# Lecture9: MOSFET, transconductance

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# Triode mode

- Equation
  - A differential equation for $V(x)$

$$I_D = W C_{ox}[V_G - V(x) - V_{TH}]\mu_n \frac{dV}{dx}$$

- Solution
  - Potential

$$V(x) = V_G - V_{TH} - \sqrt{(V_G - V_{TH})^2 - \frac{2I_D}{\mu_n C_{ox} W} x}$$

  - Current

$$I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_G - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right]$$

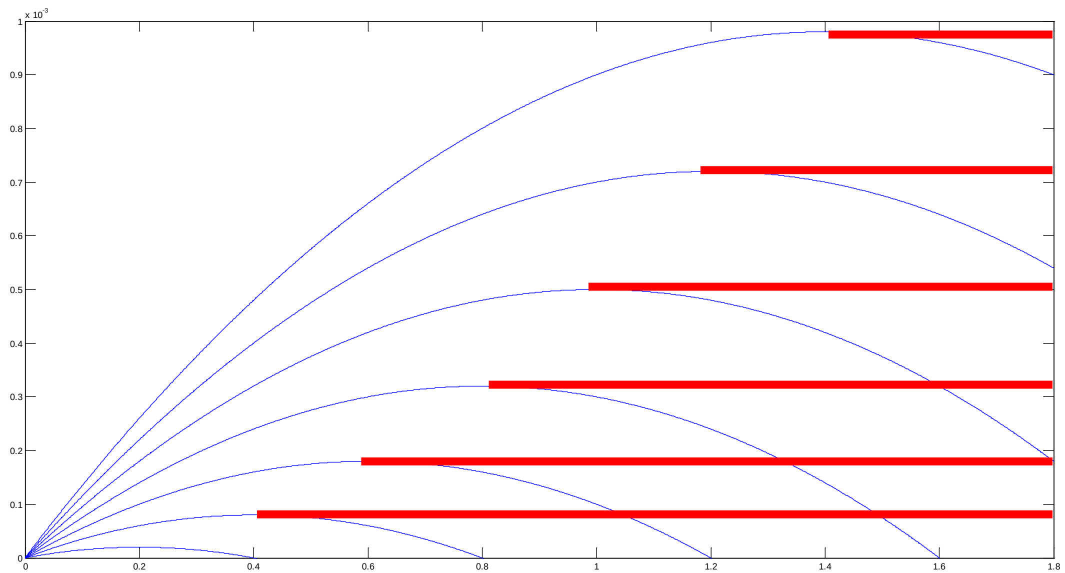
# Saturation mode

- Current usually increases as the voltage increases…
- Recall (6.3).

$$Q_{elec} = WC_{ox}[V_G - V(x) - V_{TH}] \qquad (6.3)$$

  – What happens when $V(x) = V_G - V_{TH}$?

Current

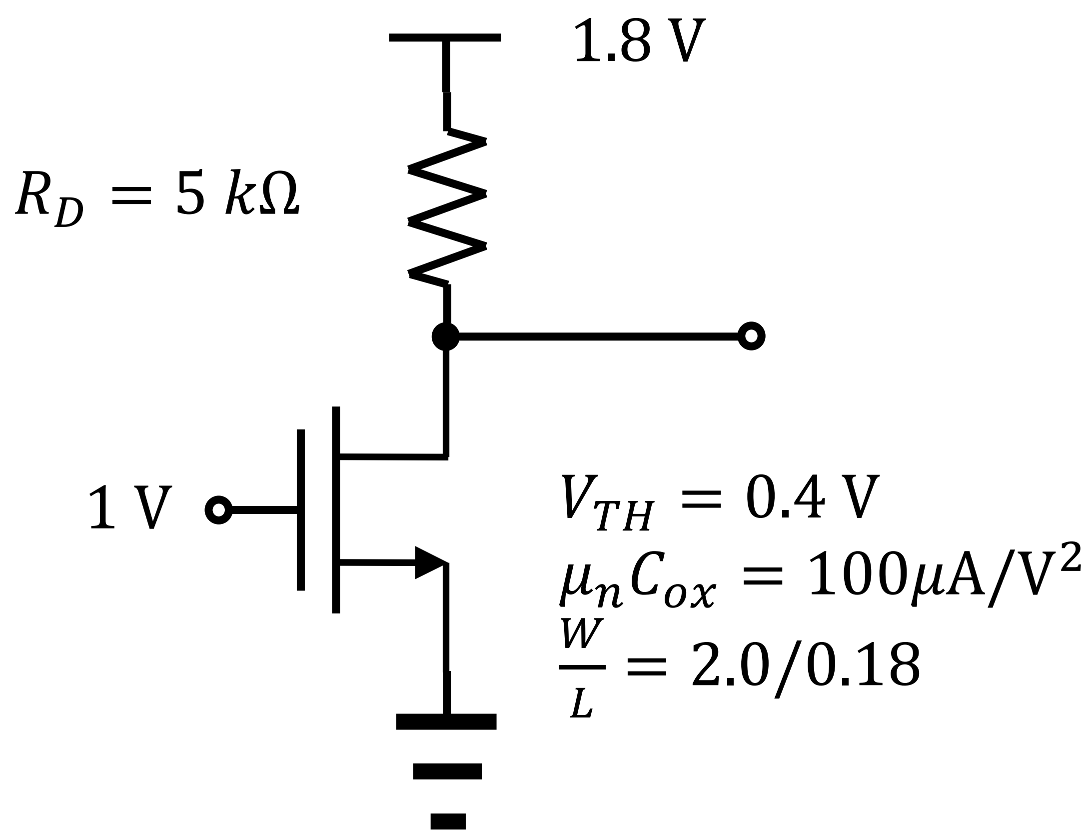



Voltage

🡐 Instead, the current is saturated. (Red lines)

# Example 6.6 (Razavi)

- Assume the saturation region.
  - Then, the saturation current becomes $200\ \mu\text{A}$.



# MOS transconductance

- "conductance" of a simple resistor
  - It means $\frac{I}{V}$.
- "trans" + "conductance"
  - Between different terminals

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \tag{6.44}$$

  - For the saturation region,

$$g_m = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_{TH})$$

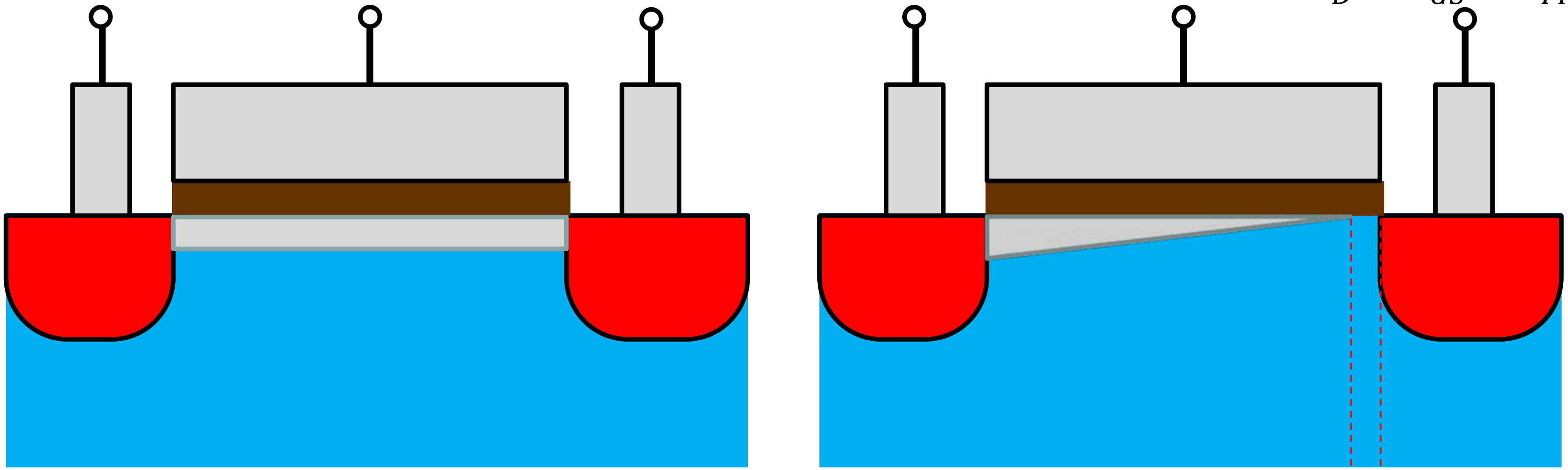
$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}$$

$$g_m = \frac{2I_D}{V_{GS} - V_{TH}}$$

# Channel length modulation

- Channel length modulation

$V_D > V_{GS} - V_{TH}$



- Output resistance?

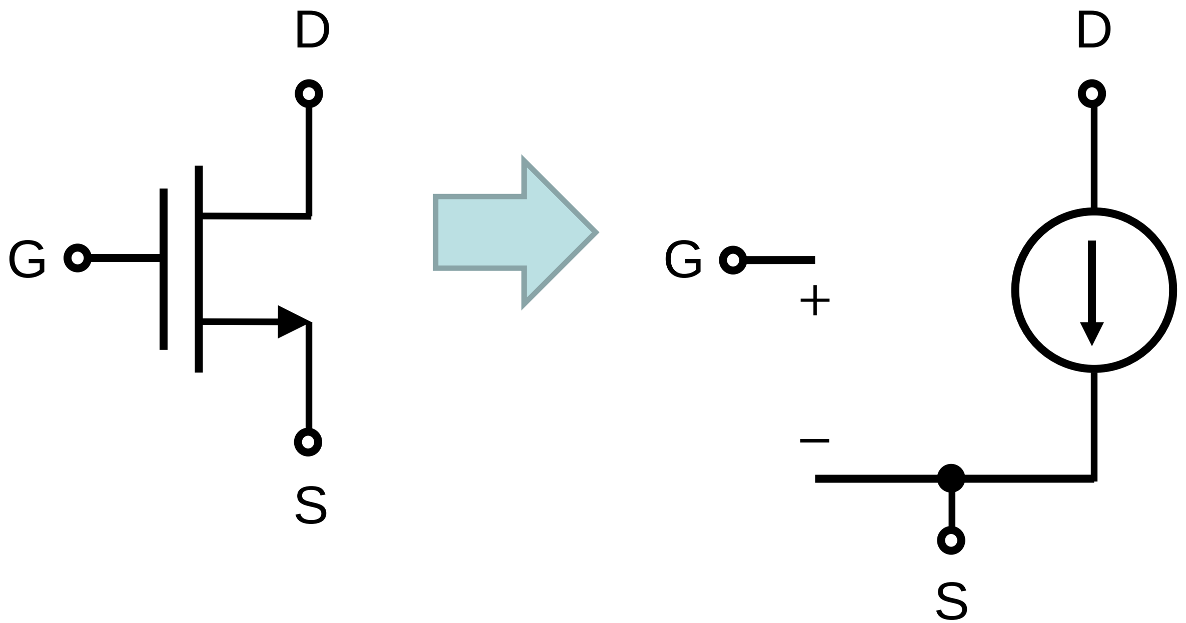
$$r_O = \frac{\Delta V_{DS}}{\Delta I_D}$$

# Large-signal model (1/2)

- Saturation region

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$

  - Drain current is determined by gate voltage. (*voltage-controlled current source*)
  - <u>*Channel-length modulation?*</u>



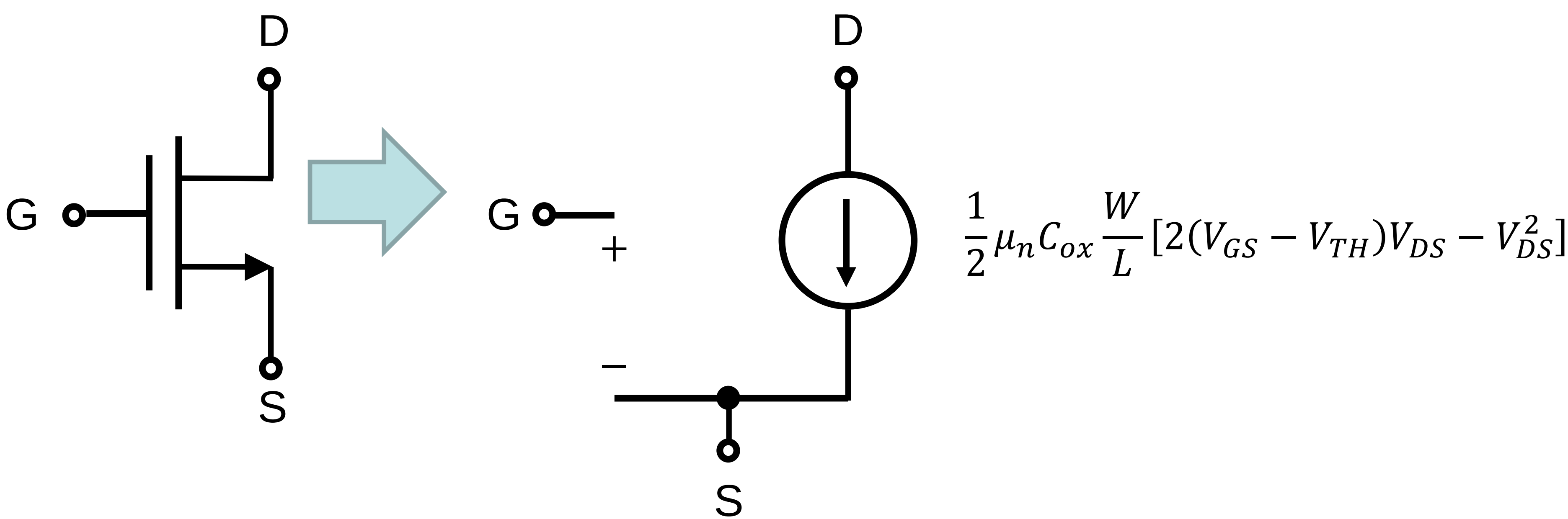

$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2$$

# Large-signal model (2/2)

- Triode region

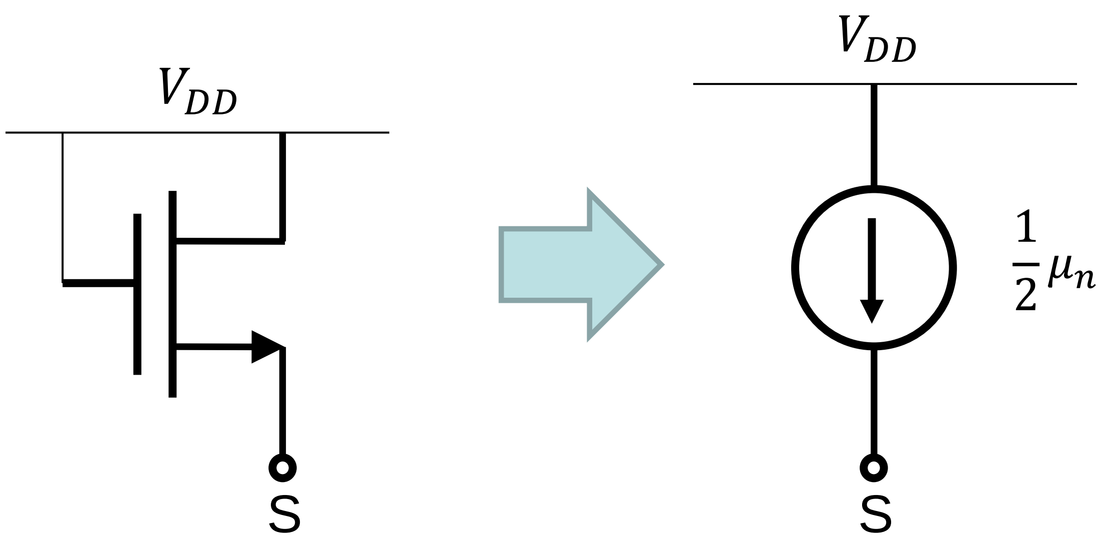
$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}[2(V_{GS}-V_{TH})V_{DS}-V_{DS}^2]$$

  – Still, it can be described by a *voltage-controlled current source*.



# Example 6.13 (Razavi)

- Always in the saturation region!
  - Any necessary condition?

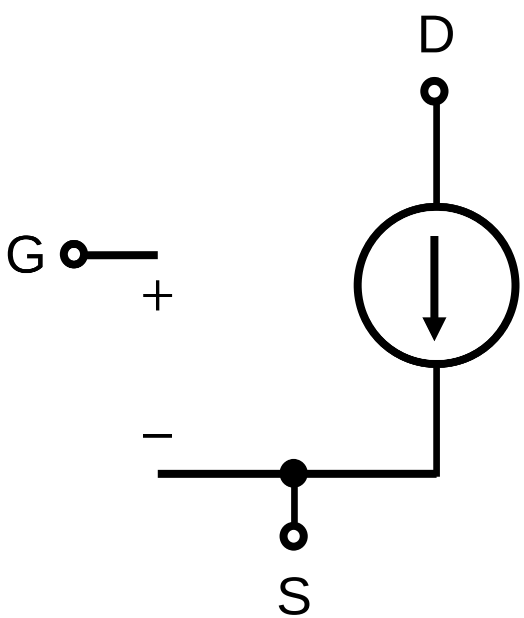


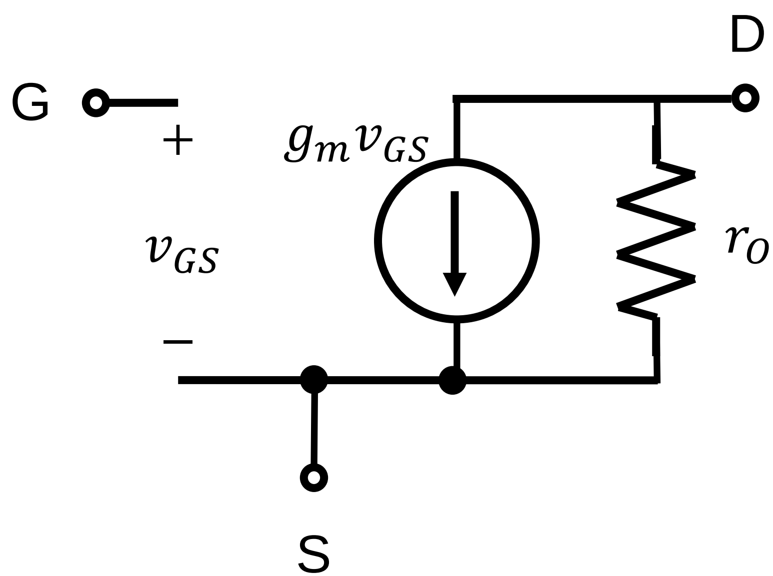

$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{DD} - V_S - V_{TH})^2$$

Gate and drain are tied.
They are connected to $V_{DD}$.

# Small-signal model

- The large-signal model is complete (within its accuracy limitation).
  - But, for small-signal analysis, it is convenient to have the small-signal model.



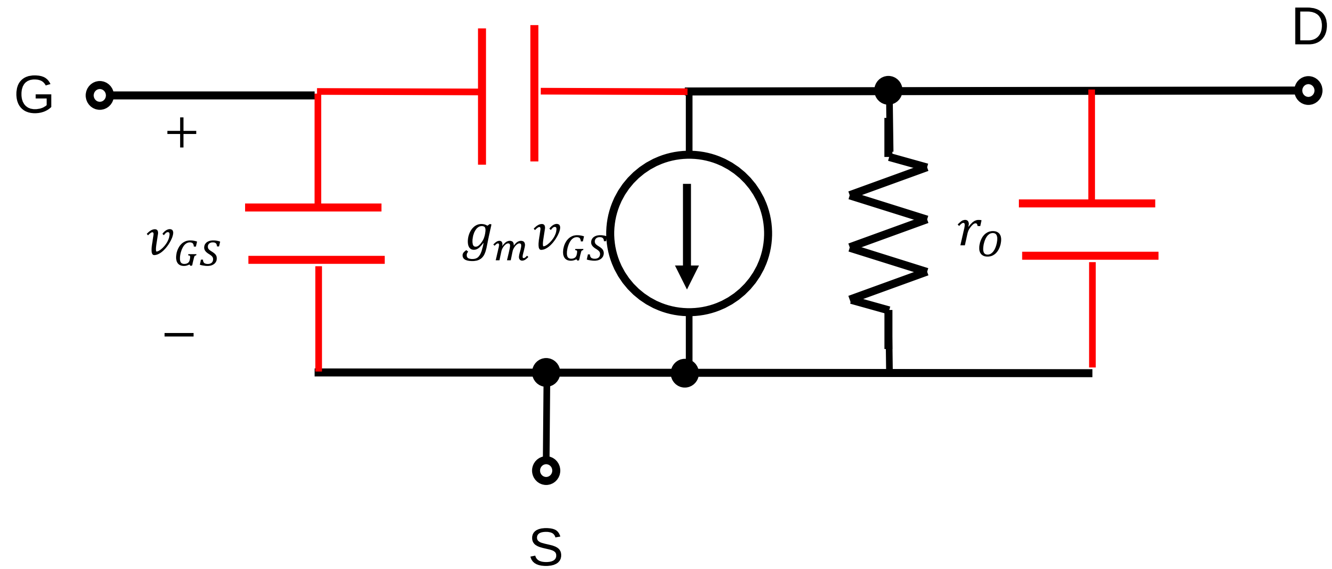




$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$

What is $g_m$ and $r_O$?

# Time-dependent one?

- Everything was in the dc steady-state…
  - How about the frequency-dependent case?
  - Capacitive components can be seen.
  - *Their physical origin?*




High-frequency, equivalent-circuit model for the case in which the source is connected to the substrate

# Homework#5 (1)

- Due: 09:00, April 9
- Write a program, which reads a netlist file.
  - Construct a square matrix, whose size is $N \times N$. The matrix is related with the vector in Homework#4.
  - Each row of the matrix represents an equation.

  - In this program, the matrix describes a system:
  - For every element terminal, the terminal current vanishes.
  - For every element tetminal, the terminal voltage is equal to the circuit node voltage.
  - For the GND node, the node voltage is zero.
  - For all other circuut nodes, the KCL is applied.

# Homework#5 (2)

- (Continued)
  - For example, consider the example in Homework#4. A voltage source and a resistor are found.
  - The matrix is explicitly shown below.

$$
\begin{array}{r}
\text{Currents} \\
\\
\text{Voltages} \\
\\
\text{Currents} \\
\\
\text{Voltages} \\
\\
\text{GND} \\
\text{KCL}
\end{array}
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\times
\begin{bmatrix}
I_1^V \\ I_2^V \\ V_1^V \\ V_2^V \\ I_1^R \\ I_2^R \\ V_1^R \\ V_2^R \\ V_0 \\ V_{in}
\end{bmatrix}
=
\begin{bmatrix}
0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{bmatrix}
$$

# Homework#5 (3)

- Solve the following problems of the mid-term exam in 2017.
  - P25
  - P26
  - P27
  - P28
  - P29
  - P30
  - P31
  - P32
  - P33