Switches and Transistors

CS 350: Computer Organization & Assembly Language Programming

A. Why?

- On/off switches are natural to use with the voltages that represent binary data.
- Transistor circuits act as switches.

B. Outcomes

After this lecture, you should

- Know what transistor switches do.
- Know how to read voltage/current diagrams.
- Know how to read transistor-level circuit diagrams.

C. Electricity and Water, Water Pressure, and Water Flow

- Electricity is the flow of electrons (or the flow of holes for electrons). An analogy often used is the flow of water through pipes and water-powered machines.
- Water pressure can cause a flow of water against resistance caused by friction of pipes (non-useful work) or useful work being done by water.
- A drop in water pressure between points A and B corresponds to a flow of water from A to B.
    - A water-powered machine uses some of the input water pressure to do some work (e.g., a water wheel might cause a flour mill to run).
    - Since it uses some of the water pressure, the output side of the machine shows less water pressure, and there is water flow from the input of the machine to the output.
    - You can have water pressure without flow (water pressing against a closed valve or capped-off pipe, e.g). In this case, there is energy available but it's not being used (alternatively, the energy is being saved for later use).

- Opening a valve on allows water to flow but whether or not water does flow depends on whether or not there's a pressure difference on the two sides of the valve — no difference in water pressure implies no flow.
- With an open valve, you can also have no flow if there's no water in the pipe — this is different from having a pipe full of water without pressure.

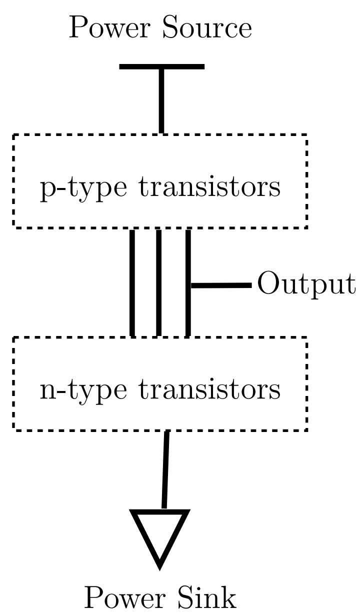
D. Electricity, Electrical Pressure, and Electrical Current

- Voltage is electrical pressure; it can cause a flow of electrical current against resistance caused by wires or other loads (light bulb, e.g.)
- When electrical current flows, it flows from a **power source** to a **power sink**.
  - In a portable device, the sink is one side of the power supply or battery.
  - In your home, the power sink is the earth (hence "ground")
    - The ground contact in a wall receptacle is connected by a wire to the cold water pipe leading outside or to a spike hammered into the earth.
    - The earth has an extremely large ability to absorb electrical charge (hence, sink).
- A drop in voltage between points A and B corresponds to an electrical current from A to B.
  - An electrically-powered device like a toaster uses energy to do some work; the use of energy corresponds to a difference in electrical pressure (a "voltage drop") on the input and output sides of the device.
- Closing a switch closed allows it to pass electrical current
  - Whether or not current actually flows depends on whether there's a voltage difference between the two sides of the switch. If there's no difference in voltage (no voltage drop) then there's no current.
  - Also, if the switch is not connected to a voltage source, there's no flow.
  - You can have voltage without current — we can connect one end of a wire to a power source but connect the other end to an open switch (or to nothing).

- **Voltage indicates bit value**: For a digital circuit, voltage comes in two ranges, high and low. We'll use high to represent logical true (= 1) and low to represent logical false (= 0). Note we're using voltage, not current flow.

E. CMOS Transistors and Circuits

- There are a number of different kinds of transistors; we're going to look at CMOS (Complementary Metal-Oxide Semiconductor) transistors.
- In addition to a kind of transistor, CMOS is a style of circuit design that imposes restrictions on what transistors can go where and on what it means for a circuit output to be true or false.
- A transistor has a **gate**, a **source**, and a **drain**.
- **A transistor acts like a switch**: When it's closed, it allows current flow from the source to the drain; when it's open, it doesn't.
- The gate controls the switch, and we control the gate by connecting it to high or low voltage.
    - **n-type transistor**: Closes its switch when the gate has high voltage.
    - **p-type transistor**: Closes its switch when the gate has low voltage.

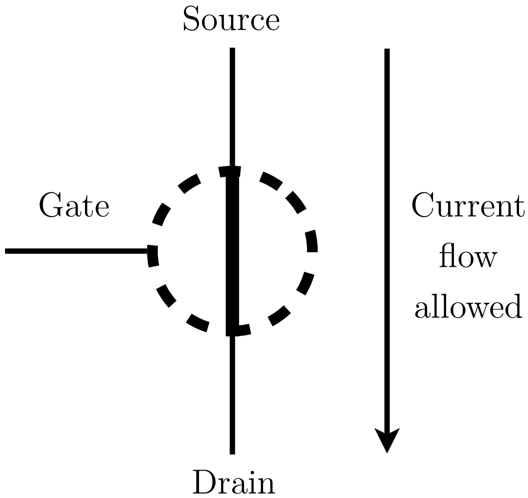


CMOS Voltage Diagram

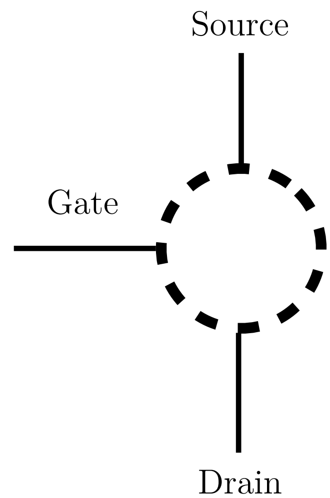
F. Voltage diagram

- A voltage diagram shows a power source, circuit, and power sink. Depending on the state of the circuit, an output of the circuit can be "on" (connected to the power source) or "off" (connected to the power sink).
- The overall power source for the circuit is indicated with a **horizontal line** at the top of the diagram.
- The power sink is indicated with a **hollow arrowhead**. (You may also see a small broom-like symbol used for ground.)

- In a CMOS circuit, the switches above the output (i.e., between the output and source) are p-type transistors; the ones below the output (i.e., between the output and sink) are n-type transistors.
- In a voltage diagram, a switch is indicated by a dotted circle. Current can flow from the **source** to the **drain** iff the **gate** causes switch the switch to be closed. In the examples below, the gate is to the left (you can also draw transistors with the gate to the right).
- A closed switch is indicated by a line connecting the source to the drain; lack of the line indicates an open switch.



Closed switch (current can flow)
n-type transistor: high voltage at gate
p-type transistor: low voltage at gate

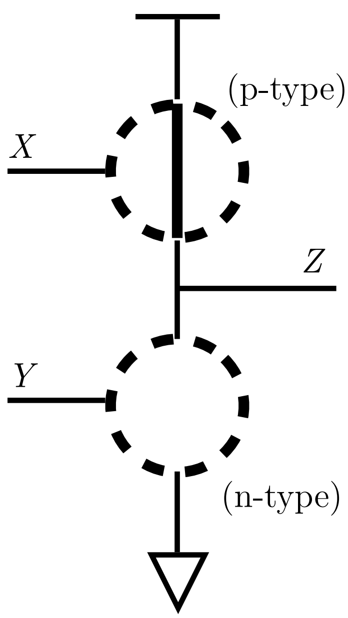


Open switch (current can't flow)
n-type transistor: low voltage at gate
p-type transistor: high voltage at gate

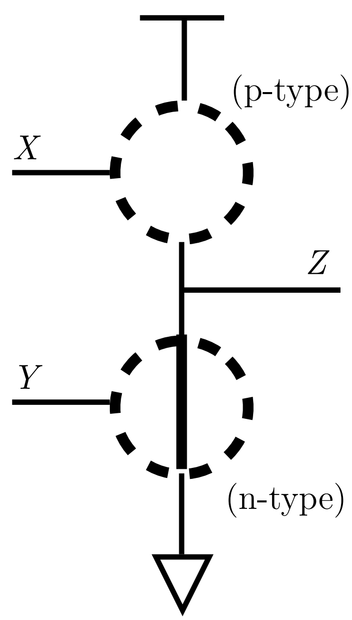
- Whether an output line is connected to the power source or power sink depends on the state of the switches of the circuit. There are four combinations of output-connected-to-source and/or -drain; two of them correspond to logical values for the output and two of them are bad and must be avoided.
- In a CMOS circuit, an output of **logical true** is indicated by connecting the output from the power source to the output AND not connecting the output

to the power sink. In the diagram below, X is connected to a p-type transistor; the transistor is closed, so X must be 0. Y is connected to an n-type transistor; the transistor is open, so $Y = 0$.

- An output of **logical false** is indicated by connecting the output from the power sink to the output AND not connecting the output to the power source. We think of there being no current flow between the output and sink (but because physical devices are not perfect, there can be a small current flow). In the diagram below, $X = 1$ and $Y = 1$.



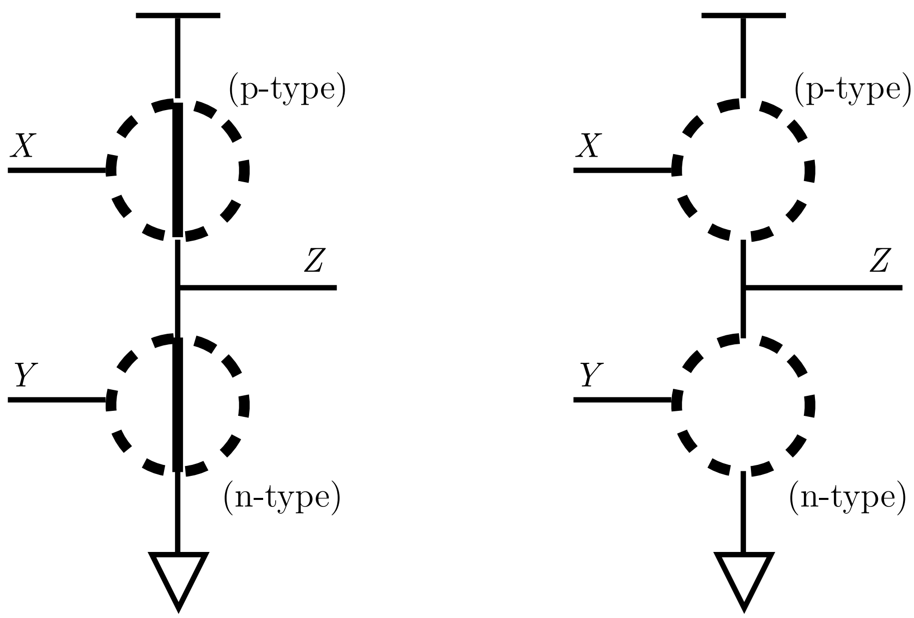
Voltage Diagram With Z = True



Voltage Diagram With Z = False

- An **open circuit** exists when the output is connected neither to the power source nor sink. In the diagram below, $X = 1$ and $Y = 0$. There is no electrical pressure between the output and power source nor the output and power sink.
    - Note: An open circuit is different from $Z = 0$ (logical false). When $Z = 0$ there's no voltage difference between Z and ground but also no resistance. In an open circuit, there's infinite resistance between Z and ground.

- A **short circuit** exists when the source and sink are directly connected. (I.e., the output is connected both to the source and the sink simultaneously.) Short circuits are bad because they can cause overheating and physical damage.
  - When we do work with electricity (make a light bulb glow or a motor run or a display light up), we make an electrical current flow against resistance. A side effect of this current flow is heat.
  - In a short circuit, the source and sink are connected only by a wire or other conductor. Wires don't offer a lot of resistance, so lots of current flows, which causes lots of heat, which can cause a fire.
- In the diagram below, $X = 0$ and $Y = 1$.



Voltage Diagram With a Short Circuit

Voltage Diagram With an Open Circuit

- For a p-type transistor to be closed, we need its gate = 0, so $X = 0$ here; symmetrically, $Y = 0$ so that its n-type transistor is open.

G. Proper CMOS Circuits

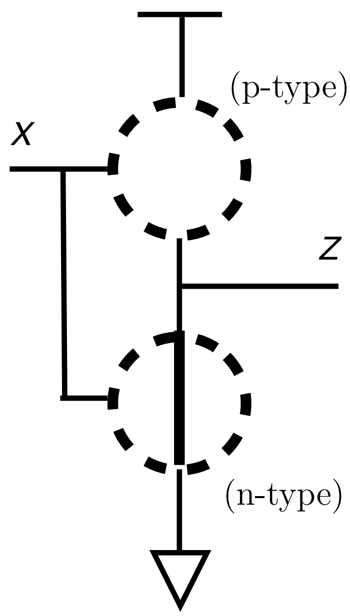
- Let's call a CMOS circuit proper if its output is always logical true or false; we never have an open circuit or short circuit (but see "Real-World CMOS Circuits" below).

- To determine whether or not a circuit is proper, we have to check each possible combination of input values to see if the output is connected to power and/or to ground.
- Here's a table for the circuit we've been looking at; the circuit is definitely not proper; it's only proper when $X = Y$.

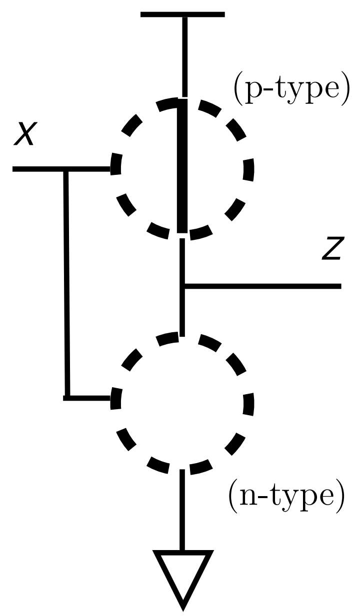
X	***Y***	***Power to Z***	***Ground to Z***	***Circuit Status***
0	0	Y	N	$Z = 1$
0	1	Y	Y	Short circuit
1	0	N	N	Open circuit
1	1	N	Y	$Z = 0$

- To get a circuit that's always proper, we can ensure $X = Y$ by connecting them. We'll have a circuit with just one input; let's call it X.

X	***Power to Z***	***Ground to Z***	***Circuit Status***
0	Y	N	$Z = 1$
1	N	Y	$Z = 0$



Voltage Diagram with $X = 1$ and $Z = 0$



Voltage Diagram with $X = 0$ and $Z = 1$

- The corrected version of the voltage diagram shows a **voltage inverter**: When the input has low voltage ($X = 0$), the output has high voltage ($Z = 1$) and vice versa. Viewed as a logical device, this is a logical not: $Z = \overline{X}$.
- In general, in terms of logical expressions, if logical expression E_1 describes when an output is connected to power and E_2 describes when an output is connected to ground, then in a proper circuit, E_1 IFF $\neg E_2$. If $E_1 \land E_2$ is true, we have a short circuit; if $\neg E_1 \land \neg E_2$ is true, we have an open circuit.

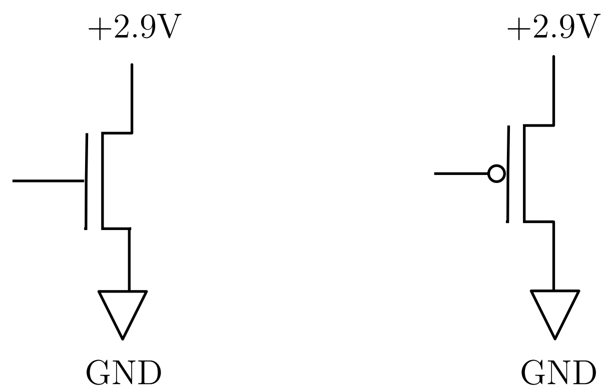
Ideal CMOS Circuits

- Surprisingly, an ideal CMOS circuit has voltage but no current flow.
- When Z is connected to ground, there's no current because there's no pressure difference between Z and ground. It's like having a pipe full of water that's standing still because there's no change of pressure applied to it;
- When Z is connected to the power source, there is electrical pressure (voltage) but no pressure difference between the source and Z, so there's no current flow. It's like having a capped-off pipe connected to a water pump — there's water pressure but no water flow.
- Note: When it comes to real-world CMOS circuits, there are some details we're glossing over:
  - The switches aren't perfect: Some current leaks through even when they're closed.
  - When we change circuit states between true and false, the switches are partly open and partly closed, so there can be a momentary short circuit (and thus some current flow). The faster the switches work, the less of this flow we get.
  - High and low voltage are ranges, not exact numbers. E.g., what we call "0" voltage can be a little > 0.00....

H. Transistor-level Diagrams

- A transistor-level diagram has the same structure as a voltage diagram, but instead of switches indicated by circles, we have transistor switches.
- The two types of transistors have slightly different graphical elements.

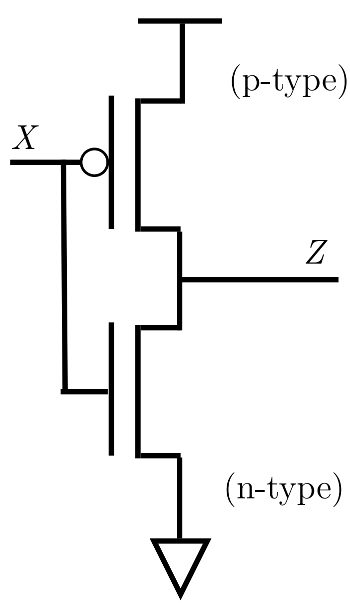
- (Note the little circuit on the p-type transistor indicating that switch is closed when the gate is not on; the little circle indicating "not" will appear later in logic gate diagrams.)



n-type Transistor (closed when gate high)

p-type Transistor (closed when gate low)

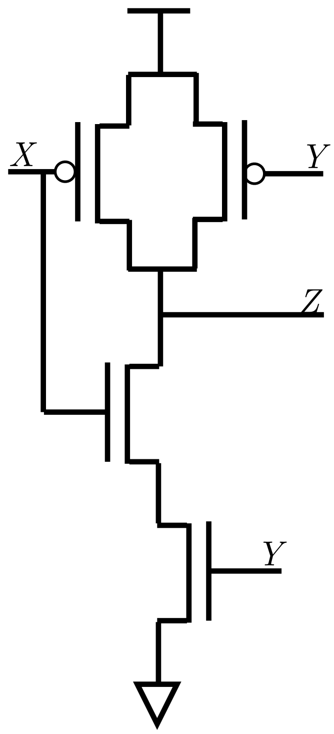
- Here's a transistor diagram for our voltage inverter/logical NOT circuit. (Recall: Transistors between power and Z are p-type; transistors between Z and ground are n-type.)



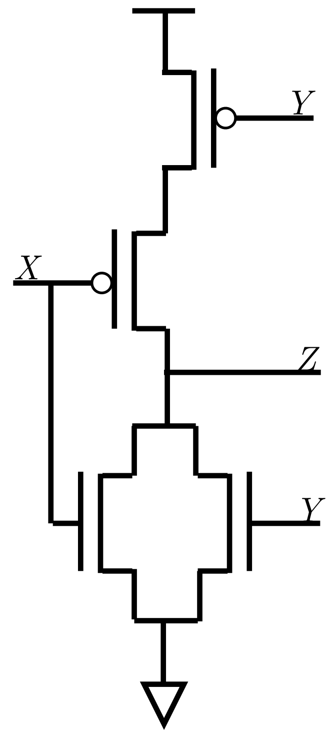
Transistor Diagram

I. Simple Two-Input Circuits

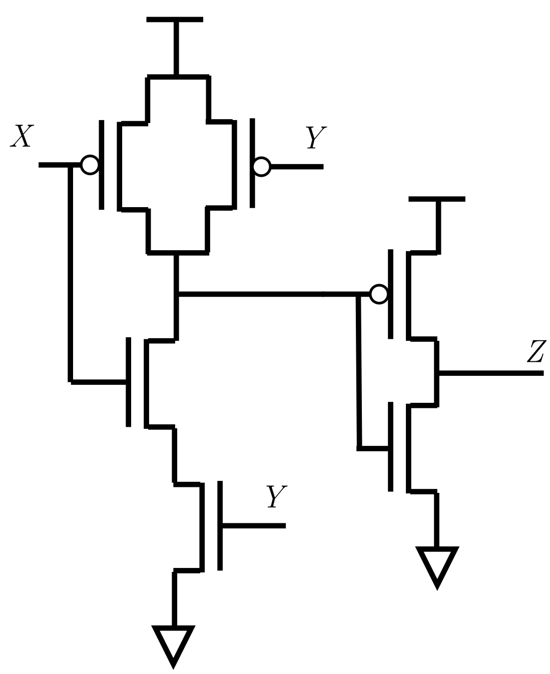
- If we have a circuit with two inputs X and Y, then either we can connect the switches for them in series or in parallel. A series connection corresponds to AND (you need both switches closed to get a connection); a parallel connection corresponds to OR (closing either or both switches gives you a connection).
- The CMOS design rules say the transistors above the output Z are p-type, so they close when $\overline{X}$ and $\overline{Y}$ are true. The linking of Z to power will depend on how we connect the $\overline{X}$ and $\overline{Y}$ switches:
  - If we connect them in series, we connect Z to power when $\overline{X}\ \overline{Y}$ holds.
  - If we connect them in parallel, we connect Z to power when $\overline{X} + \overline{Y}$ holds.
- The design rules also say that the connection between Z and ground has to occur exactly opposite of when Z is connected to power.
  - If Z is connected to power when $\overline{X}\ \overline{Y}$ (i.e., when $\neg (X + Y)$ holds), then Z must be connected to ground when $X + Y$ holds.
  - If Z is connected to power when $\overline{X} + \overline{Y}$ (i.e., $\neg (X\ Y)$ holds) holds, then it must be connected to ground when $X\,Y$ holds.
- Because of the p-type transistors between the power source and output, it's easy to implement NAND and NOR. If you want plain AND or OR, you can send the output of a NOR or NAND through an inverter (to take the logical NOT):
  - $X\ OR\ Y = NOT(\overline{X}\ AND\ \overline{Y})$
  - $X\ AND\ Y = NOT(\overline{X}\ OR\ \overline{Y})$



Transistor Diagram for Z = X NAND Y



Transistor Diagram for Z = X NOR Y



Transistor Diagram for Z = X AND Y

p

Switches and Transistors

CS 350: Computer Organization & Assembler Language Programming

A. Why?

- On/off switches are natural to use with the voltages that represent binary data.
- Transistor circuits act as switches.

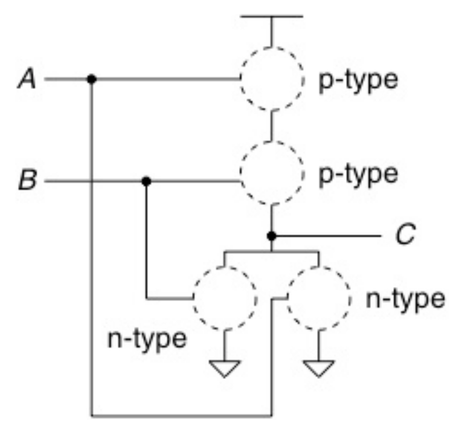
B. Outcomes

At the end of this activity you should:

- Know what transistor switches do.
- Be able to read a simple voltage/current diagram.
- Be able to read a transistor-level diagram.

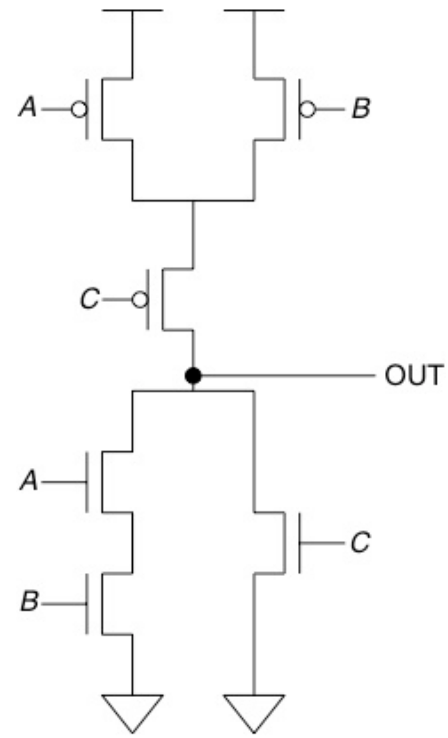
C. Questions

1. Exercise 3.4: (a) Replace the missing parts with either a wire or no wire to give the output C a logical value of 1. (b) Describe a set of inputs that give the output C a logical value of 0. (c) Replace the missing parts with wires or no wires corresponding to that set of inputs.



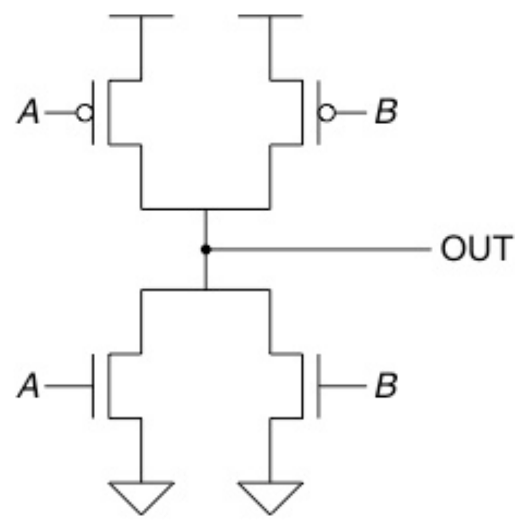
Exercise 3.4

2. From Exercise 3.5: Complete a truth table for the given transistor-level circuit. Include columns to show when the output is connected to the power source and when the output is connected to the power sink. If any combination of inputs causes a short circuit or open circuit, indicate when.



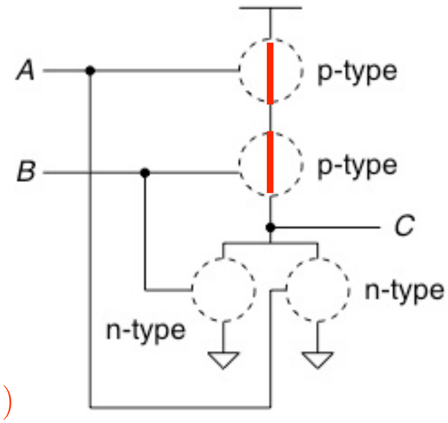
Exercise 3.5

3. From Exercise 3.7: The circuit shown has a major flaw. What is it? (Hint: When is the output connected to voltage? When is the output connected to ground?)



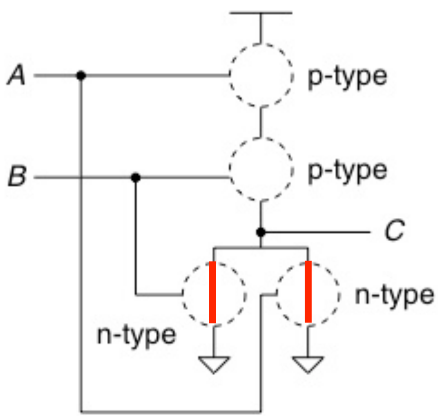
Exercise 3.7

Solution

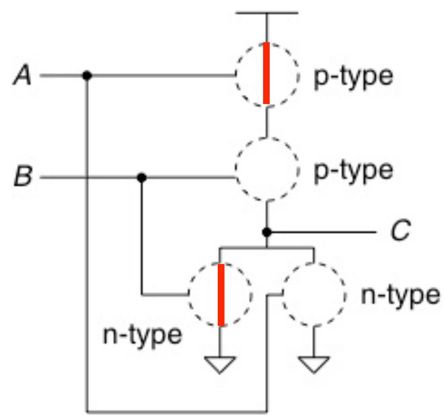


1(a): $A = B = 0$ (i.e., $\overline{A}\ \overline{B} = 1$)

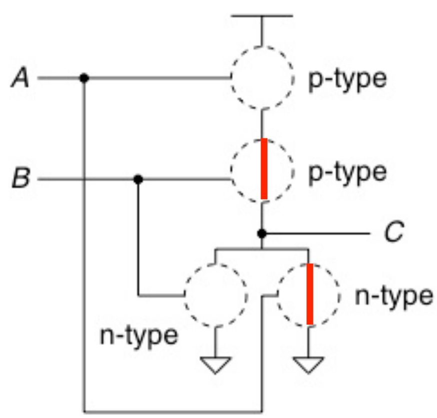
1(b,c) There are 3 right answers: $A\ \ B$, $\overline{A}\ \ B$, $A\ \overline{B}$:



$C = 0$ because $AB = 1$



$C = 0$ because $\overline{A}\ \ B = 1$



$C = 0$ because $A\ \overline{B} = 1$

2. The circuit has no short circuits or open circuits.

A	***B***	***C***	***Out to power***	***Out to sink***	***Output***
0	0	0	Y	N	1
0	0	1	N	Y	0
0	1	0	Y	N	1
0	1	1	N	Y	0
1	0	0	Y	N	1
1	0	1	N	Y	0
1	1	0	N	Y	0
1	1	1	N	Y	0

3. We can get a short circuit; here's a truth table for the circuit:

A	***B***	***Out to power***	***Out to sink***	***Output***
0	0	Y	N	1
0	1	Y	Y	Short
1	0	Y	Y	Short
1	1	N	Y	0

We can also reason about this symbolically: The output is connected to power iff $\overline{A}$ $+\overline{B}$; output is connected to ground iff $A + B$. Let E_1 and E_2 be these two expressions. Note that by DeMorgan's law, $\overline{E}_1 = A\ B$ and $\overline{E}_2 = \overline{A}\ \ \overline{B}$.

- An output of logical true happens when $E_1\ \overline{E}_2 = 1$; i.e., $(\overline{A}+\overline{B})(\overline{A}\ \ \overline{B})$ $= (\overline{A}\ \ \overline{A}\ \ \overline{B}\ + \overline{B}\ \ \overline{A}\ \ \overline{B}) = \overline{A}\ \ \overline{B}$.
- An output of logical false happens when $\overline{E}_1\ E_2 = 1$; i.e., $(A\ B)(A + B)$ $= (A\ B\ A + A\ B\ \ B) = A\ B$.
- A short circuit happens when $E_1\ E_2 = 1$; i.e., $(\overline{A}+\overline{B})(A + B) =$ $\overline{A}\,A + \overline{A}\ \ B + \overline{B}\ \ A + \overline{B}\ \ B = \overline{A}\ \ B + A\ \overline{B}$.
- An open circuit happens when $\overline{E}_1\ \overline{E}_2 = 1$; i.e., when $(A\ B)\ (\overline{A}\ \ \overline{B})$, which equals 0. Since the circuit is open iff false is true, we never have an open circuit.

