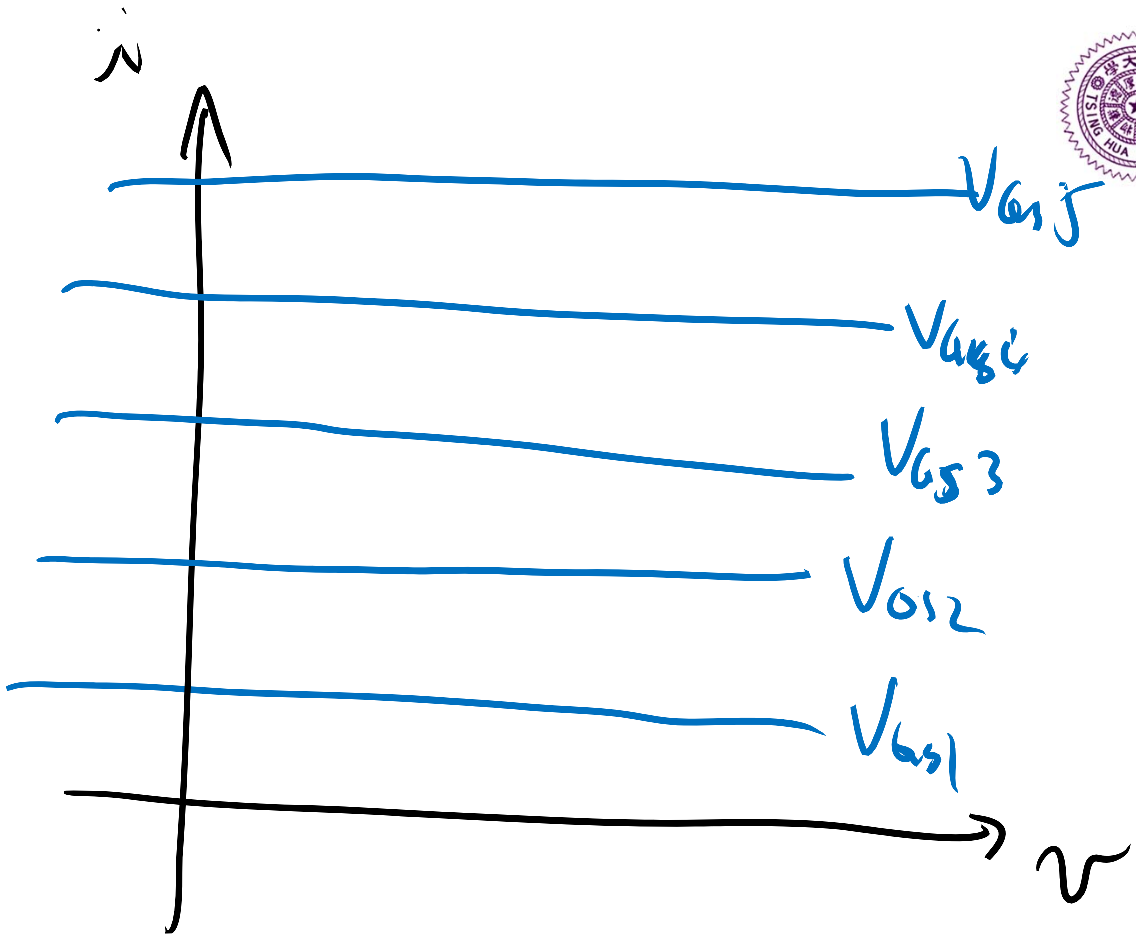


$Q_n(y=0) = -C_{ox}(5-0-1) = -4C_{ox}$

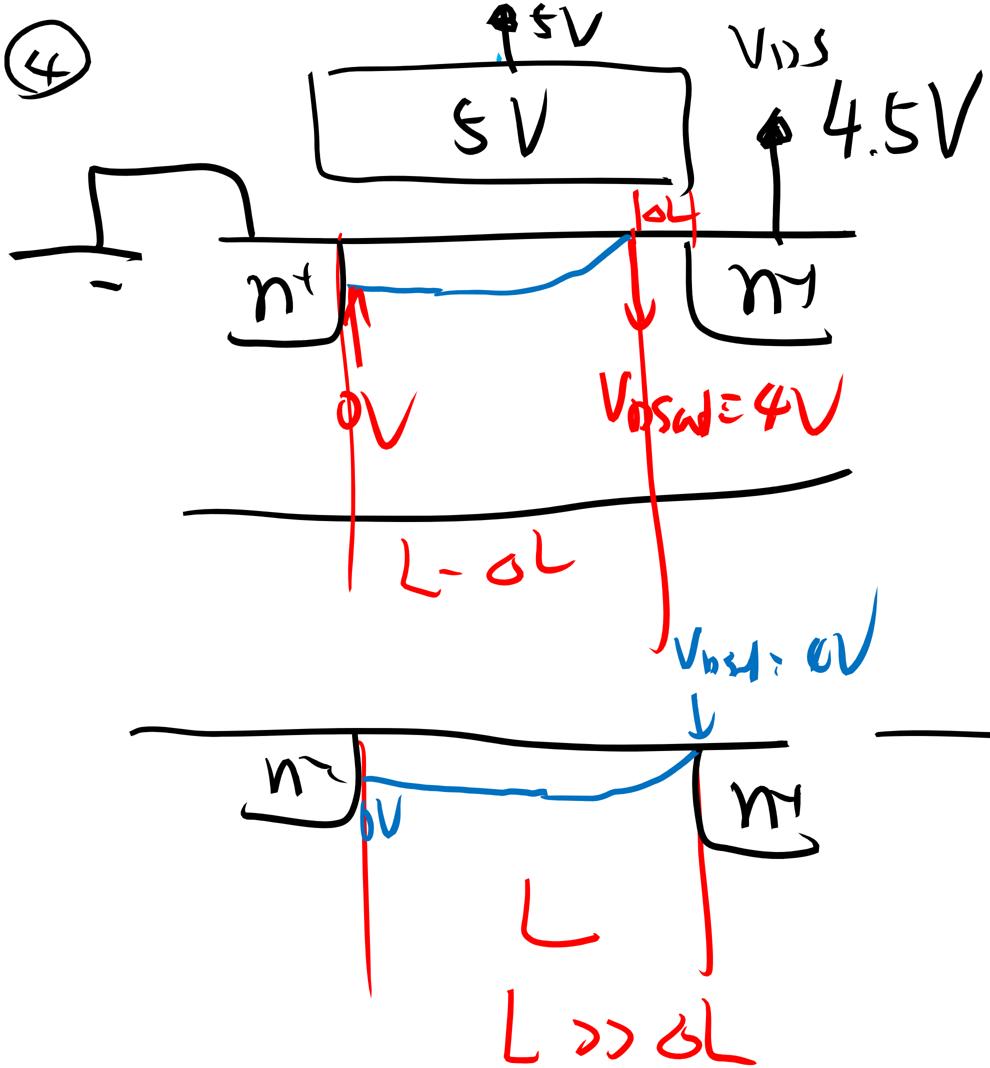
$Q_n(y=L) = -C_{ox}(5V-3V-1) = -C_{ox}$

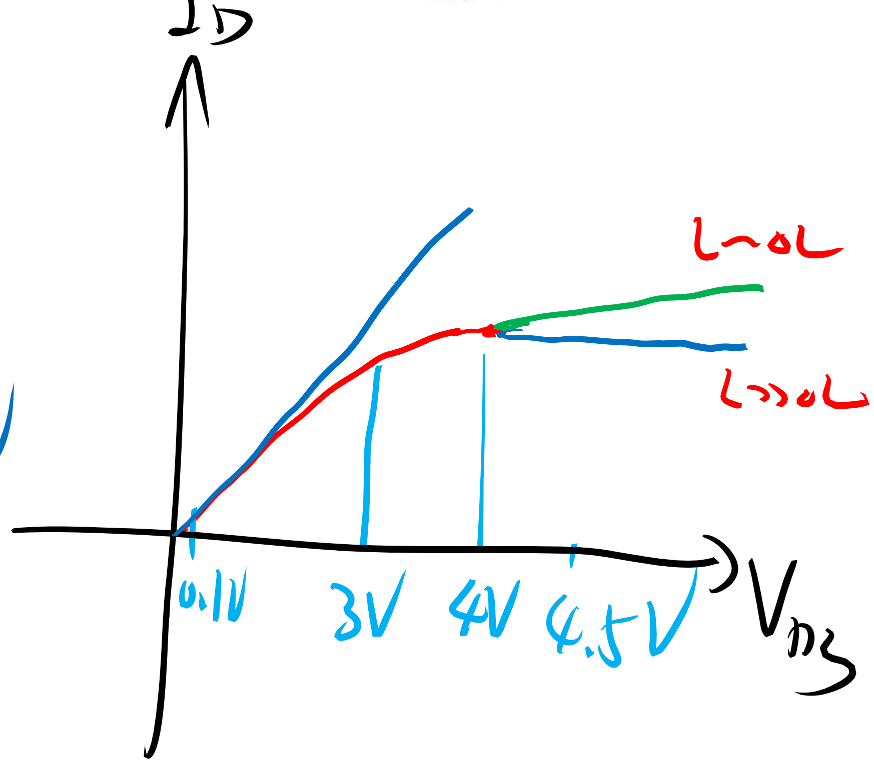
③ $V_{DS} = 4V = V_{Dsat} = V_{GS} - V_T$ $Q_n = 0$





$i = g_m V_{GS}$





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Actual *i-v* characteristics of the MOSFET

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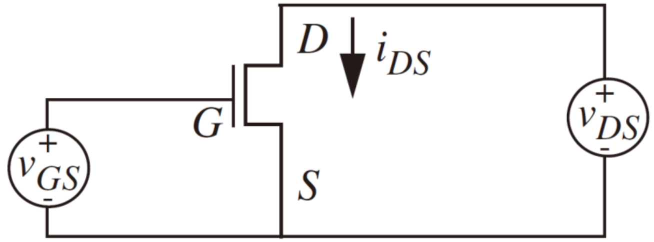
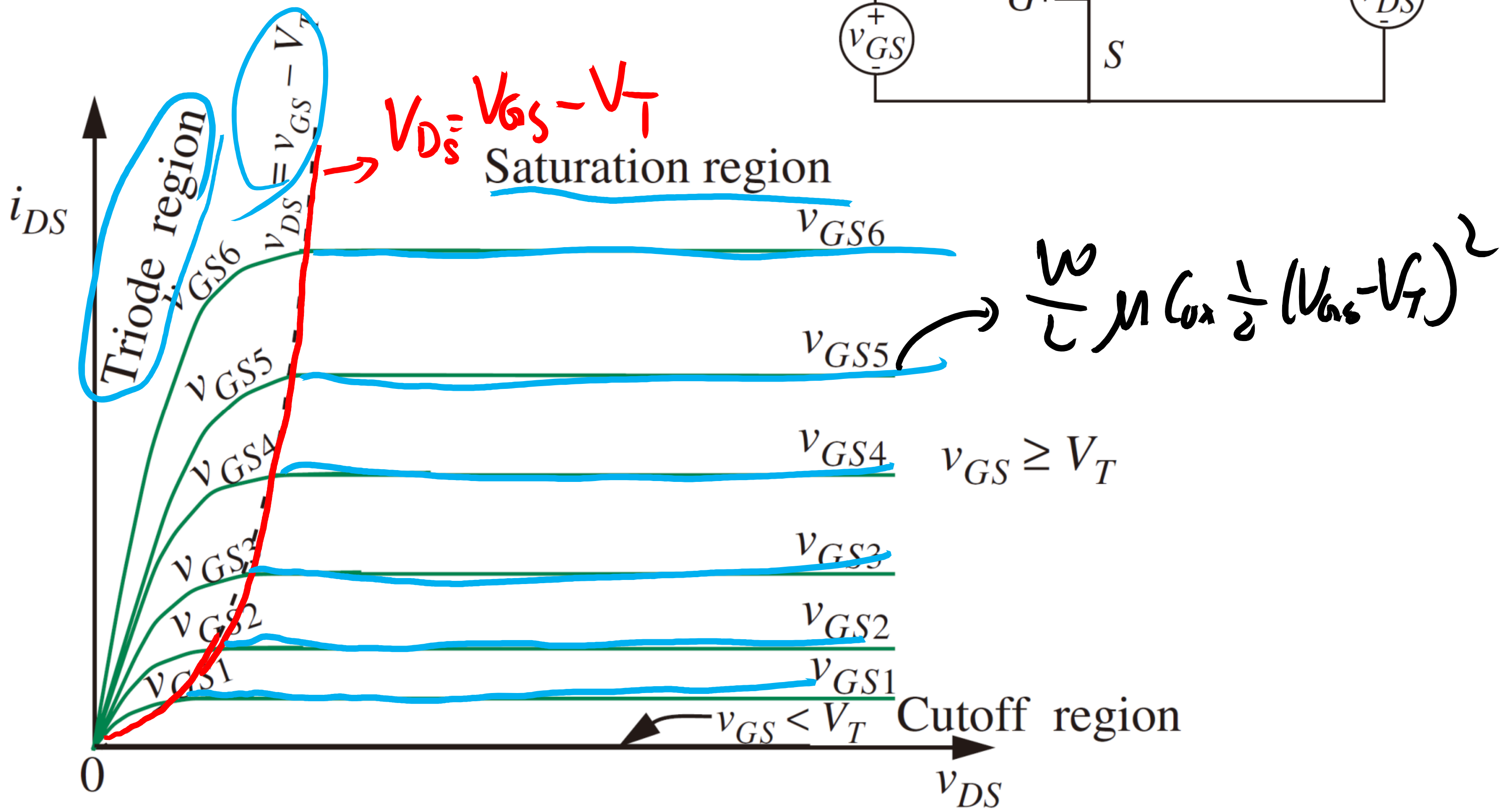
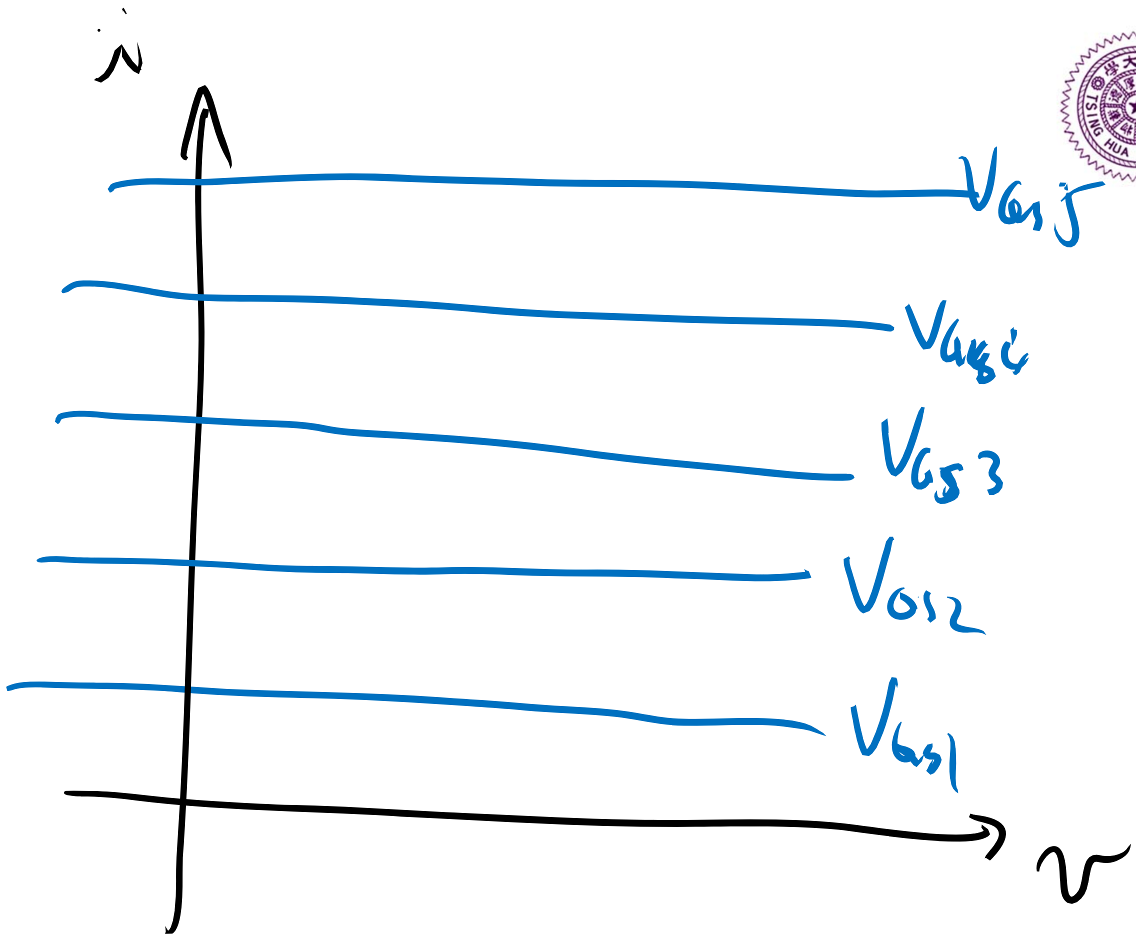
- Setup for observing MOSFET characteristics.





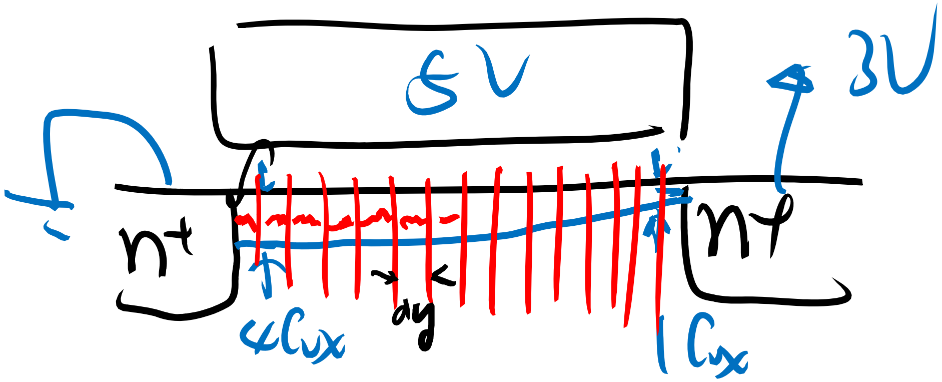
Actual *i*-*v* characteristics showing the ***triode***, ***saturation***, and ***cutoff*** regions

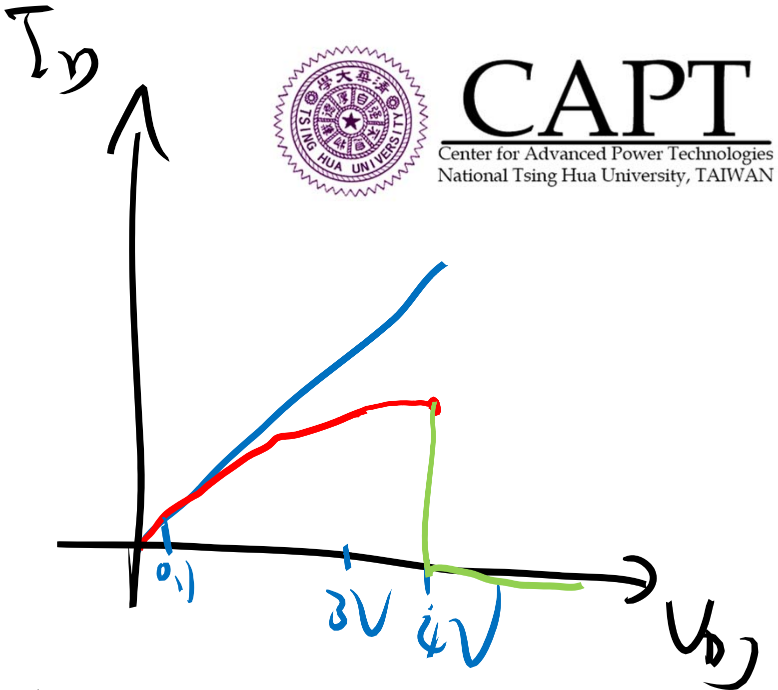


$i = g_m V_{GS}$

② $V_{GS} = 5V$, $V_{DS} = 3V$

$V_T = 1V$





$V_c(y)$

$dV_c(y)$

$$R(y) = \frac{dy}{W}\,\frac{1}{\mu C_{ox}(V_{GS}-V_c(y)-V_T)}$$

$$dV_c(y) = I_D \cdot R(y)$$

$$dV_c(y) = I_D\,\frac{dy}{W}\,\frac{1}{\mu C_{ox}(V_{GS}-V_c(y)-V_T)}$$

$$\int_0^{V_{DS}} W\mu C_{ox}(V_{GS}-V_c(y)-V_T)\,dV_c(y) = \int_0^{L} I_D\,dy$$

$$W\mu C_{ox}\left[(V_{GS}-V_T)V_C-\frac{1}{2}V_C^2\right]\Bigg|_0^{V_{DS}} = I_D \cdot y\Big|_0^L$$

$$I_D \cdot L = W\mu C_{ox}\left[(V_{GS}-V_T)V_{DS}-\frac{1}{2}V_{DS}^2\right]$$

$$I_D = \frac{W}{L}\mu C_{ox}\left[(V_{GS}-V_T)V_{DS}-\frac{1}{2}V_{DS}^2\right]$$

at $V_{DS\,sat} = V_{GS}-V_T$

$$I_{D\,sat} = \frac{W}{L}\mu C_{ox}\left[(V_{GS}-V_T)^2-\frac{1}{2}(V_{GS}-V_T)^2\right]$$

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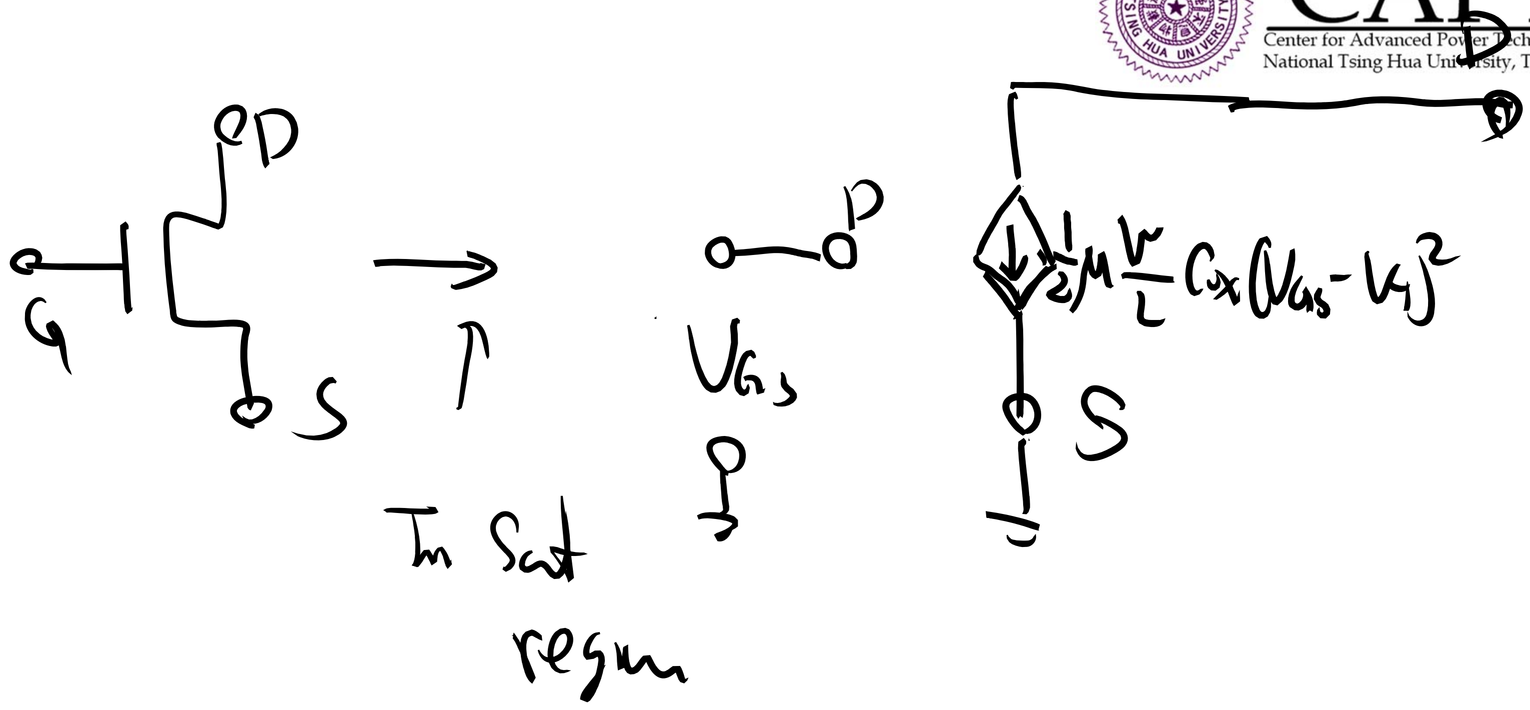
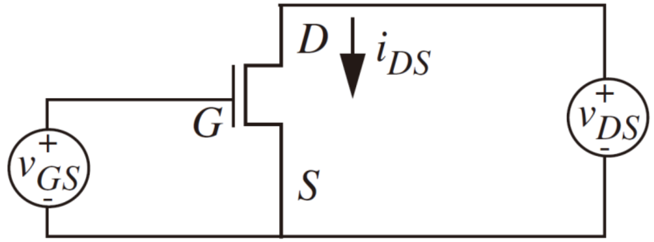
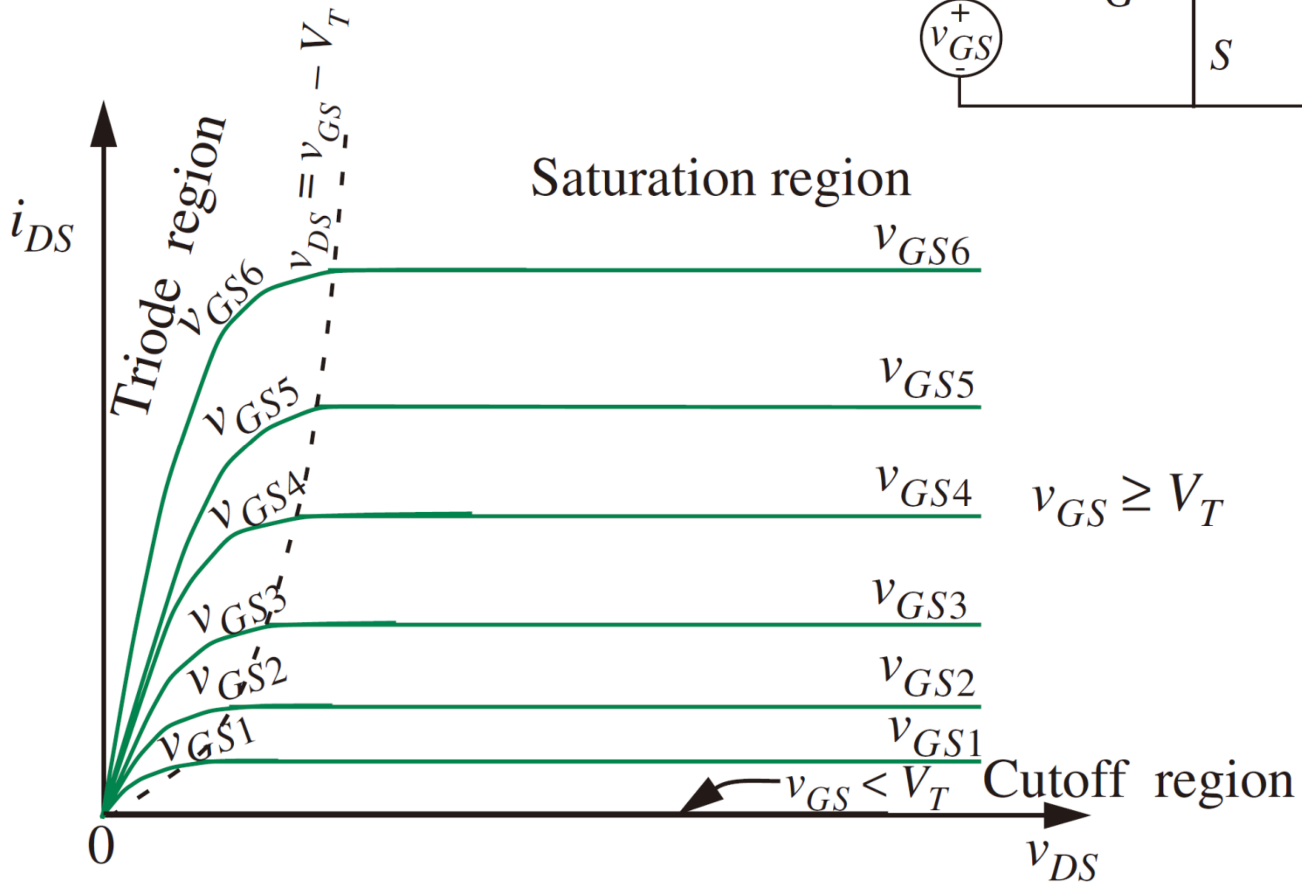
$$I_{D_{sat}} = \frac{W}{L} \mu C_{ox} \frac{1}{2} (V_{GS} - V_T)^2$$


D
G
S
In Sat
regim
VGS
D
S
1/2 μ W/L Cox (VGS - Vt)^2

Actual *i-v* characteristics of the MOSFET

- Setup for observing MOSFET characteristics.

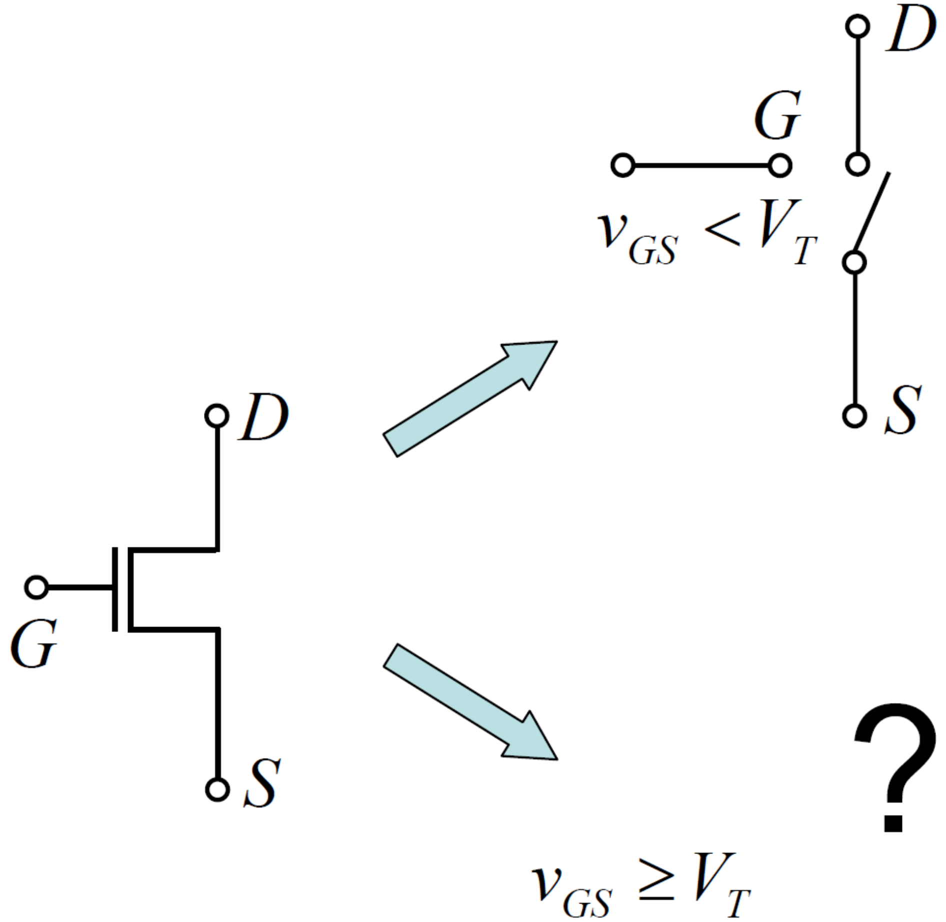




Actual *i*-*v* characteristics showing the ***triode***, ***saturation***, and ***cutoff*** regions

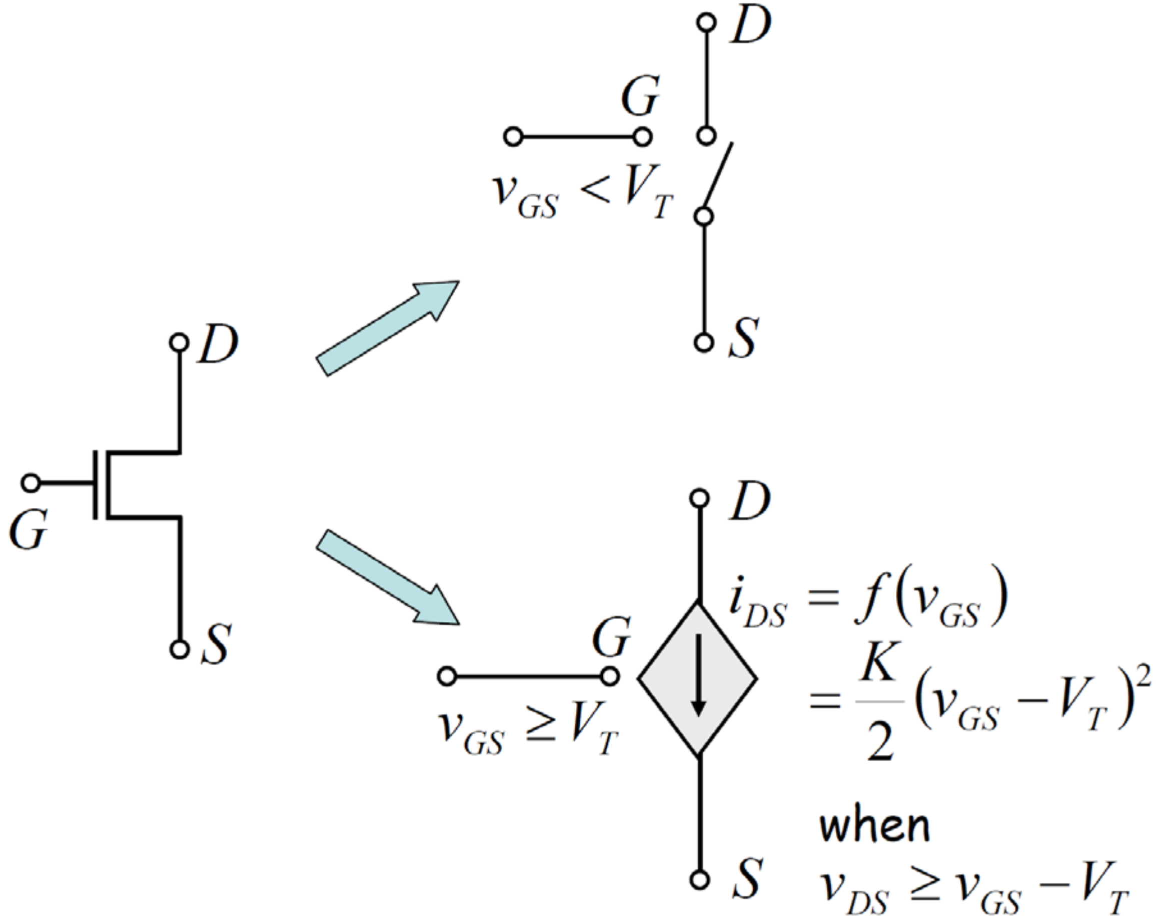
New Model Needed

- First, we sort of lied. The on-state behavior of the MOSFET is quite a bit more complex than either the ideal switch or the resistor model would have you believe.



SCS model of MOSFET

- The switch current source (SCS) model of the MOSFET
- This is more accurate than the S or SR model



MOSFET amplifier

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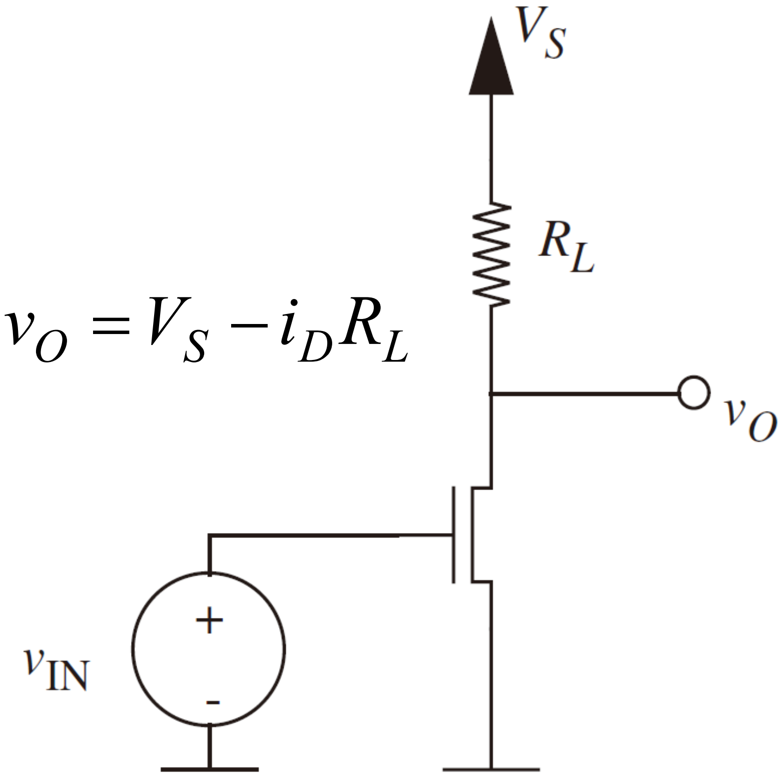
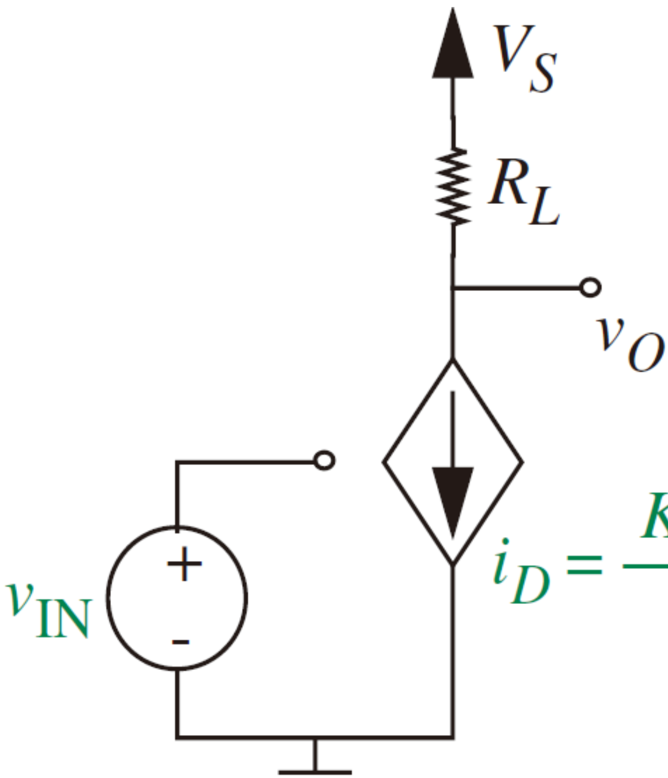
- Find the transfer function for the MOSFET amplifier if MOSFET operated in saturation region.

$$v_O = V_S - K\frac{(v_{IN} - V_T)^2}{2}R_L$$

$$v_O = V_S - i_D R_L$$

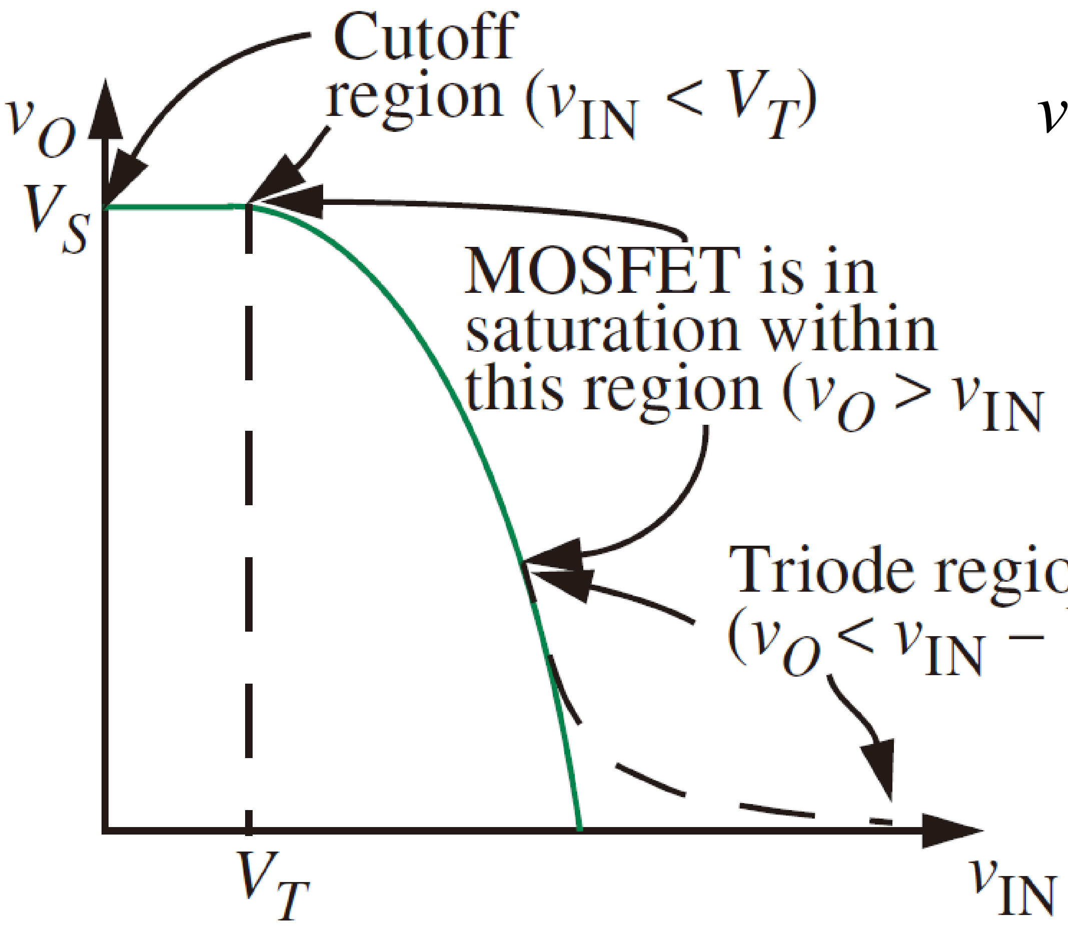




$$i_D = \frac{K(v_{IN} - V_T)^2}{2}$$

Transfer Function with SCS Model

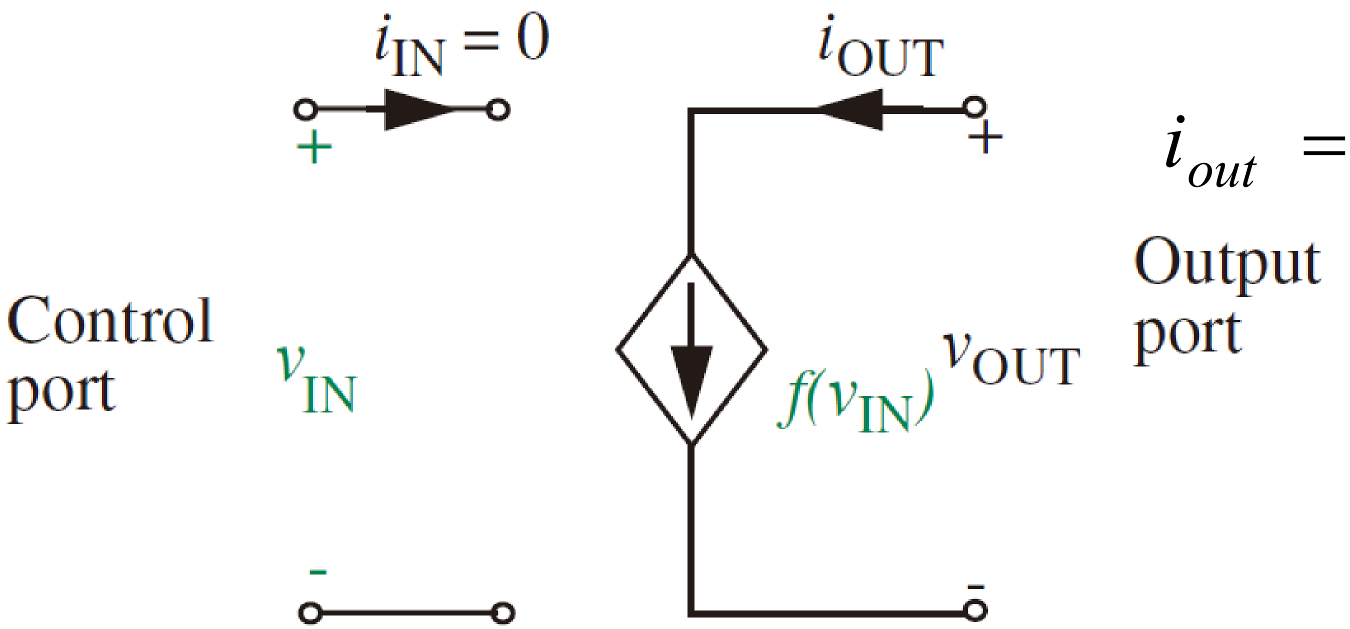
- Find the transfer function for the MOSFET amplifier if MOSFET operated in saturation region.



$$v_O = V_S - K\frac{(v_{IN} - V_T)^2}{2}R_L$$

Dependent Source

- New type of Element: ***Dependent source***



$$i_{out} = f(v_{in})$$

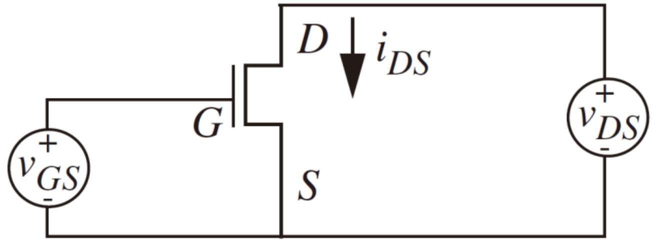
For MOSFET

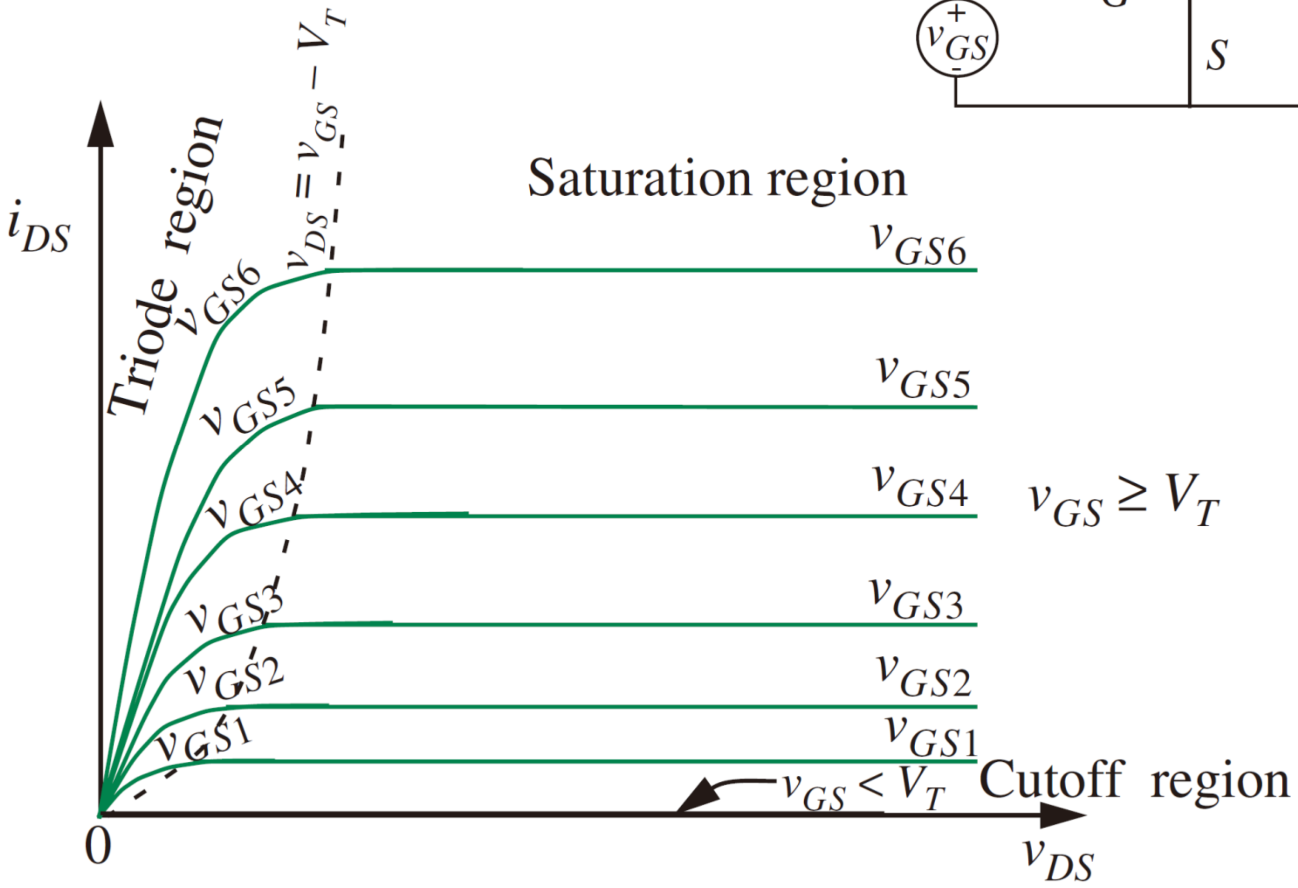
$$i_{out} = \frac{k}{2}(v_{in} - V_T)^2 \text{ for } v_{in} \geq V_T$$

$$i_{out} = 0 \text{ for } v_{in} < V_T$$

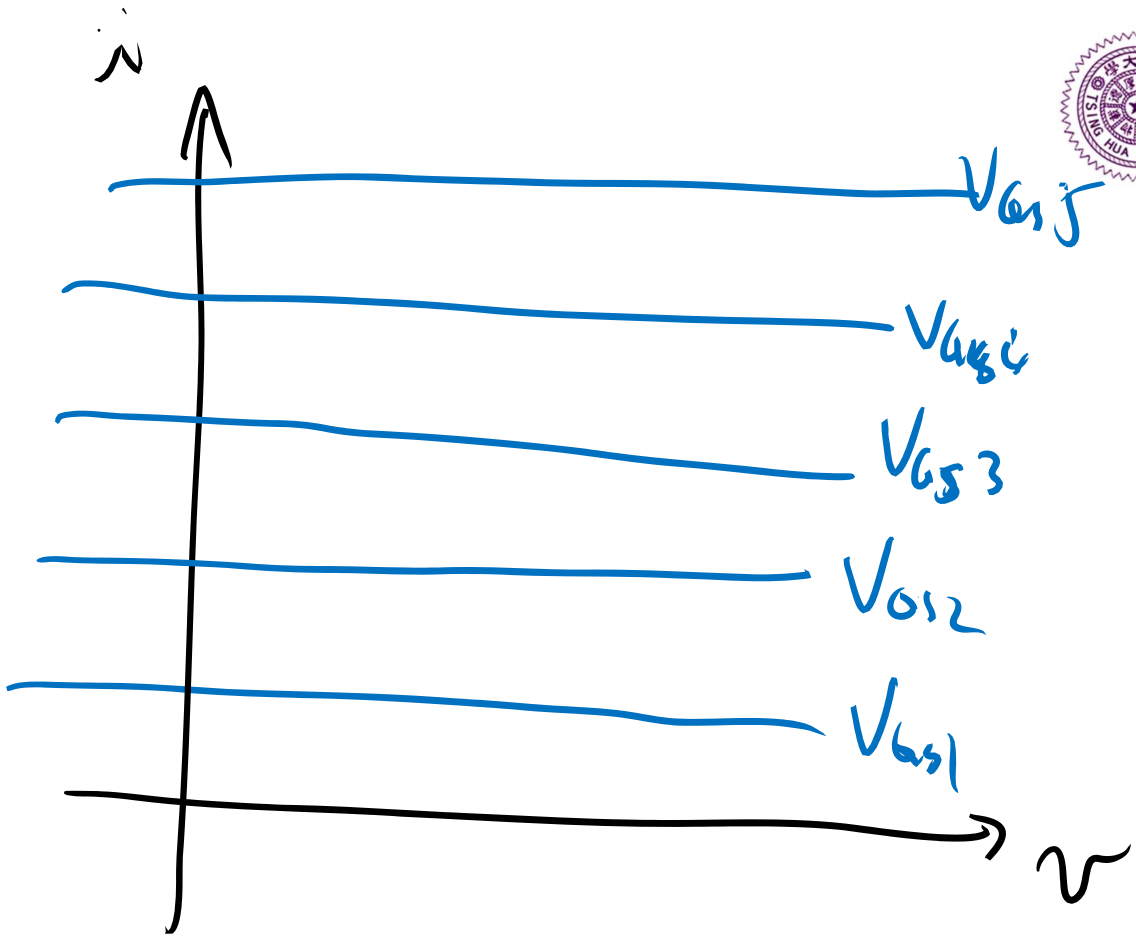
Actual *i-v* characteristics of the MOSFET

- Setup for observing MOSFET characteristics.





Actual *i*-*v* characteristics showing the ***triode***, ***saturation***, and ***cutoff*** regions



$i = g_m V_{GS}$

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$i_D = I_D + i_d$

DC   small signal

$i_D = \frac{k}{2}(v_{GS} - V_T)^2$

$I_D + i_d = \frac{k}{2}(V_{GS} + v_{gs} - V_T)^2$

$= \frac{k}{2}(V_{GS} - V_T)^2 + \frac{k}{2} 2 (V_{GS} - V_T) v_{gs} + \frac{k}{2} v_{gs}^2$

$i_d = k(V_{GS} - V_T) v_{gs} + \frac{k}{2} v_{gs}^2$ (crossed out) small signal mode

$i_d = k(V_{GS} - V_T) v_{gs}$ ←   → li

Linear Dependent Source

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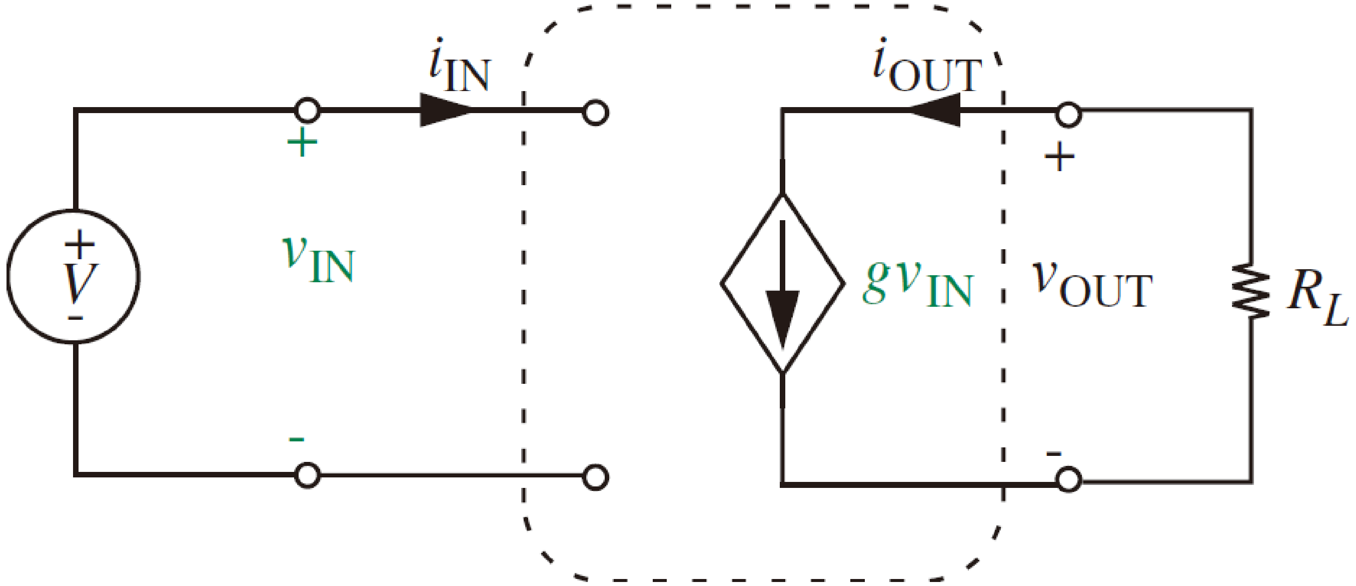
- If the ***Dependent source*** is linear, say $f(v_{in}) = gv_{in}$.



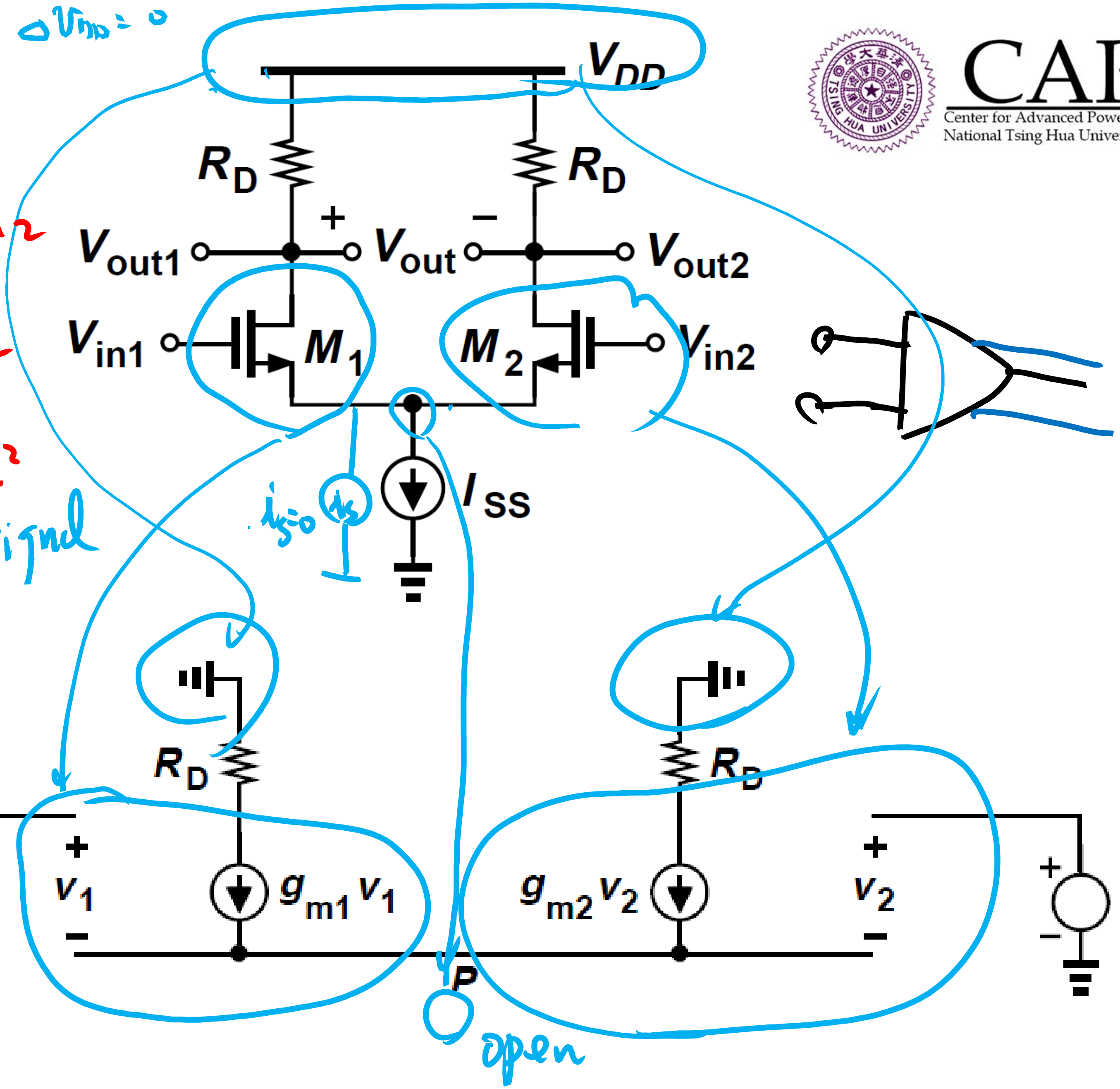
- This type of dependent sources is called ***voltage-controlled current source* (VCCS).** Current at output port is a function of voltage at the input port. g is called the ***transconductance***.

V_{in1}

$= V_{in1} + V_{in2}$

$= \frac{V_{in1} + V_{in2}}{2} + \frac{V_{in1} - V_{in2}}{2}$

small signal



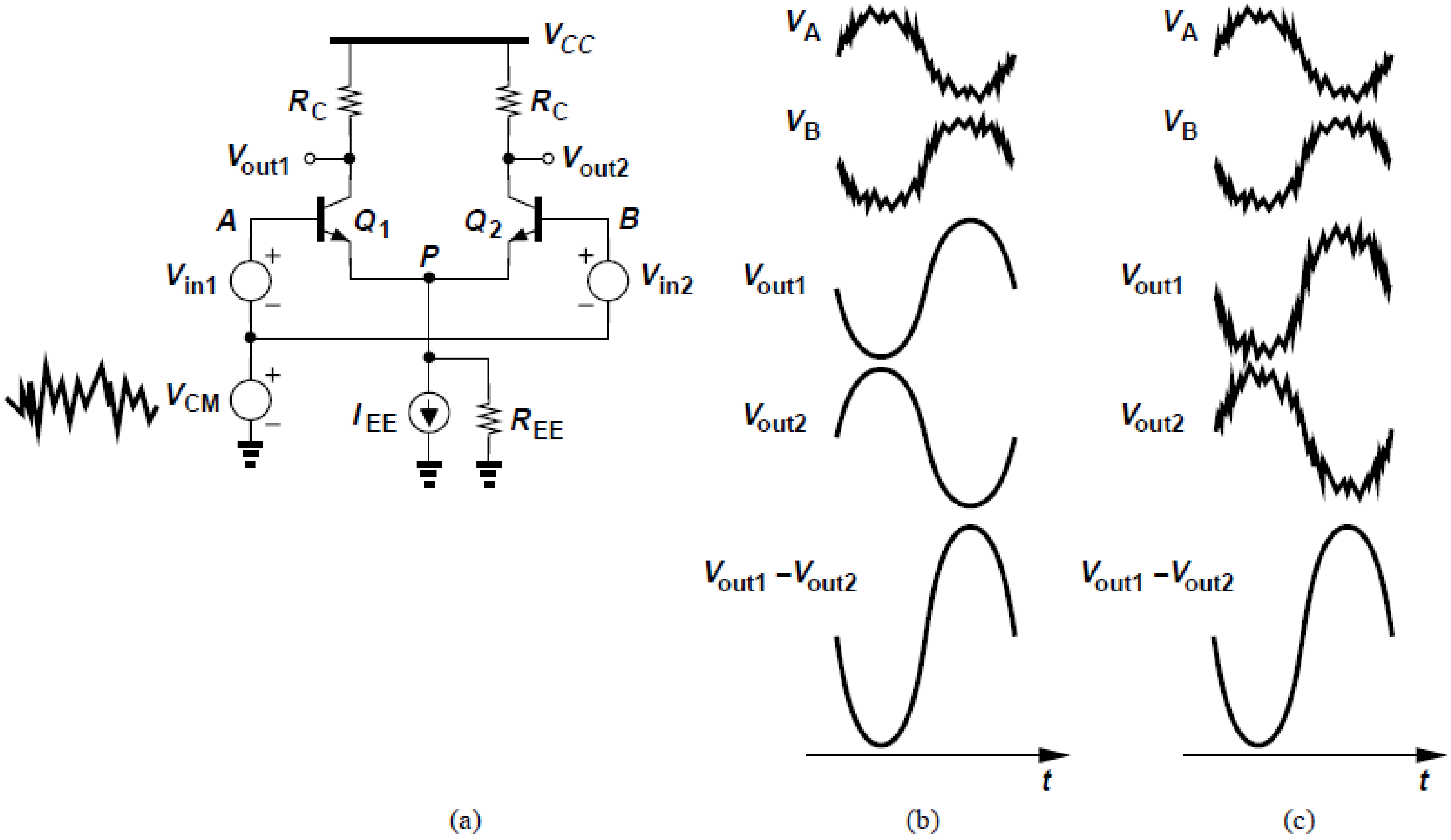


Figure 10.44 (a) Differential pair sensing input CM noise, (b) effect of CM noise at output with $R_{EE} = \infty$, (c) effect of CM noise at the output with $R_{EE} \neq \infty$.

Noise Immunity of Diff. Amp.

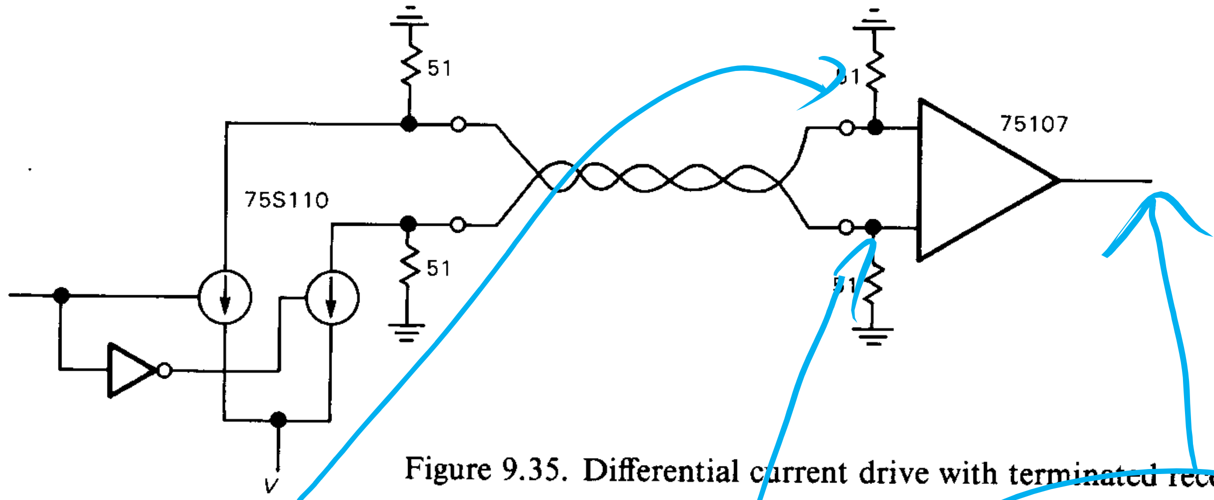


Figure 9.35. Differential current drive with terminated receiver

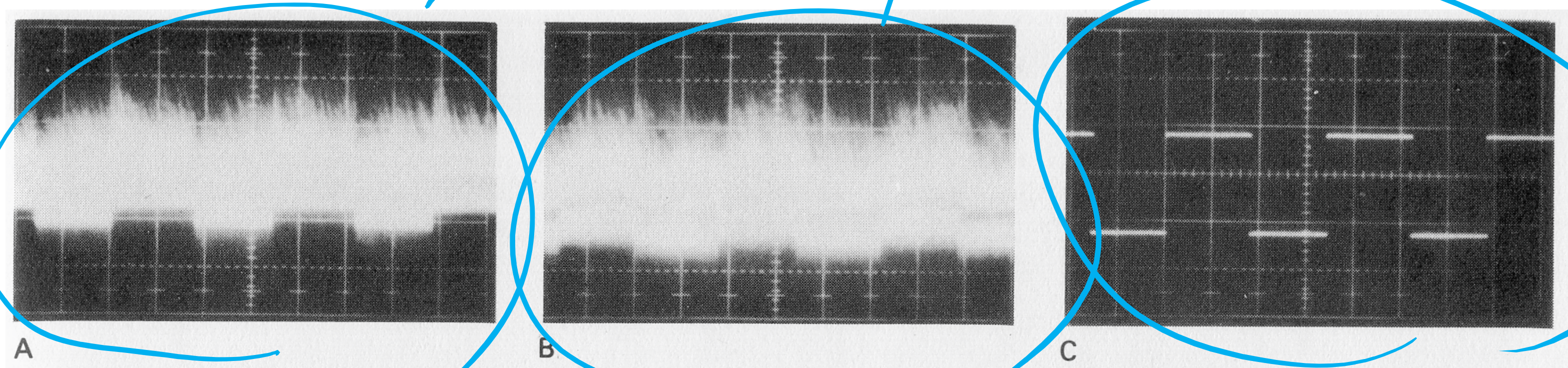
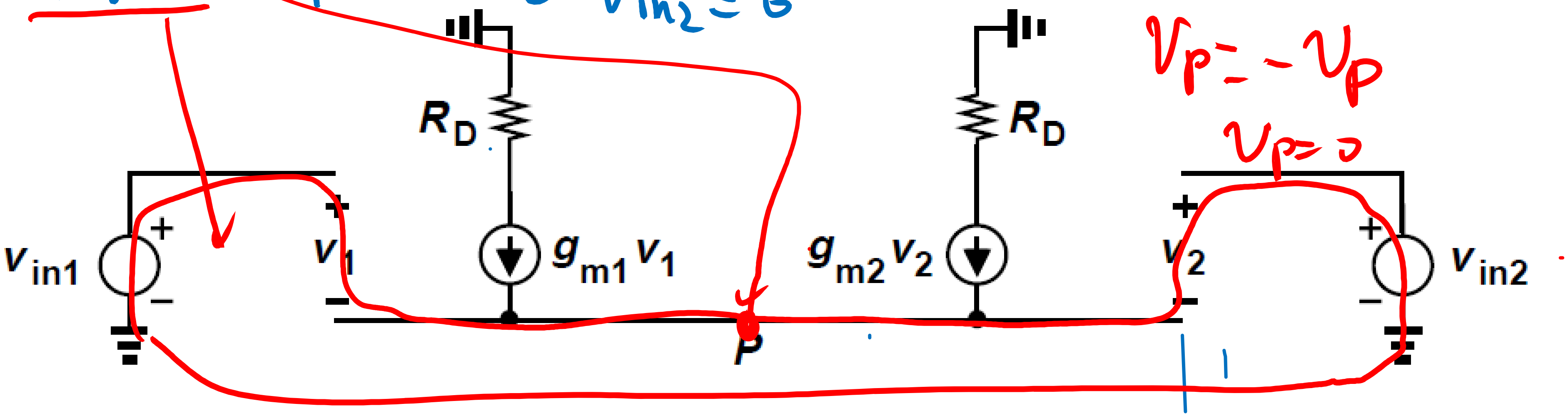


Figure 9.36. Scope photos showing excellent noise immunity of differential data transmission (75108 differential receiver). (Courtesy of Texas Instruments, Inc., Dallas, Texas.)
A. (+) receiver input.
B. (−) receiver input.
C. Receiver output.

KCL: $g_{m1}v_1 + g_{m2}v_2 = 0$

KVL: $V_{in1} - V_1 + V_2 - V_{in2} = 0$



assume $g_{m1} = g_{m2}$ ⇒ from KCL ⇒ $v_1 = -v_2$

V_{in1} 和 V_{in2} 是 differential 信号 ⇒ $V_{in1} = -V_{in2}$

KVL: $V_{in1} - V_1 = V_{in2} - V_2 = -V_{in1} - (-V_1)$

$= -V_{in1} + V_1 = -(V_{in1} - V_1)$

($V_{in1} - V_1$ ‖ v_p)

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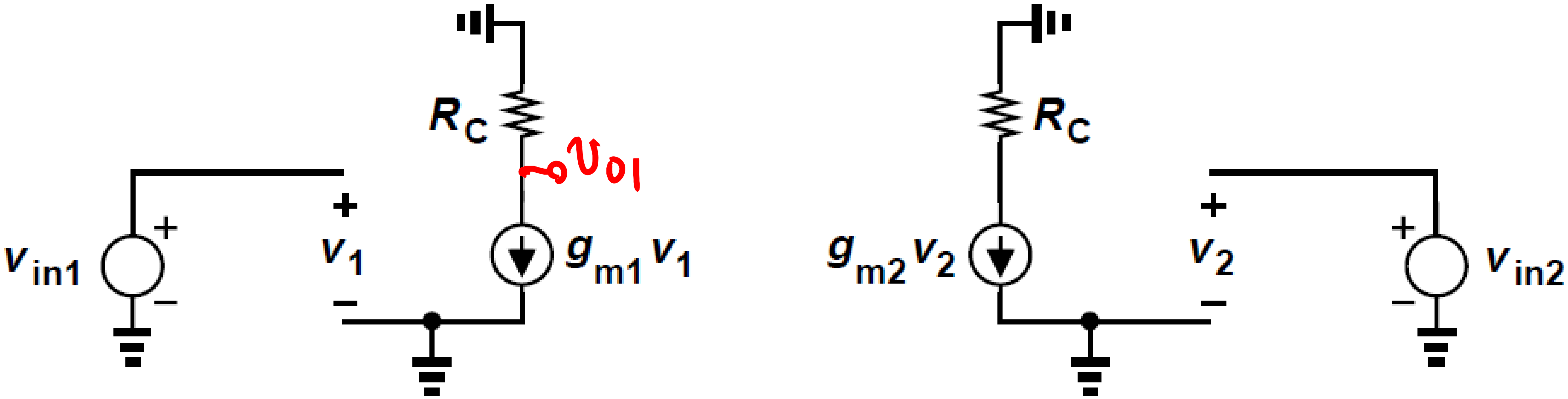
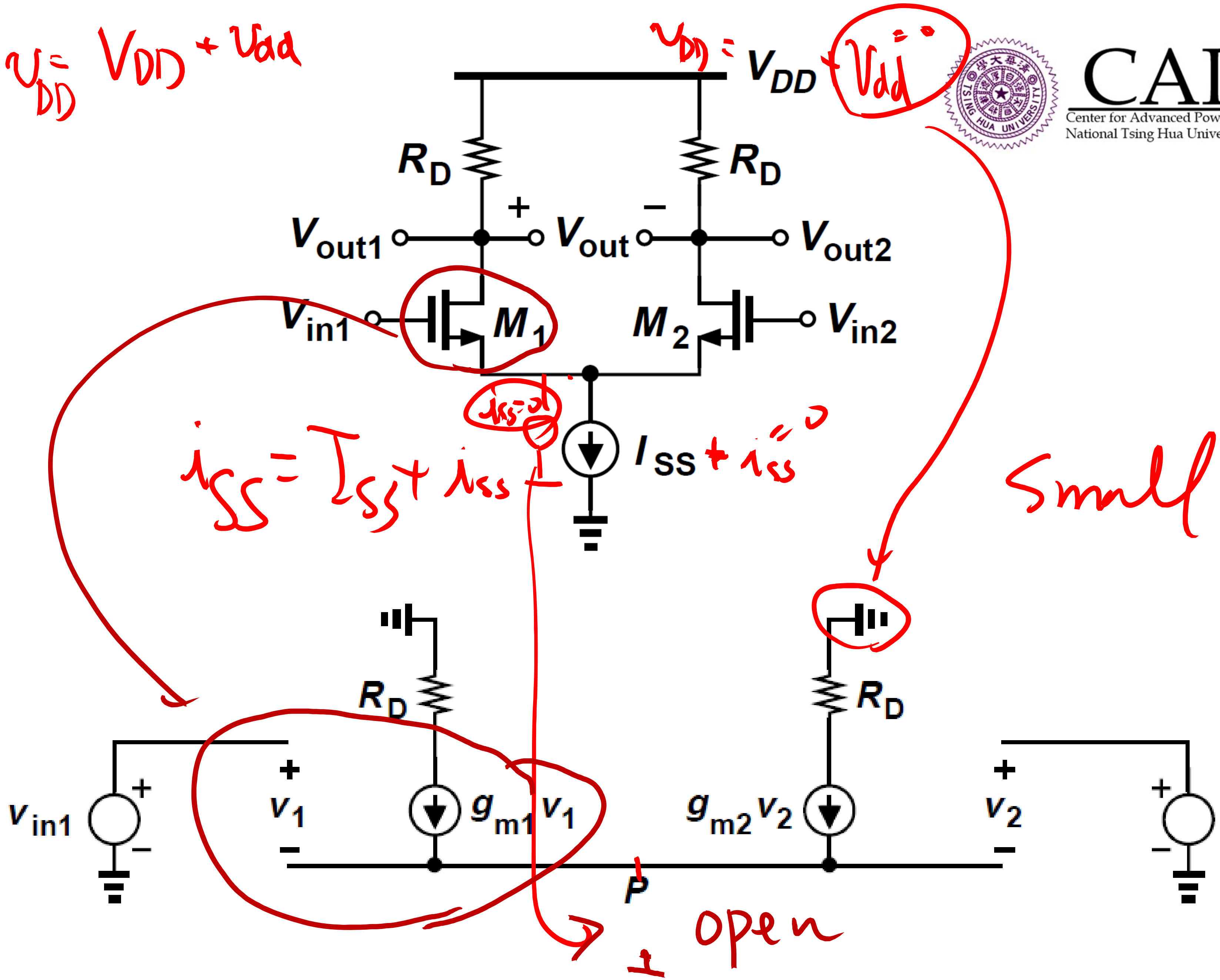
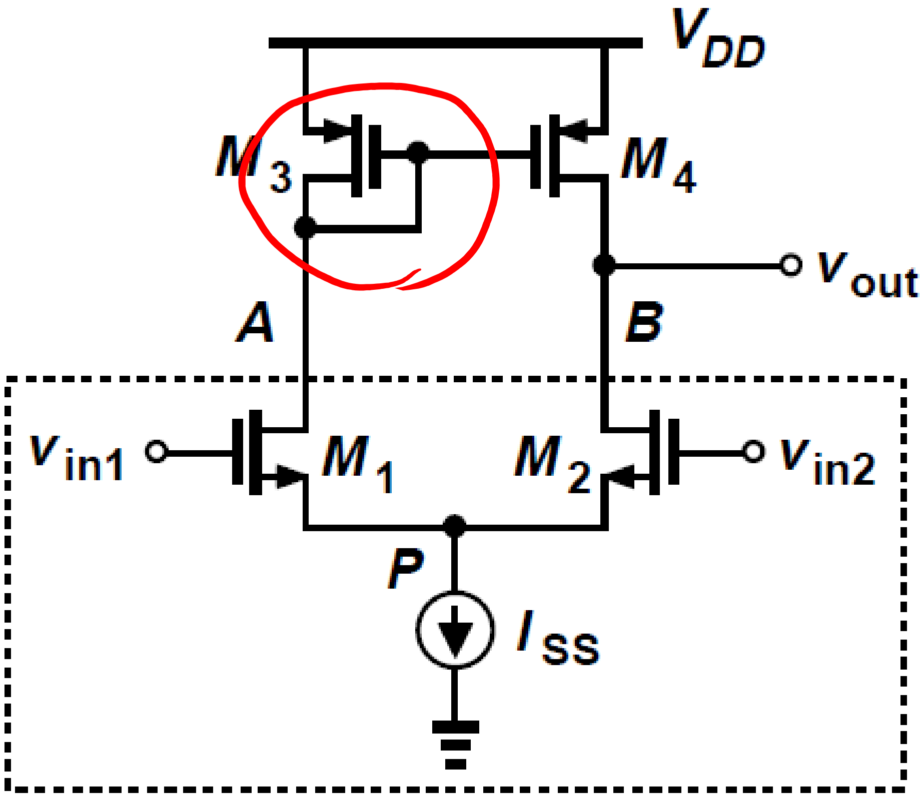
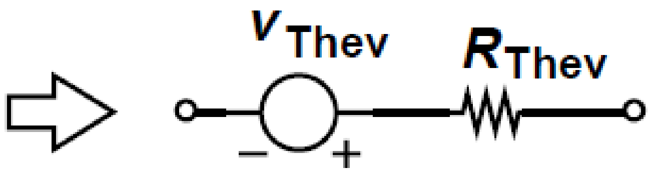


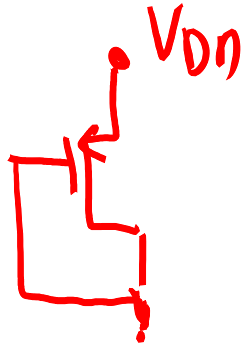
$$v_{o1} = -g_{m1} v_{in1} \cdot R_C$$

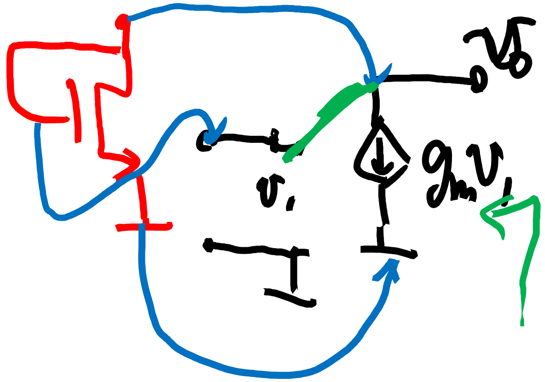
$$v_{o2} = -g_{m2} v_{in2} \cdot R_C$$

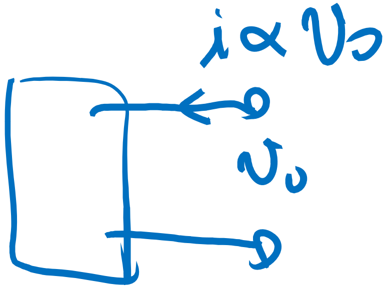

VDD
RD
RD
+
−
Vout1
Vout
Vout2
Vin1
M1
M2
Vin2
ISS
Small
RD
RD
vin1
+
−
+
v1
−
gm1v1
gm2v2
+
v2
−
+
−
vin2
P
open







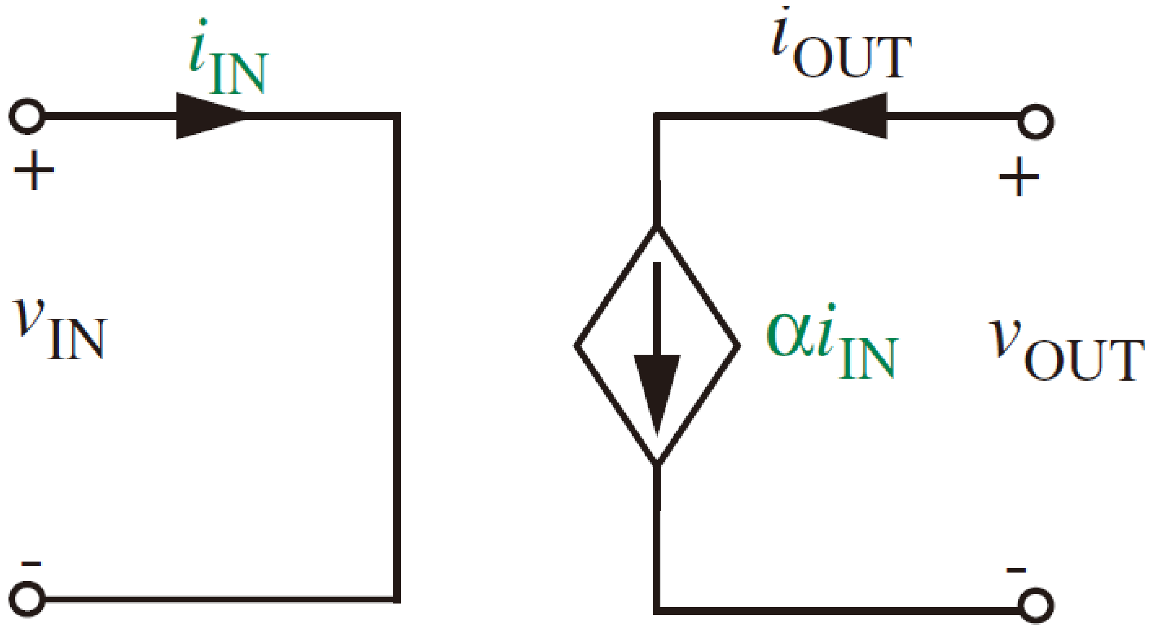




$$= \; r = \frac{v_o}{i} = \frac{v_o}{g_m v_o} = \frac{1}{g_m}$$

Other Linear Dependent Source

- There are 4 types of linear dependent sources : (a) ***Voltage-controlled current source*** (VCCS); (b) ***Current-controlled current source*** (CCCS); (c) ***Voltage-controlled voltage source*** (VCVS); (d) ***Current-controlled voltage source*** (CCVS).
- ***Current-controlled current source*** (CCCS) with α referred as current transfer ratio.



Other Linear Dependent Source

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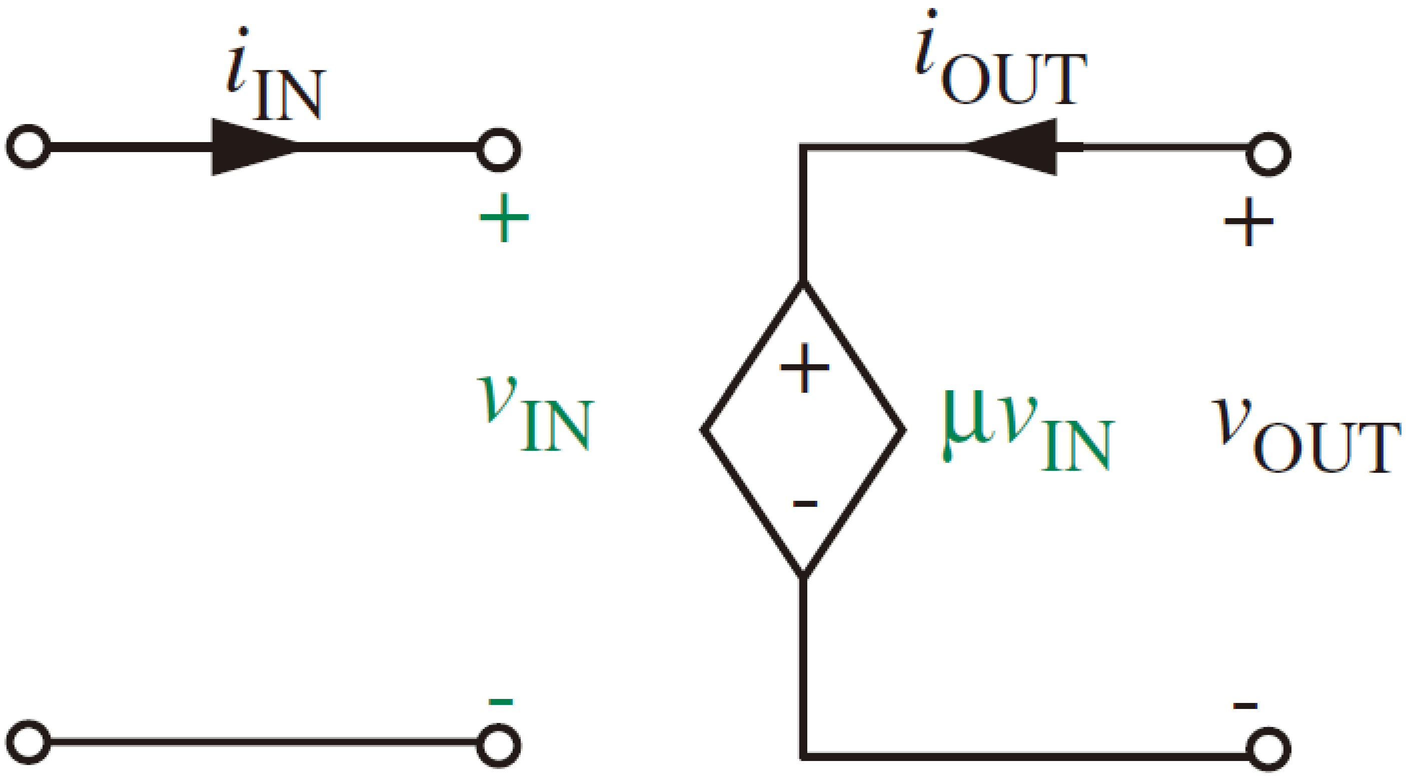
- ***Voltage-controlled voltage source*** (VCVS) with μ is referred to as a voltage transfer ratio.



Other Linear Dependent Source

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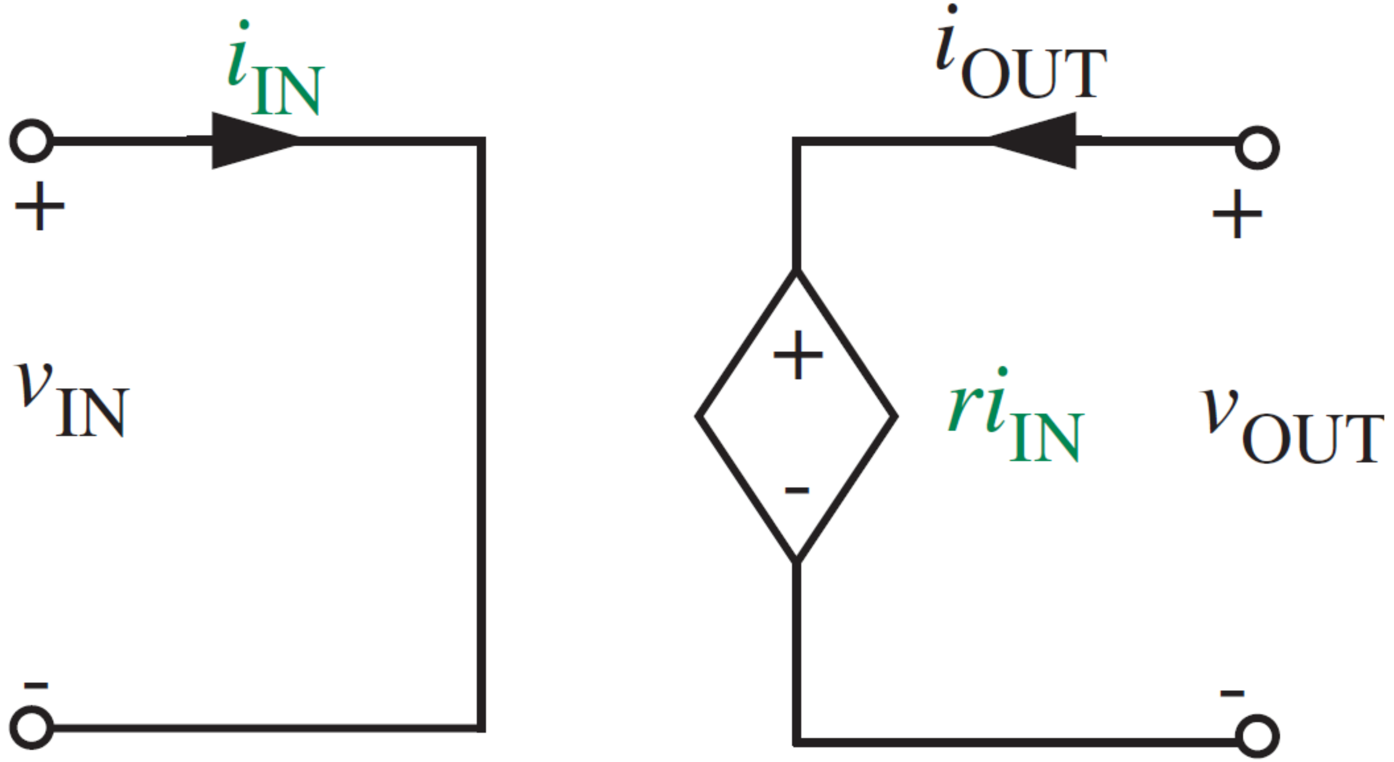
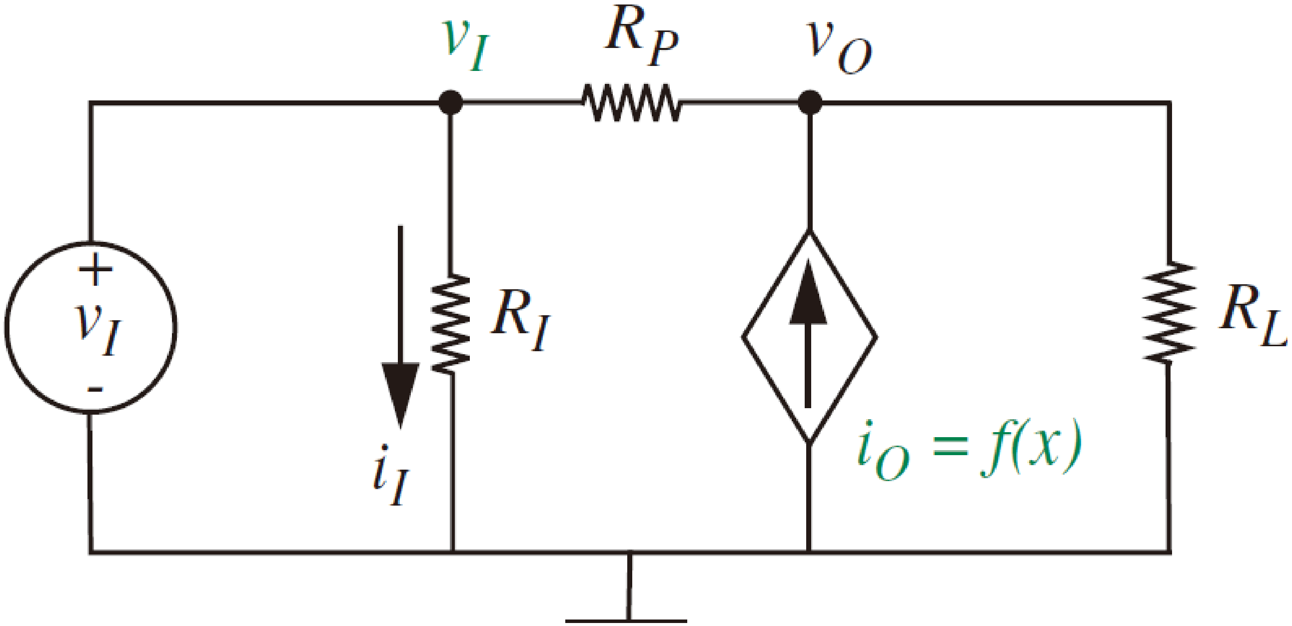
- ***Current-controlled voltage source*** (CCVS) with r is referred to as a transresistance.



Dependent Source and Node Eqs

- Find v_O/v_I of the following circuit, for (1) $i_O = -G_m v_I$ and (2) $i_O = -\beta\, i_I$.



$$\frac{v_I - v_O}{R_p} + i_O = \frac{v_O}{R_L}$$

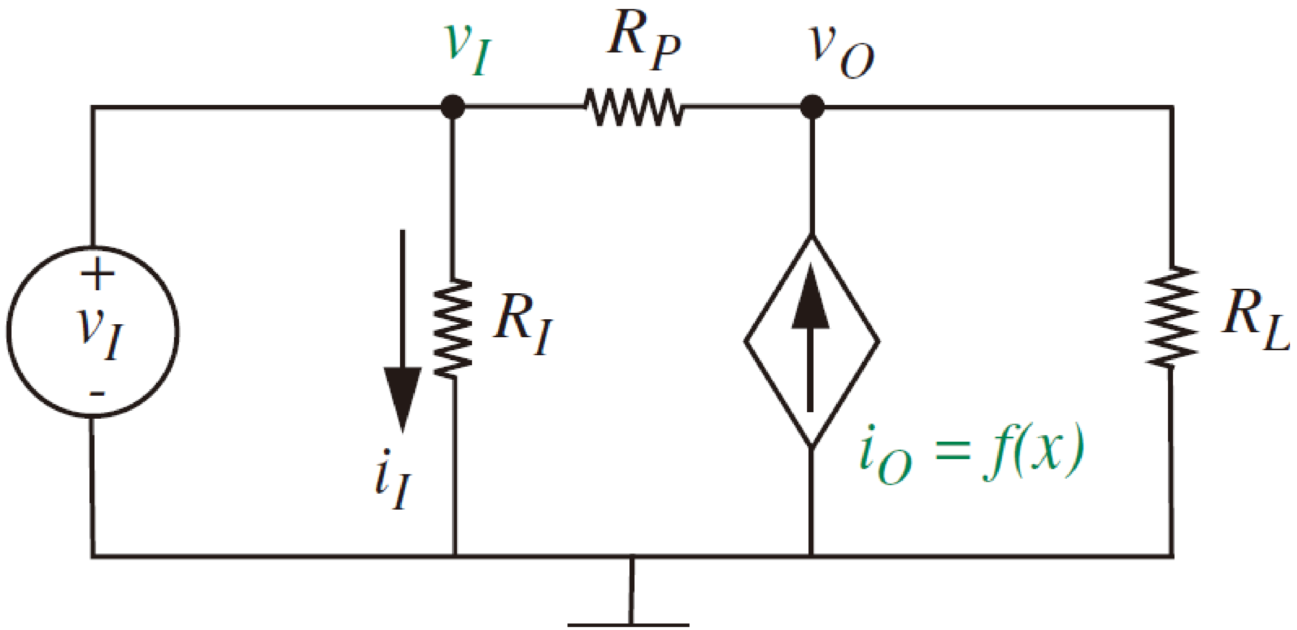
$$i_O = -G_m v_I$$

$$\frac{v_I - v_O}{R_p} - G_m v_I = \frac{v_O}{R_L}$$

$$\frac{v_O}{v_I} = \frac{(1 - G_m R_p) R_L}{R_p + R_L}$$

Dependent Source and Node Eqs

- Find v_O/v_I of the following circuit, for (1) $i_O = -G_m v_I$ and (2) $i_O = -\beta\, i_I$.



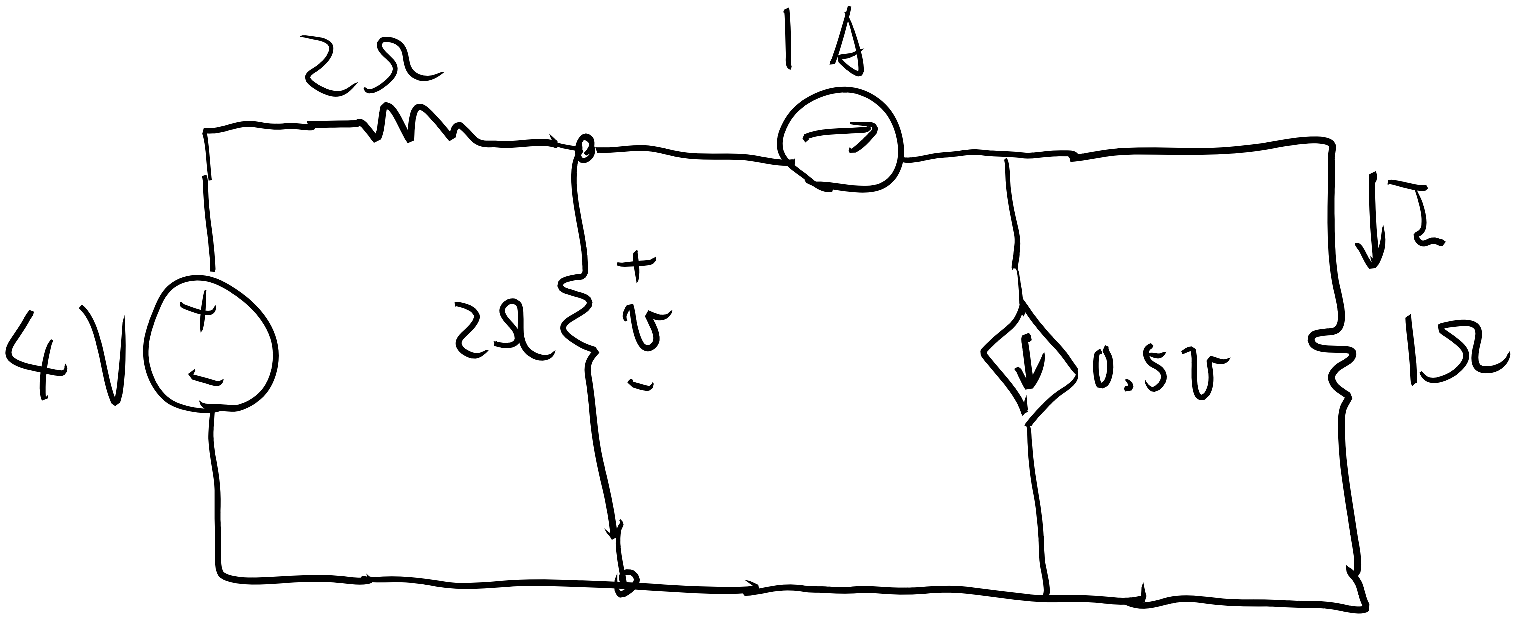
$$\frac{v_I - v_O}{R_p} + i_O = \frac{v_O}{R_L}$$

$$i_O = -\beta i_I = -\beta \frac{v_I}{R_I}$$

$$\frac{v_I - v_O}{R_p} - \beta \frac{v_I}{R_I} = \frac{v_O}{R_L}$$

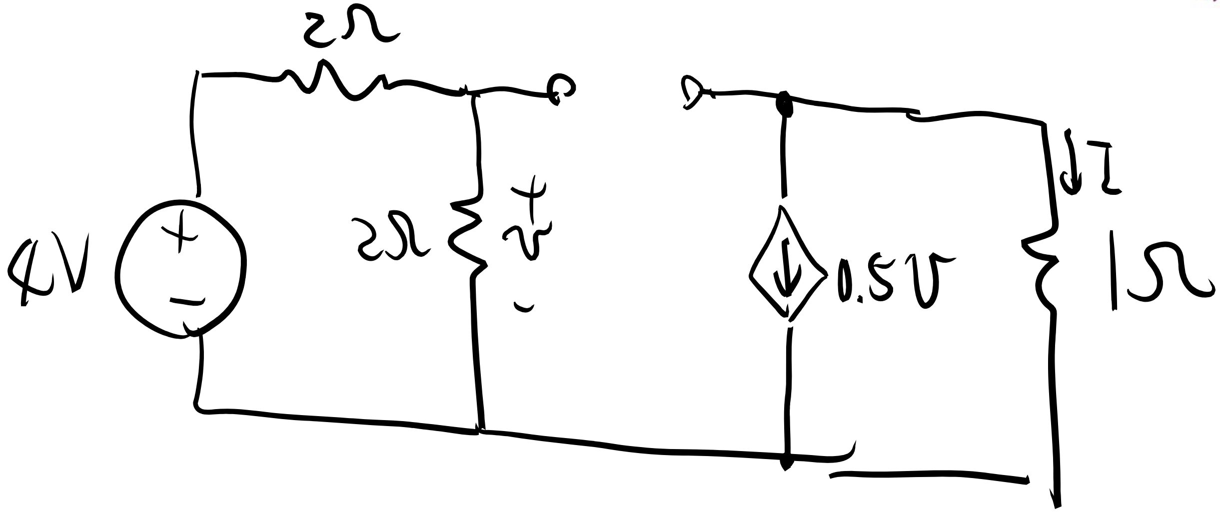
$$\frac{v_O}{v_I} = \frac{\left(1 - \beta \frac{R_p}{R_I}\right) R_L}{R_p + R_L}$$

• Superposition

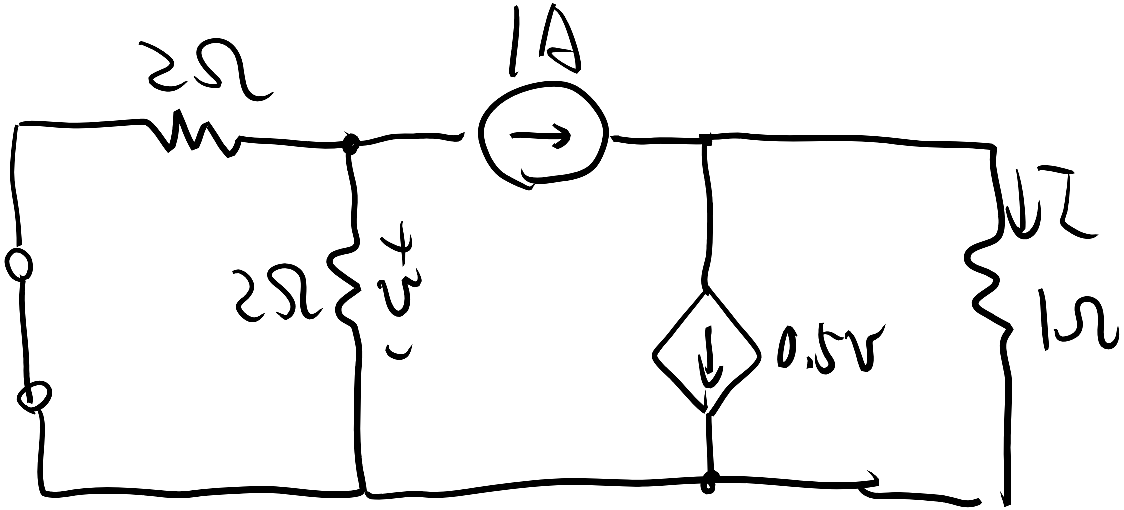


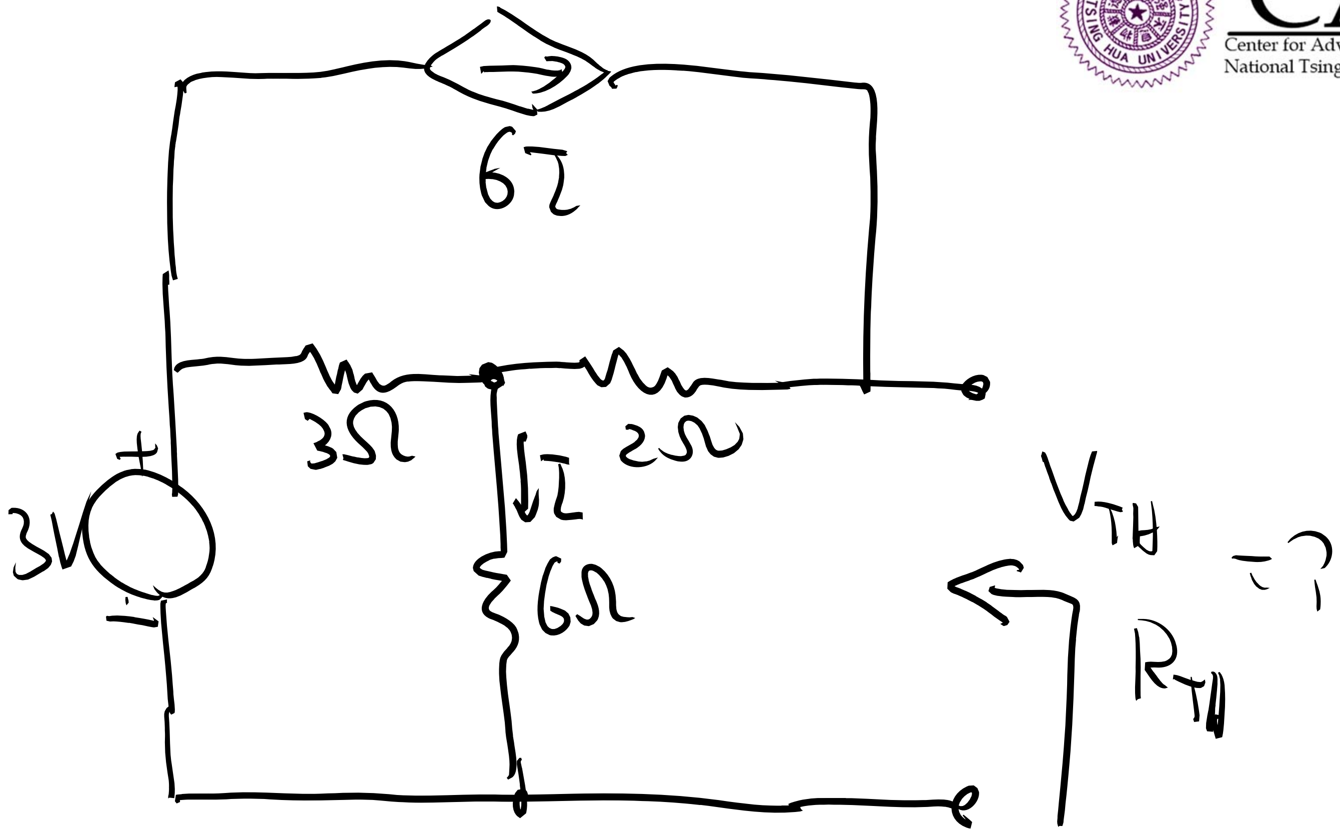
求 v 及 I

① 4V only



② 1A only





6I
3Ω
2Ω
I
6Ω
3V
+
-
V_{TH}
=?
R_{TH}

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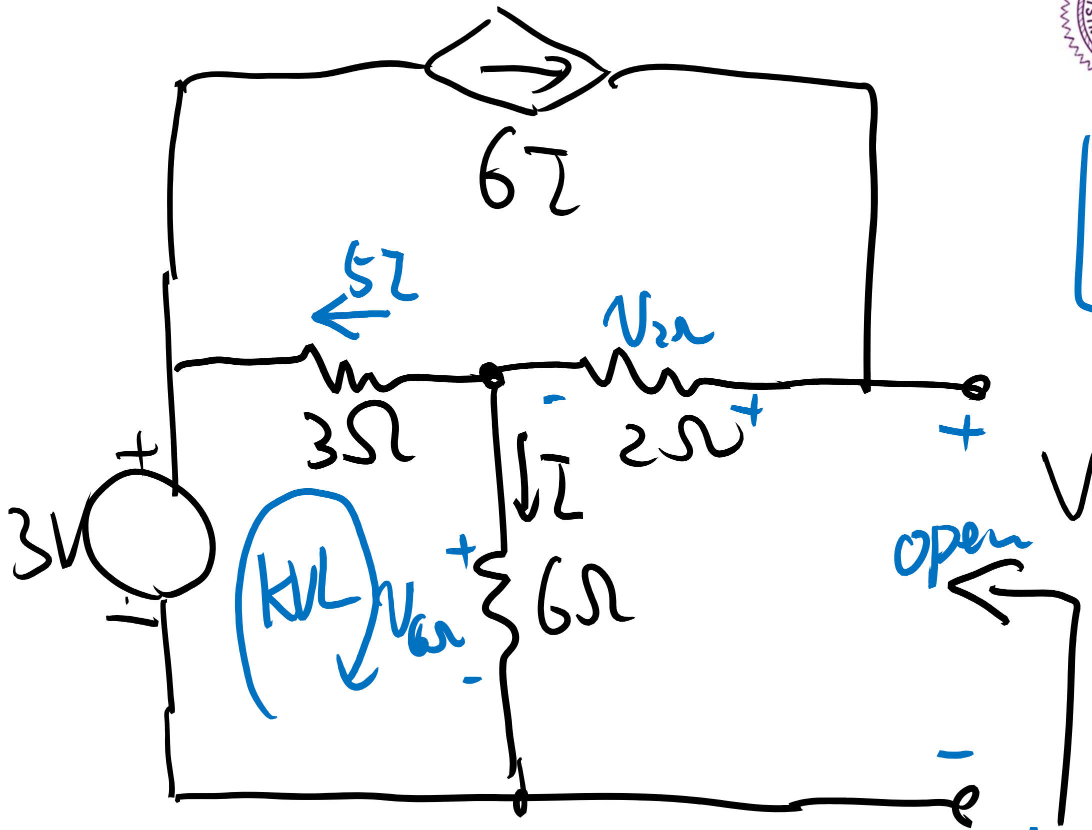
$$V_{TH} = -6V$$



$$V_{TH} = V_{oc} = ?$$

$$+(6\Omega)I - 3V - (3\Omega)(5I) = 0$$

$$-3V - 9I = 0$$

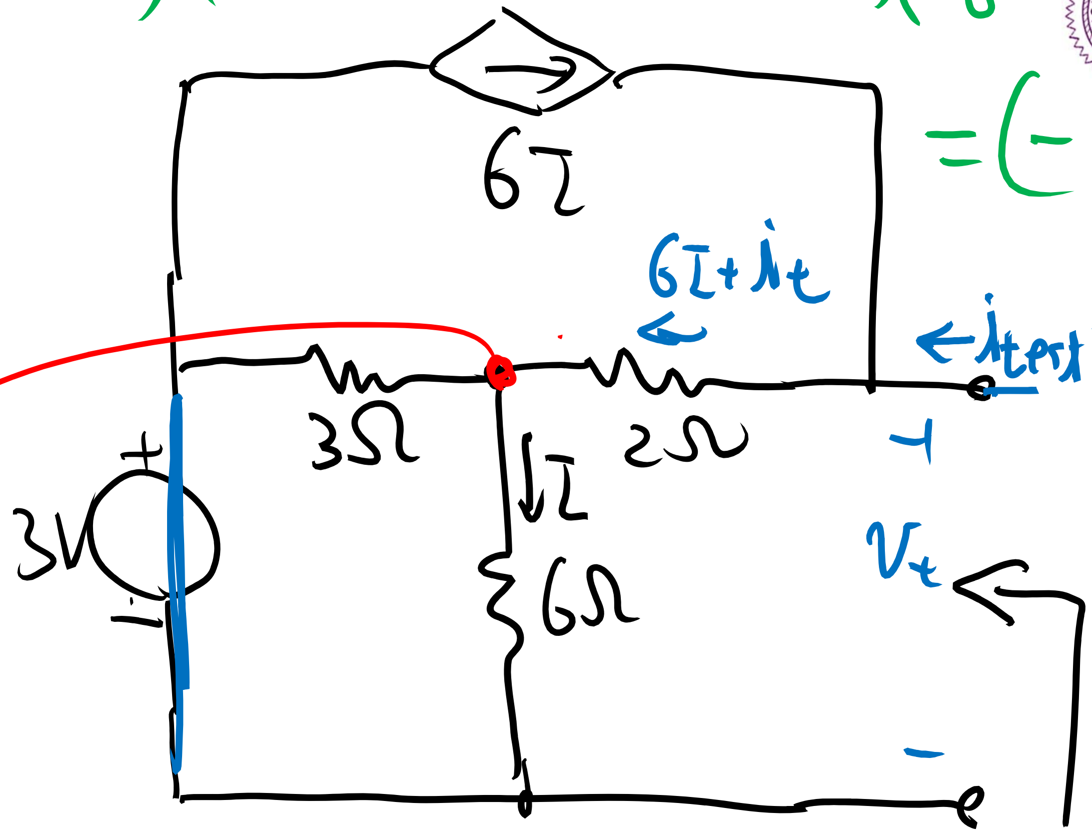
$$I = -\frac{1}{3}A$$

$$V_{Th} = V_{oc} = (6I)(2\Omega) + (I)(6\Omega) = (18)(I) = (18)\left(-\frac{1}{3}A\right) = -6V$$

$V_t = (2\Omega)\left(6\cdot\left(-\frac{1}{3}i_t\right)+i_t\right) + (6\Omega)\left(-\frac{1}{3}i_t\right)$

$= (-4\Omega)\, i_t$

$\Rightarrow R_{TH} = -4\Omega$



$R_{TH} = ?$

$V_t = (2\Omega)(6I+i_t)+(6\Omega)I$

KCL $\Rightarrow (6I+i_t)\cdot\frac{3\Omega}{3\Omega+6\Omega} = I \Rightarrow I = -\frac{1}{3}i_t$

Conclusions

- The Three-terminal switch
- The Inverter
- The Logic Circuits and the Three-terminal switch
- BJT and MOSFET
- Switch Model (S Model) of the MOSFET
- MOSFET Inverter
- Switch -Resistor Model (SR Model) of the MOSFET
- The Switch Current Source (SCS) model of the MOSFET
- The Dependent Sources