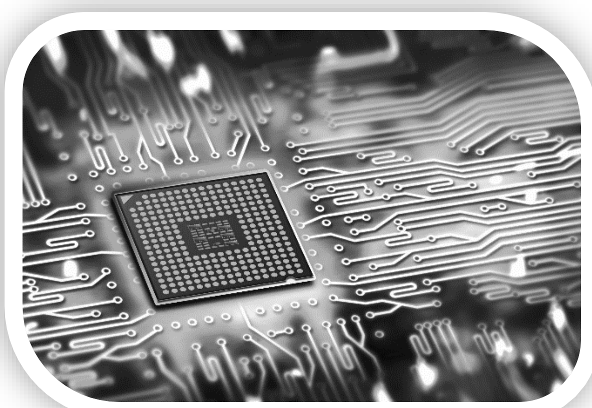
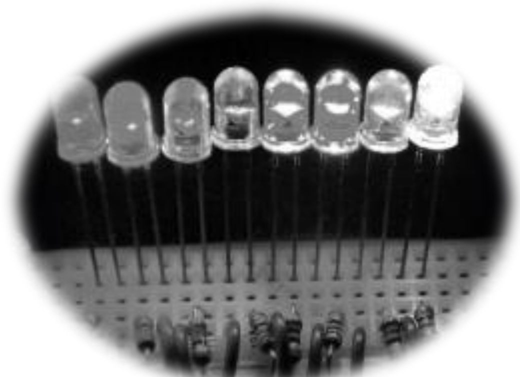
Introduction to Electronics
EHB222E



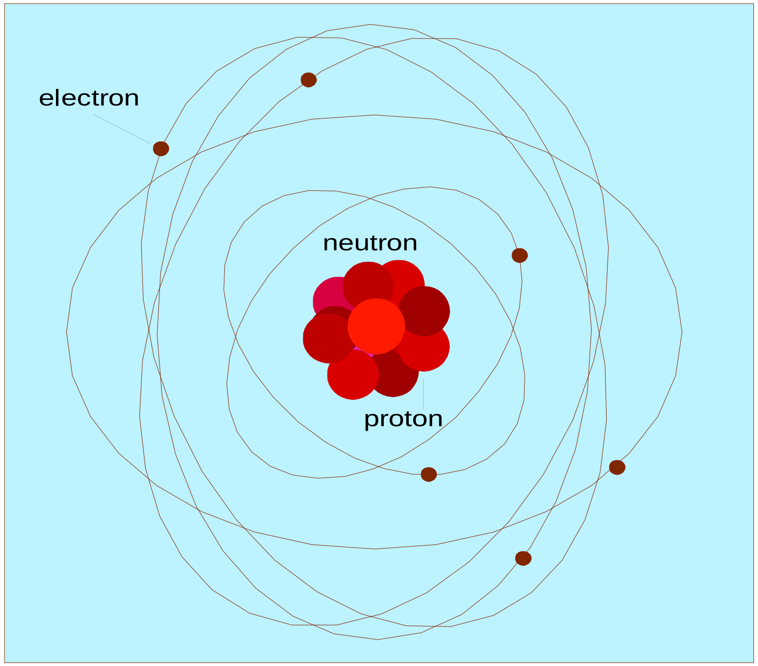


Introduction to Electronics

- Introduction
- Semiconductors & Doping, Basics of pn junction
- Diodes
- BJT Transistors
- MOSFET Transistors
- Operational Amplifiers

What is Electricity?

- Electricity is generated from the motion of tiny charged atomic particles called electrons and protons!
- Protons = +
- Electrons = -



What is Current?

- When electrons flows through a conductor
- We call this flow as "current."
- Only some materials have free electrons inside.

YES!

Conductors:

silver
copper
gold
aluminium
iron
steel
brass
bronze
mercury
graphite
salty water

Insulators:

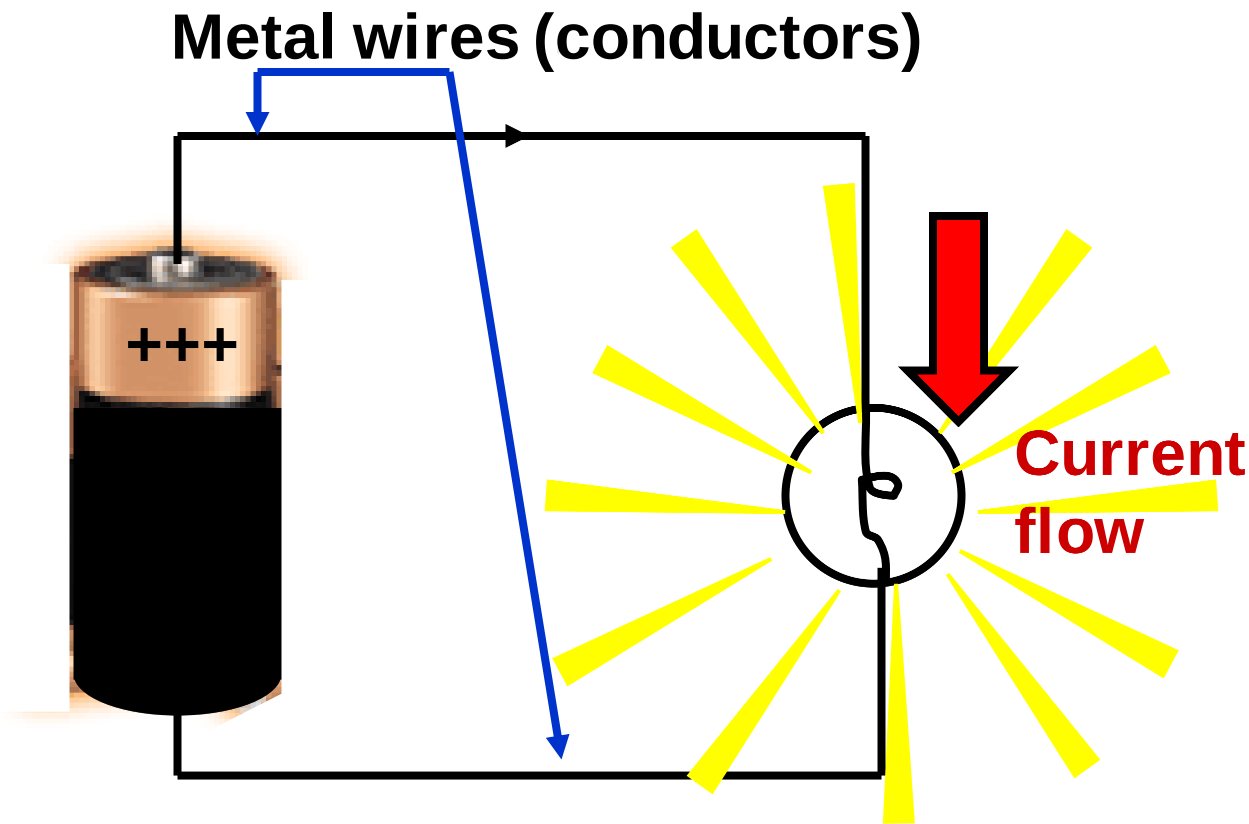
No free electrons = No current

NO!

glass
rubber
oil
asphalt
fiberglass
porcelain
ceramic
quartz
(dry) cotton
(dry) paper
(dry) wood
plastic
air
diamond
pure water

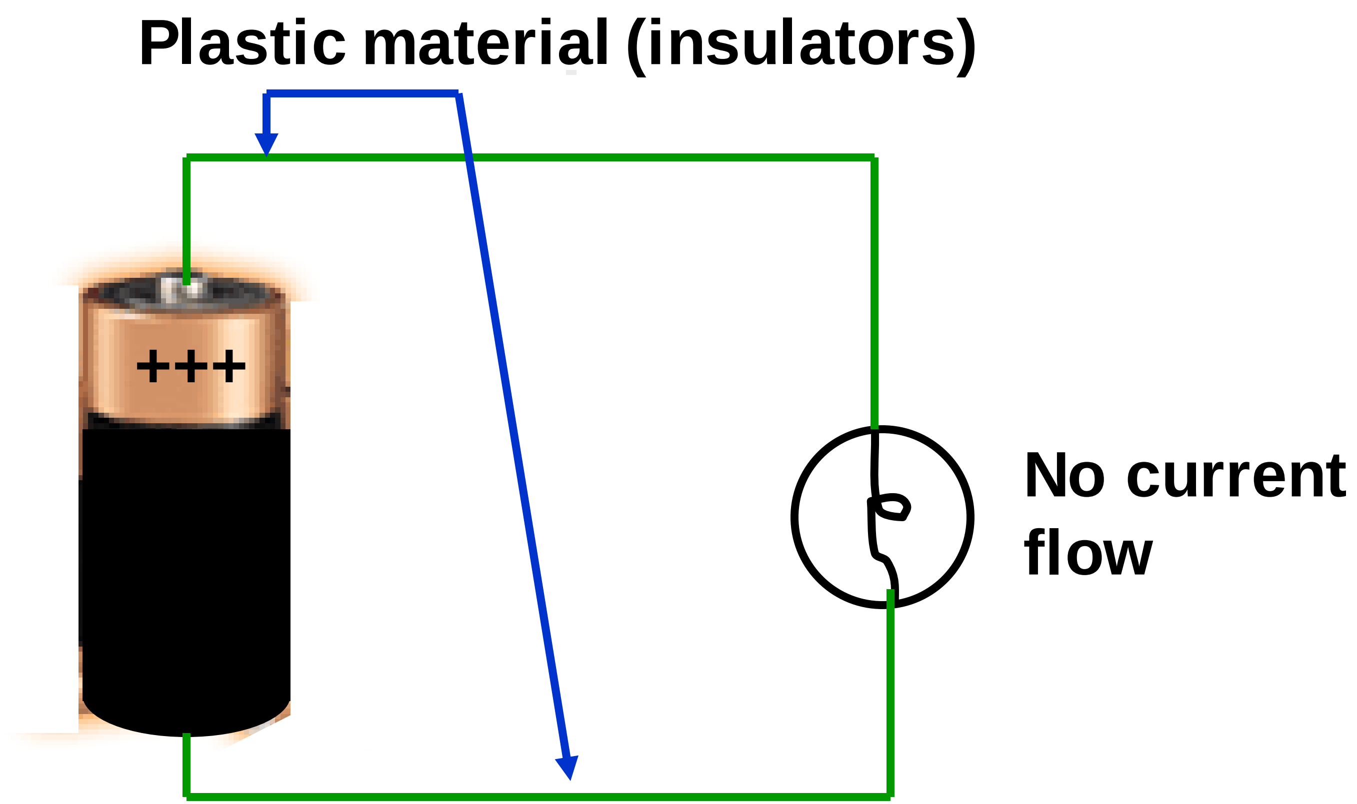
How Does Current Flow?

Current can only flow through conductors



When Does Current NOT Flow?

Current cannot flow through insulators



Note that Air is an Insulator

Current cannot flow through insulators

No current flow

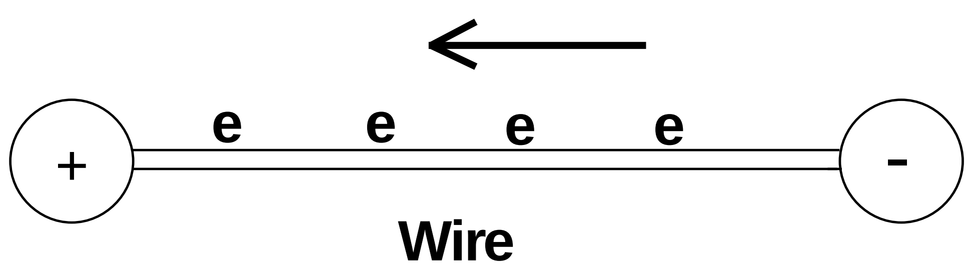
That's why a battery doesn't discharge if left on its own.

Current

- Current is the amount of electric charge (coulombs) flowing past a specific point in a conductor over an interval of one second.

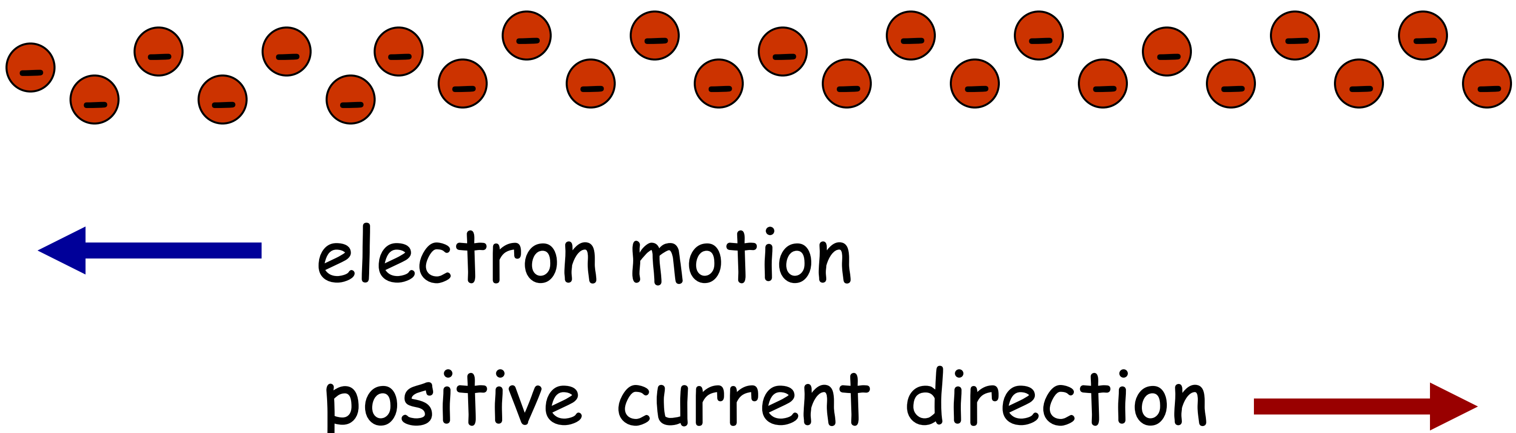
  1 ampere = 1 coulomb/second

- Electron flow is from a lower potential (voltage) to a higher potential (voltage).



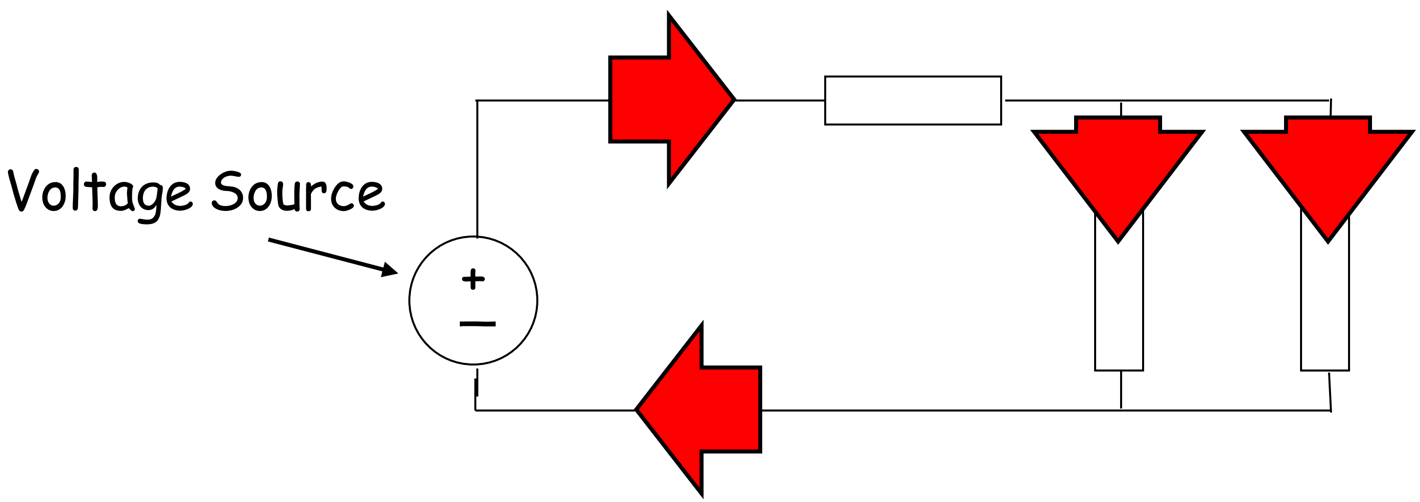
Sign Convention for Current Flow

- Electrons carry negative charge
- Positive current flow is in opposite direction



Current Flow

- The direction of current flow is indicated by an arrow.



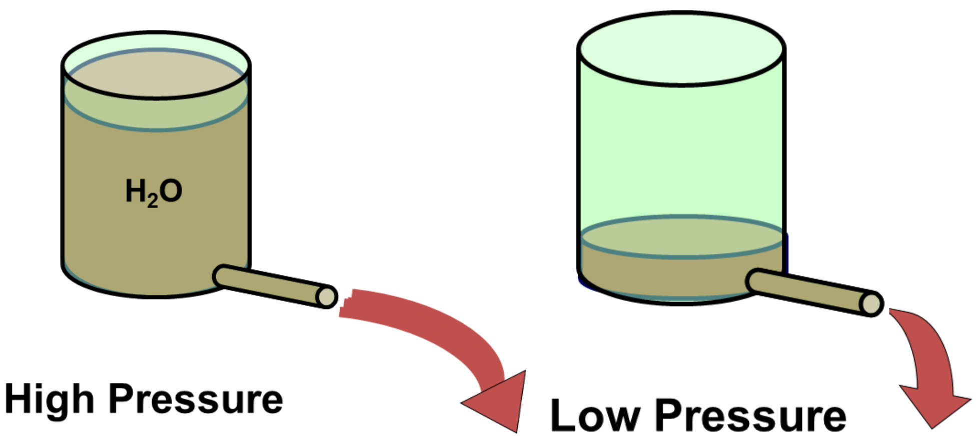
Note: The **voltage sources** in the circuit flow of current through nodes and wires.

What is Voltage?

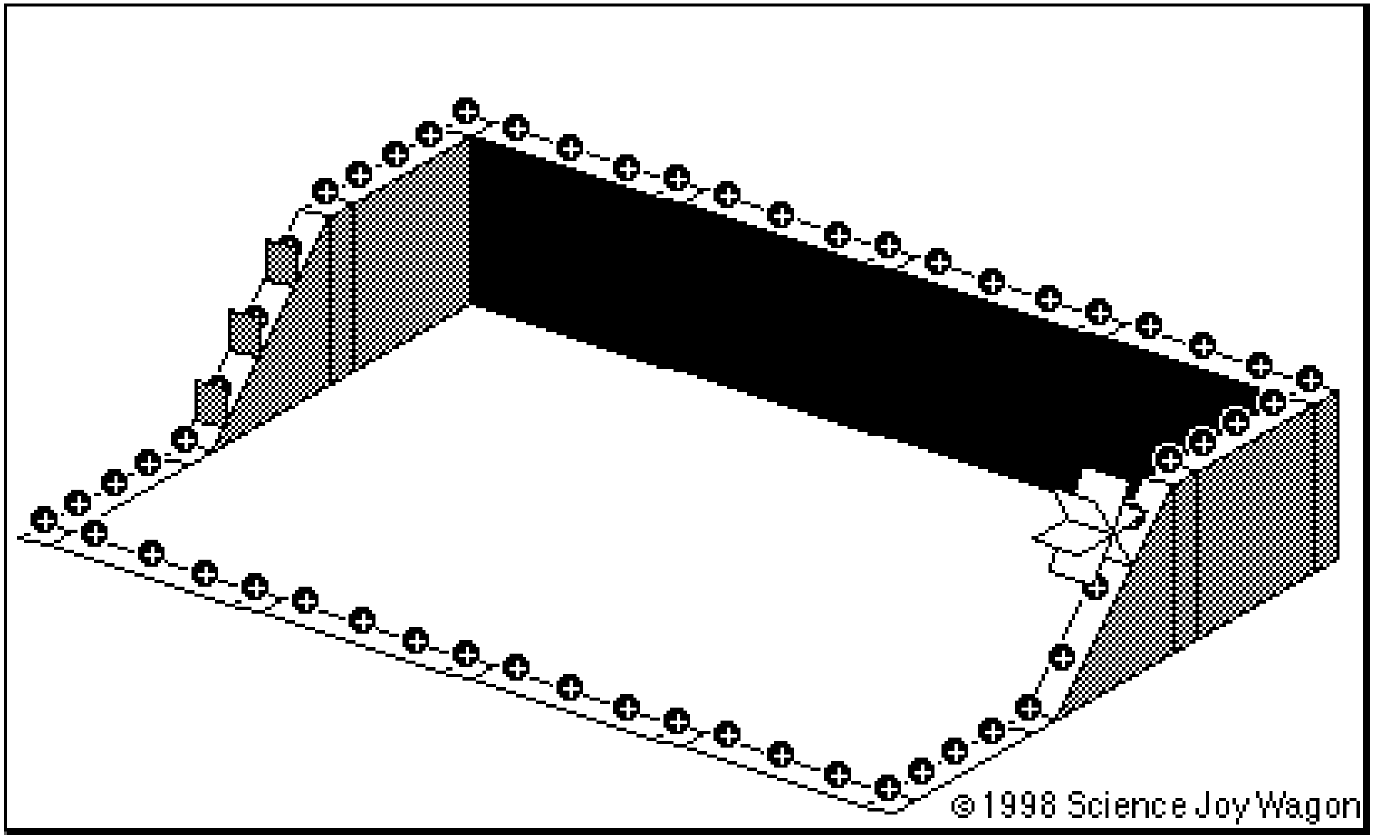
Voltage is the difference in energy level from one end of the battery (or any other energy source) to the other.

The **energy difference** causes the charges to move from a higher to lover voltage in a closed circuit

V = "Electrical pressure" - measured in *volts*.



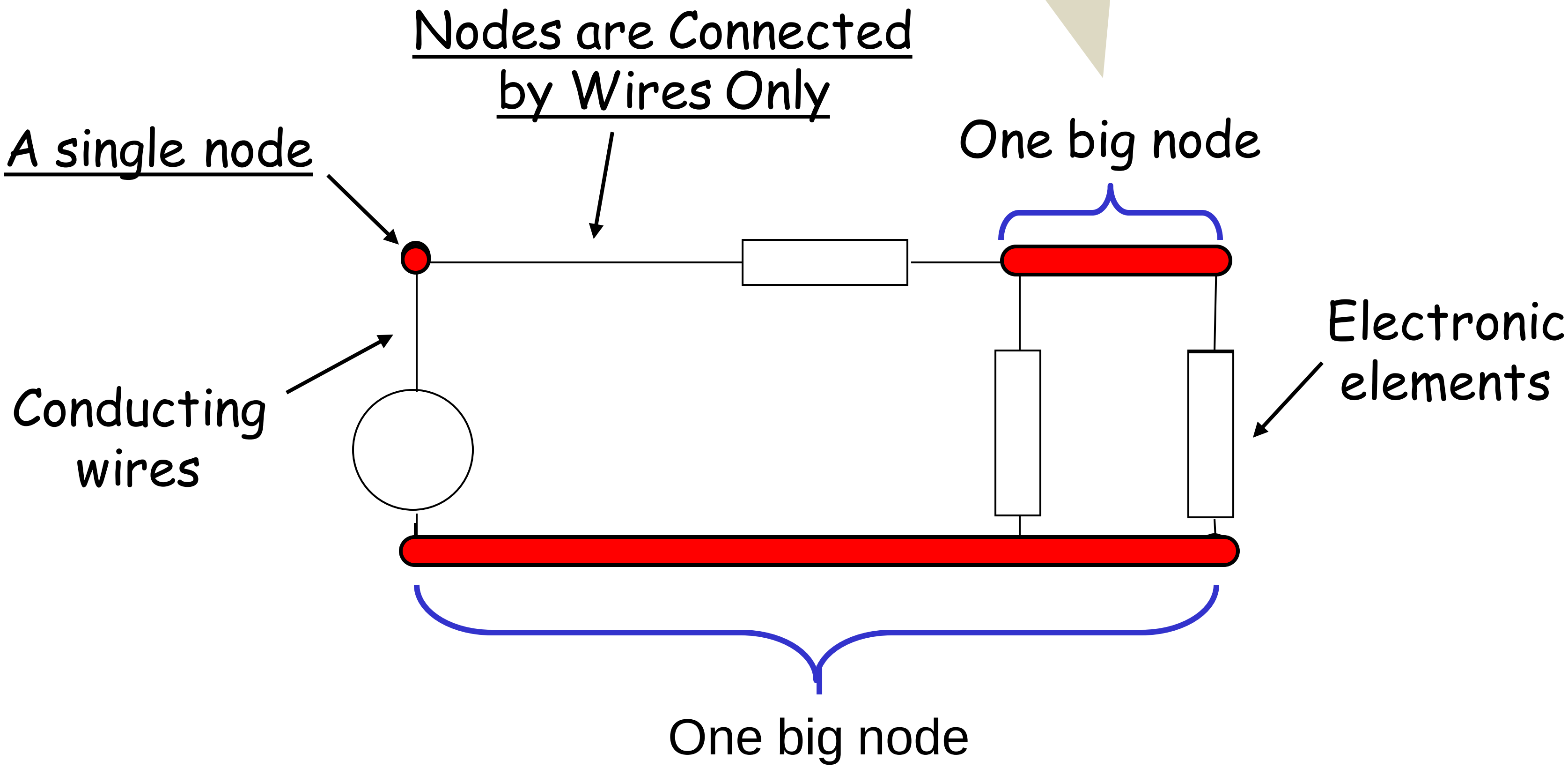
A battery in an electrical circuit plays the same role as a pump in a water system.



A battery establishes a difference of potential that can pump electrons

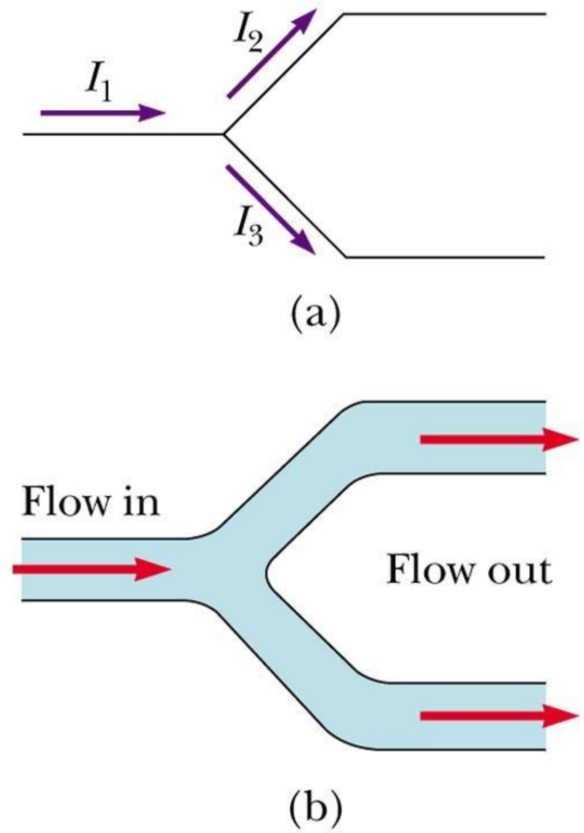
Electric Circuit

Two or more nodes connected just by wires can be considered as one single node.



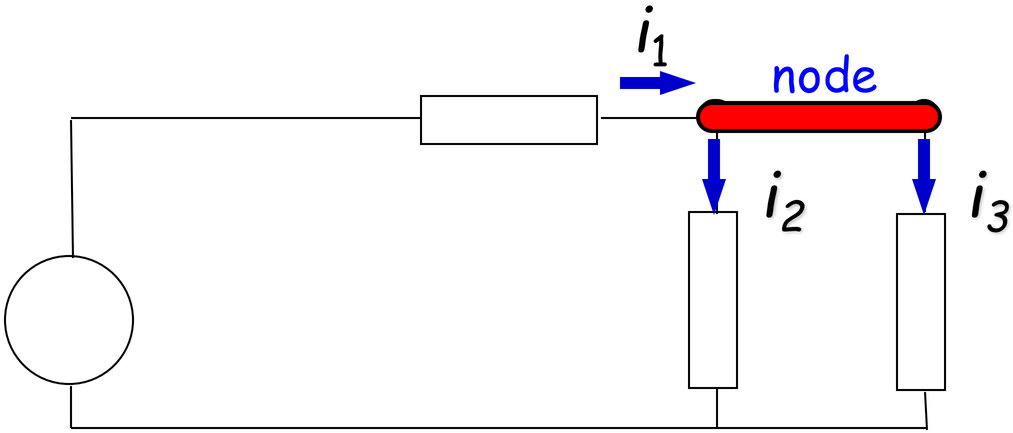
From Conservation of Charge

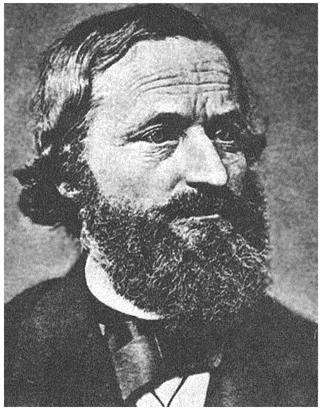
- $I_1 = I_2 + I_3$
- Diagram b shows a mechanical analog



Kirchhoff's Current Law

- The sum of currents flowing **into** a node must be balanced by the sum of currents flowing **out** of the node.





Gustav Kirchoff
was an 18th century German mathematician

i_1 flows **into** the node

i_2 flows **out** of the node

i_3 flows **out** of the node

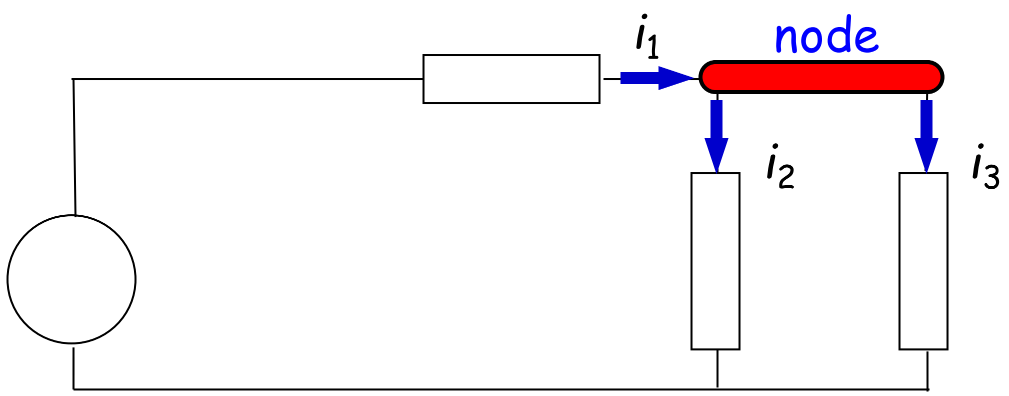
$$\boxed{i_1 = i_2 + i_3}$$

Kirchhoff's Current Law:

$i_1 = i_2 + i_3$

- This equation can also be written in the following form:

$i_1 - i_2 - i_3 = 0$



A formal statement of **Kirchhoff's Current Law**:

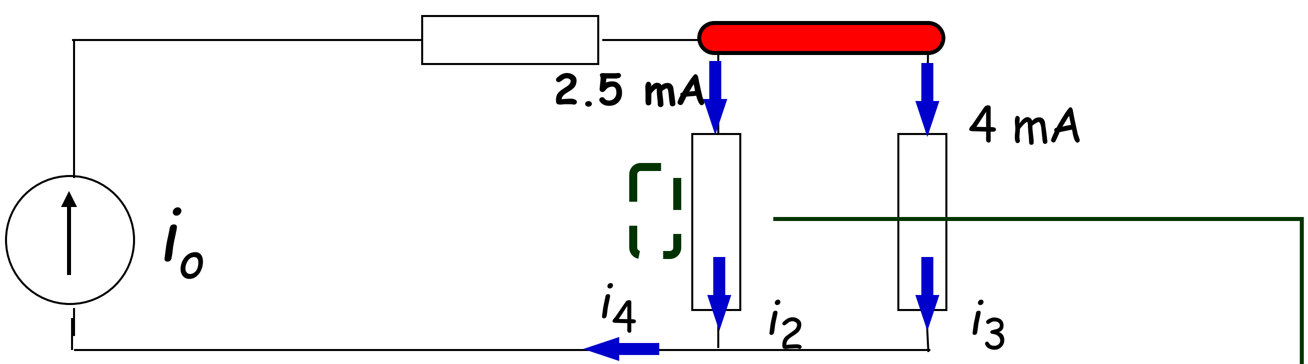
The sum of *all* the currents **entering** a node is zero.

(i_2 and i_3 **leave** the node, hence currents $-i_2$ and $-i_3$ **enter** the node.)

Example 1: Kirchhoff's Current Law:

Q: How much is the current I_o?

A: $i_o = 2.5\ mA + 4\ mA = 6.5\ mA$

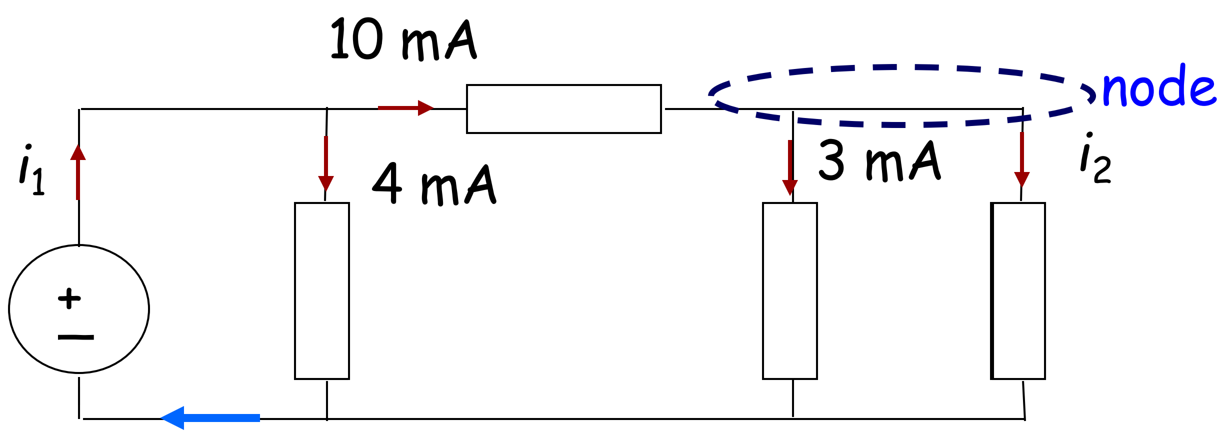


- Note that a "node" need not be a discrete point
- The dotted circle is a node with 2.5 mA entering
- Hence i_2 = 2.5 mA exits the "node".
  Similarly, i_3 = 4 mA.
- From KCL, $i_4 = i_2 + i_3$ = 6.5 mA, and $I_o = i_4$

Example 2: Kirchhoff's Current Law:

Q: How much are the currents $\boldsymbol{i_1}$ and $\boldsymbol{i_2}$?

A: $\boldsymbol{i_2} = 10\ \mathrm{mA} - 3\ \mathrm{mA} = 7\ \mathrm{mA}$
$\boldsymbol{i_1} = 10\ \mathrm{mA} + 4\ \mathrm{mA} = 14\ \mathrm{mA}$



4 mA + 3 mA + 7 mA = 14 mA

Sometimes Kirchhoff's Current Law is abbreviated just by

KCL

Review: Different ways to state KCL:

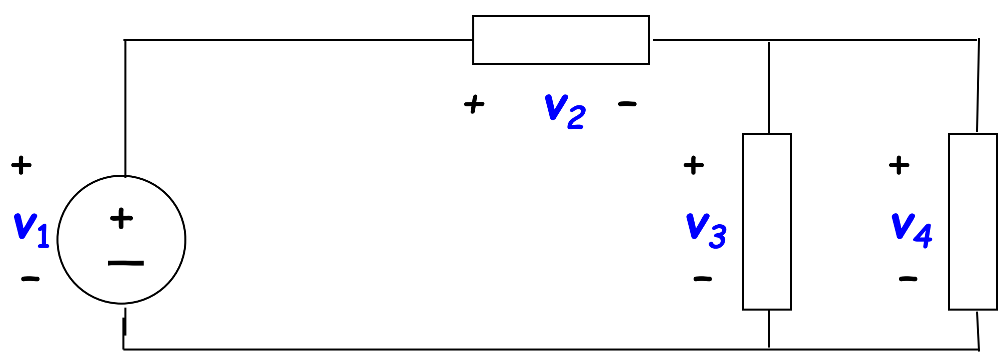
- ✓ The sum of *all* currents **entering** a node must be zero.
- ✓ The net current entering a node must be zero.
- ✓ Whatever flows into a node must come out.

more to follow…

Voltage (Difference in energy level)

- **Voltages** are measured *across* the nodes of a network.

- The **direction** of a voltage is indicated by + and – signs.

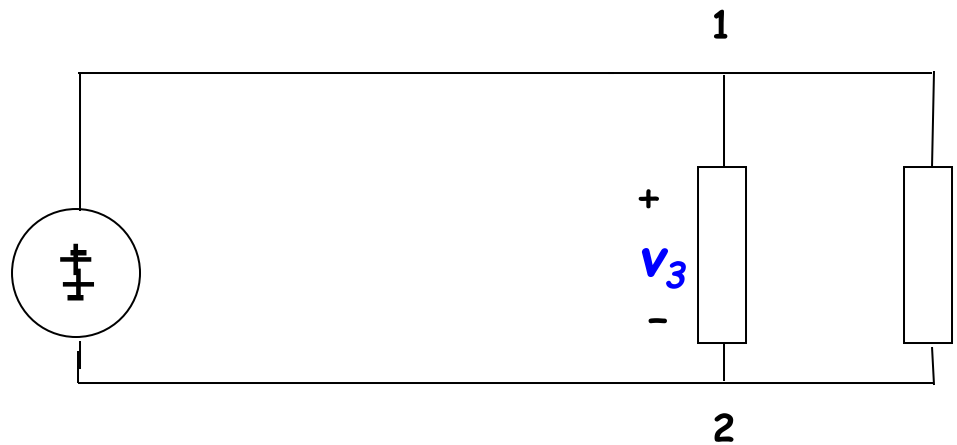


Remember: The **voltage sources** in the network flow of current through the branches.

Every Voltage has a Value and a Polarity

- The polarity is defined by the person drawing the network.

- The value is determined by the properties of the circuit.



Example:

The plus and minus signs above define the polarity of v_3 as "positive" from node 1 to node 2.

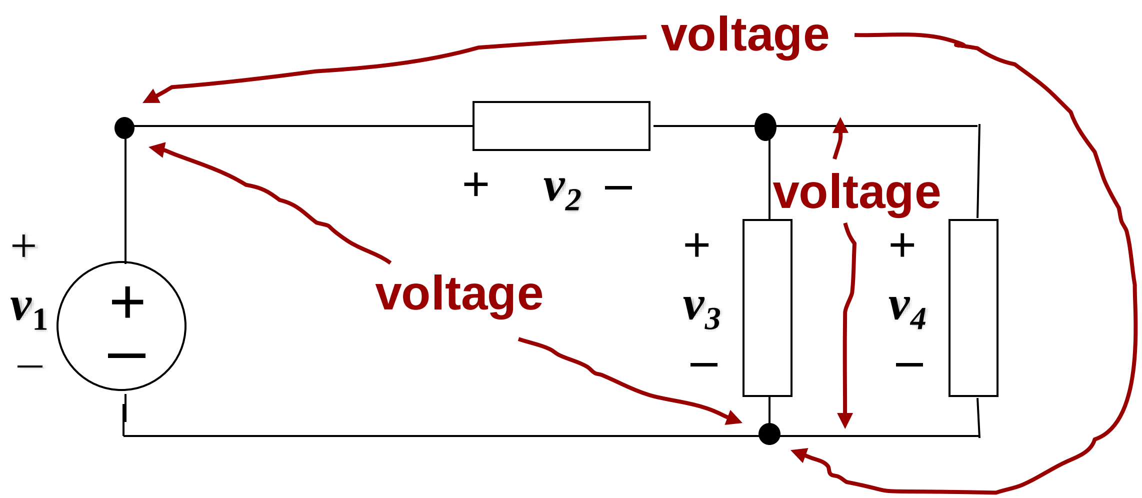
Suppose that +5 V appears physically from node 1 to node 2 . Then $v_3 = 5$ V.

Converse:

Suppose that +5 V appears physically from node 2 to node 1 . Then $v_3 = -5$ V.

Kirchhoff's Voltage Law

The voltage measured between any two nodes does not depend of the path taken.



Example of KVL: $v_1 = v_2 + v_3$

Similarly: $v_1 = v_2 + v_4$

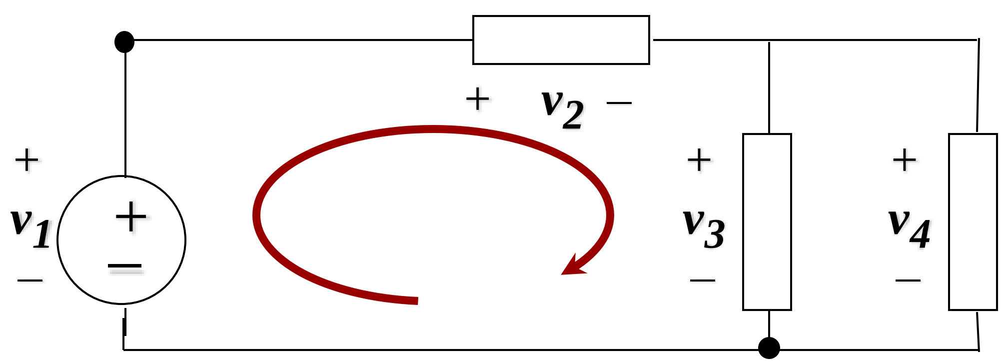
and: $v_3 = v_4$

Kirchhoff's Voltage Law:

$$v_1 = v_2 + v_3$$

- This equation can also be written in the following form:

$$-v_1 + v_2 + v_3 = 0$$



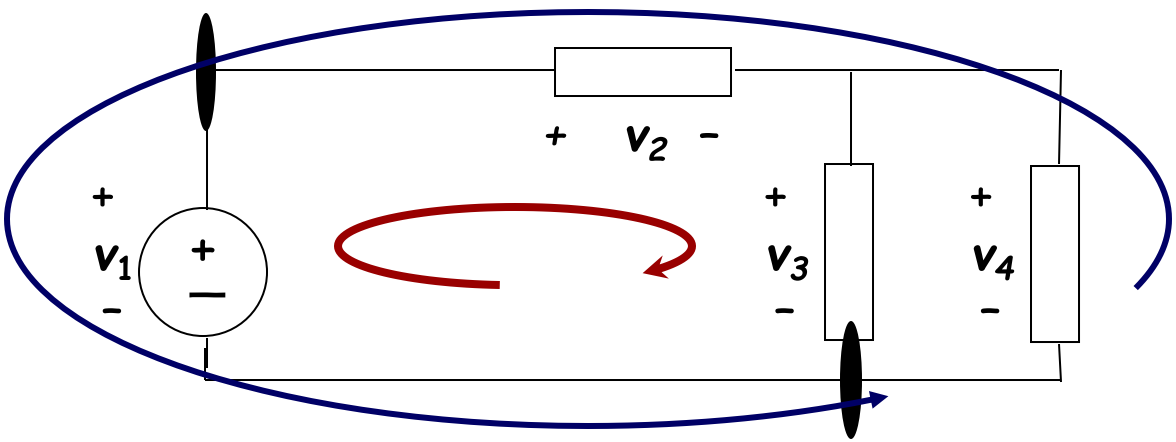
A formal statement of **Kirchhoff's Voltage Law**:

The sum of voltages around a **closed loop** is zero.

Using the Formal Definition of KVL

"The sum of voltages around a closed loop is zero."

- Define an arrow direction around a closed loop.
- Sum the voltages that are encountered around the loop.
- If the arrow first encounters a **plus** sign, enter that voltage with a (+) into the KVL equation.
- If the arrow first encounters a **minus** sign, enter that voltage with a (–) into the KVL equation.



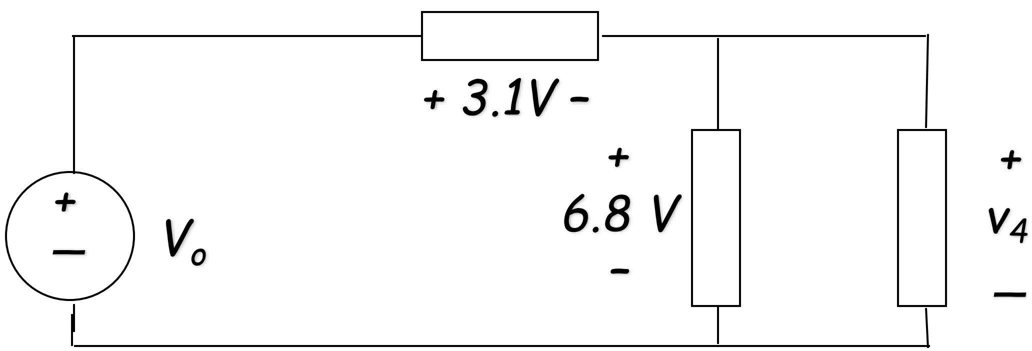
For the inner loop : $-v_1 + v_2 + v_3 = 0$

For the outer loop: $-v_4 - v_2 + v_1 = 0$

Example 1: Kirchhoff's Voltage Law:

Q: How much is the voltage V_o?

A: $V_o = 3.1\text{ V} + 6.8\text{ V}$



Q: How much is the voltage v_4?

A: $v_4 = 6.8\text{ V}$

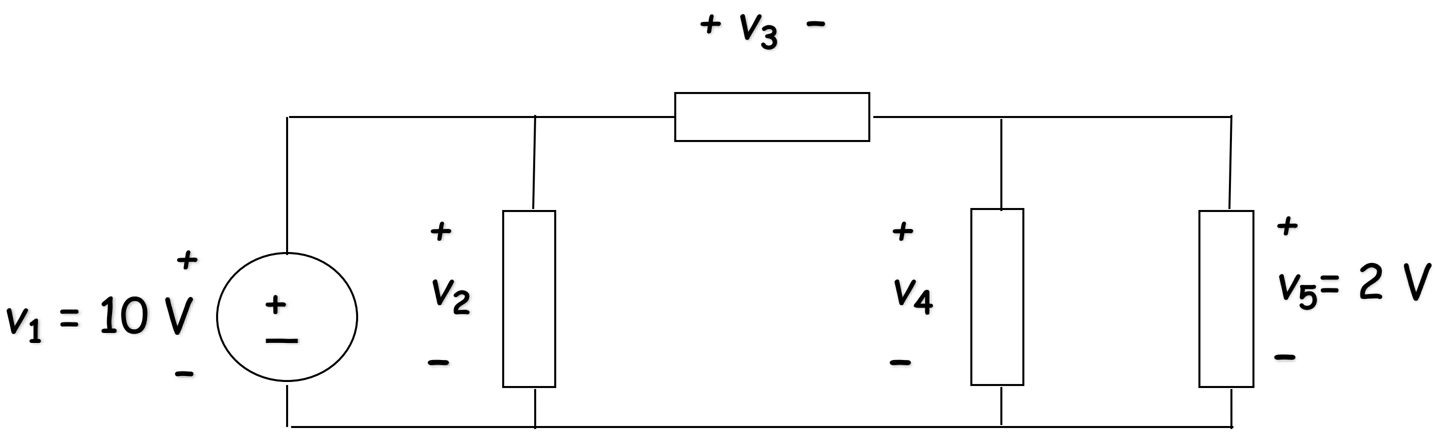
Example 2: Kirchhoff's Voltage Law:

Q: If $v_1 = 10$ V and $v_5 = 2$ V, what are v_2, v_3, and v_4?

A: $-v_1 + v_2 = 0 \Rightarrow v_2 = -10$ V

$-v_2 + v_3 + v_5 = 0 \Rightarrow v_3 = 10\text{ V} - 2\text{ V} = 8$ V

$-v_4 + v_5 = 0 \Rightarrow v_4 = 2$ V

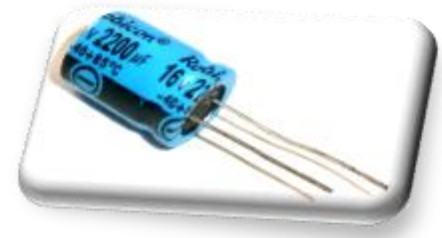


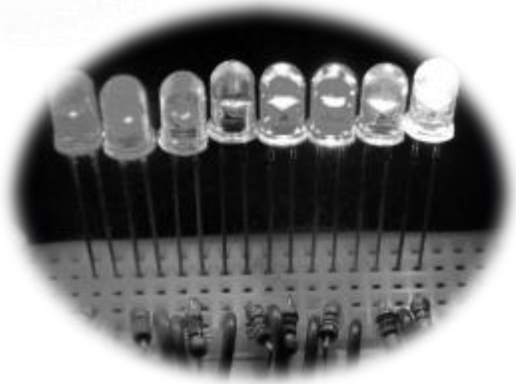
Electronic Circuits

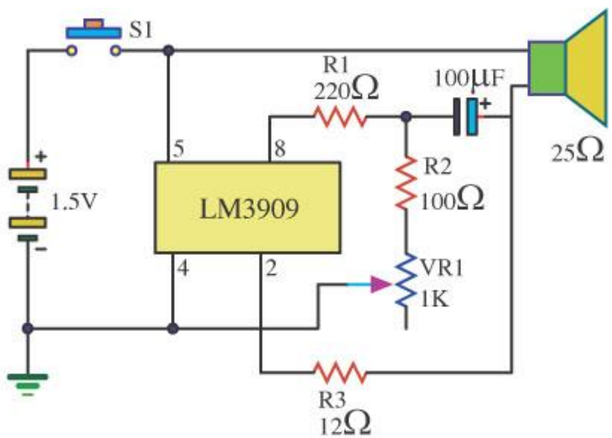
Circuits are obtained by connecting electronic elements

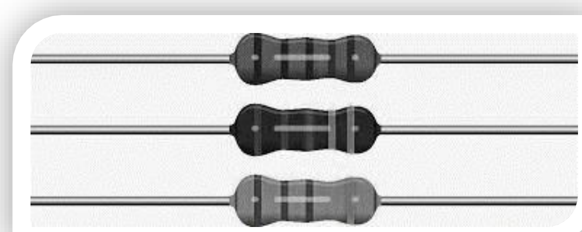
Typical electronic elements are

- diodes
- resistors,
- capacitors,
- inductors





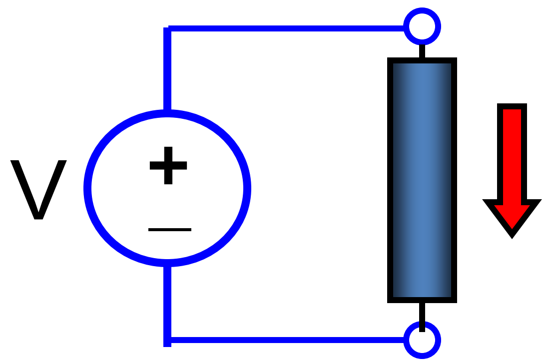




Ohm's Law & Resistors

Georg Ohm

Let us remind the Ohm's Law



$$I = \frac{V}{R}$$

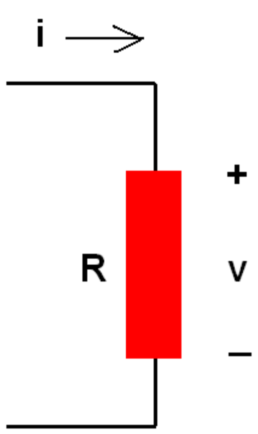
$$R = \frac{V}{I}$$

- Assume that the wires are "perfect conductors"
- The unknown circuit element limits the flow of current.
- The resistive element has ***resistance*** *R*

Ohm's Law

Voltage drop across a resistor is proportional to the current flowing through the resistor

$$v = iR$$



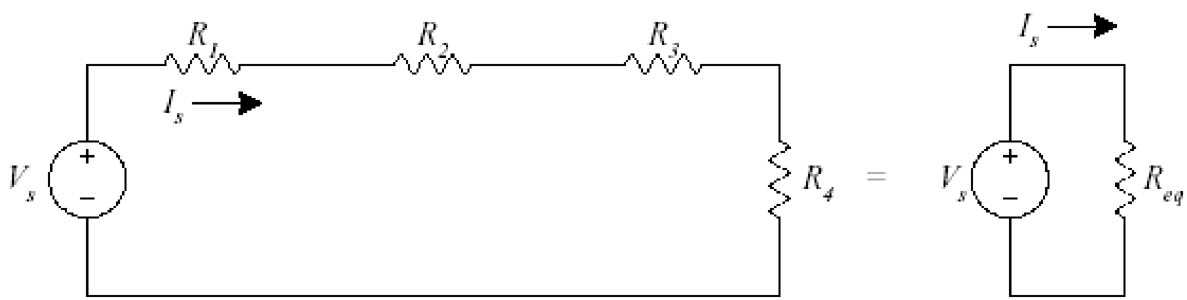
If the resistor is a perfect conductor (or a short circuit)

R = 0 ohm, then

$v = iR = 0\ V$

no matter how much current is flowing through the resistor

Resistors in Series

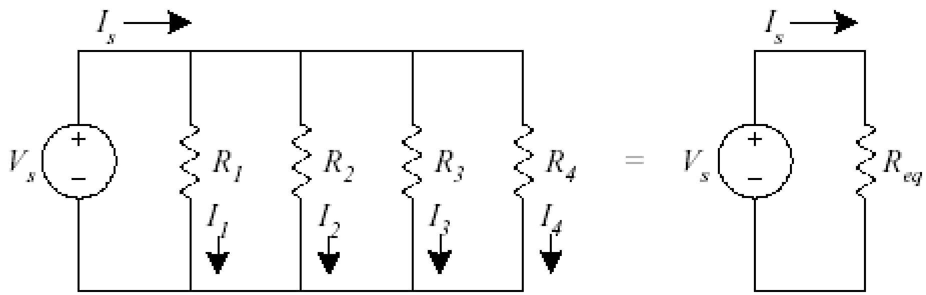


By KVL

$$\begin{aligned} V_s &= R_1 I_s + R_2 I_s + R_3 I_s + R_4 I_s \\ &= I_s (R_1 + R_2 + R_3 + R_4) \\ &= R_{eq} I_s \\ R_{eq} &= R_1 + R_2 + R_2 + R_4 \end{aligned}$$

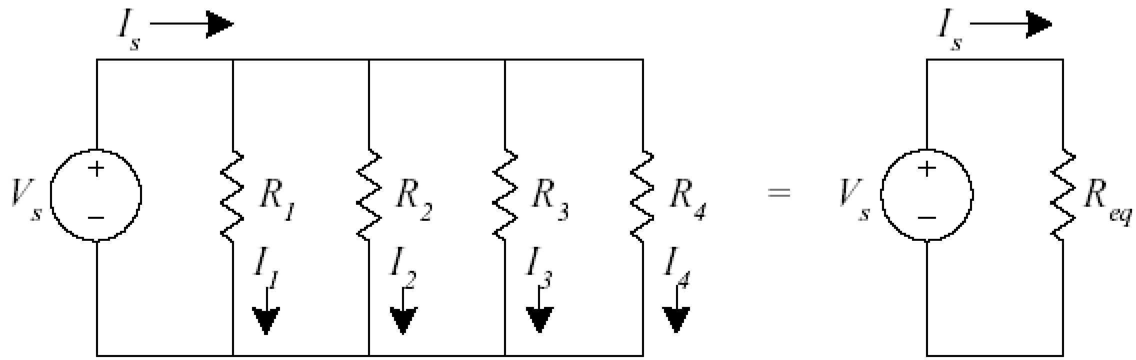
- Resistors in series add

Resistors in Parallel



$$
\begin{aligned}
I_s &= I_1 + I_2 + I_3 + I_4 \\
&= V_s/R_1 + V_s/R_2 + V_s/R_3 + V_s/R_4 \\
&= V_s \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \right) \\
&= \frac{V_s}{R_{eq}} \\
\frac{1}{R_{eq}} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \\
R_{eq} &= \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}
\end{aligned}
$$

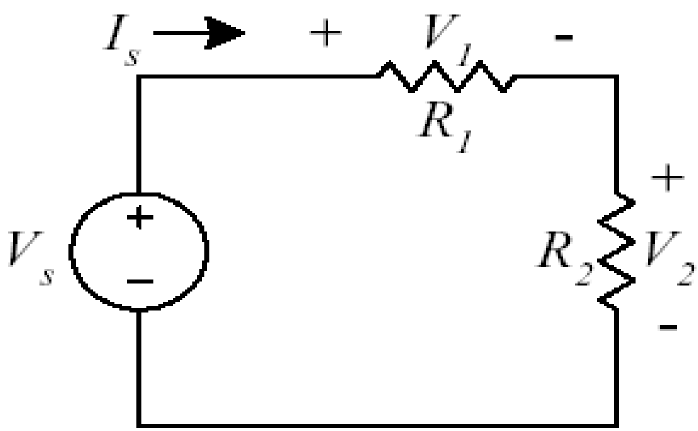
Resistors in Parallel



$$\begin{aligned}\frac{1}{R_{eq}} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \\ G_{eq} &= G_1 + G_2 + G_3 + G_4\end{aligned}$$

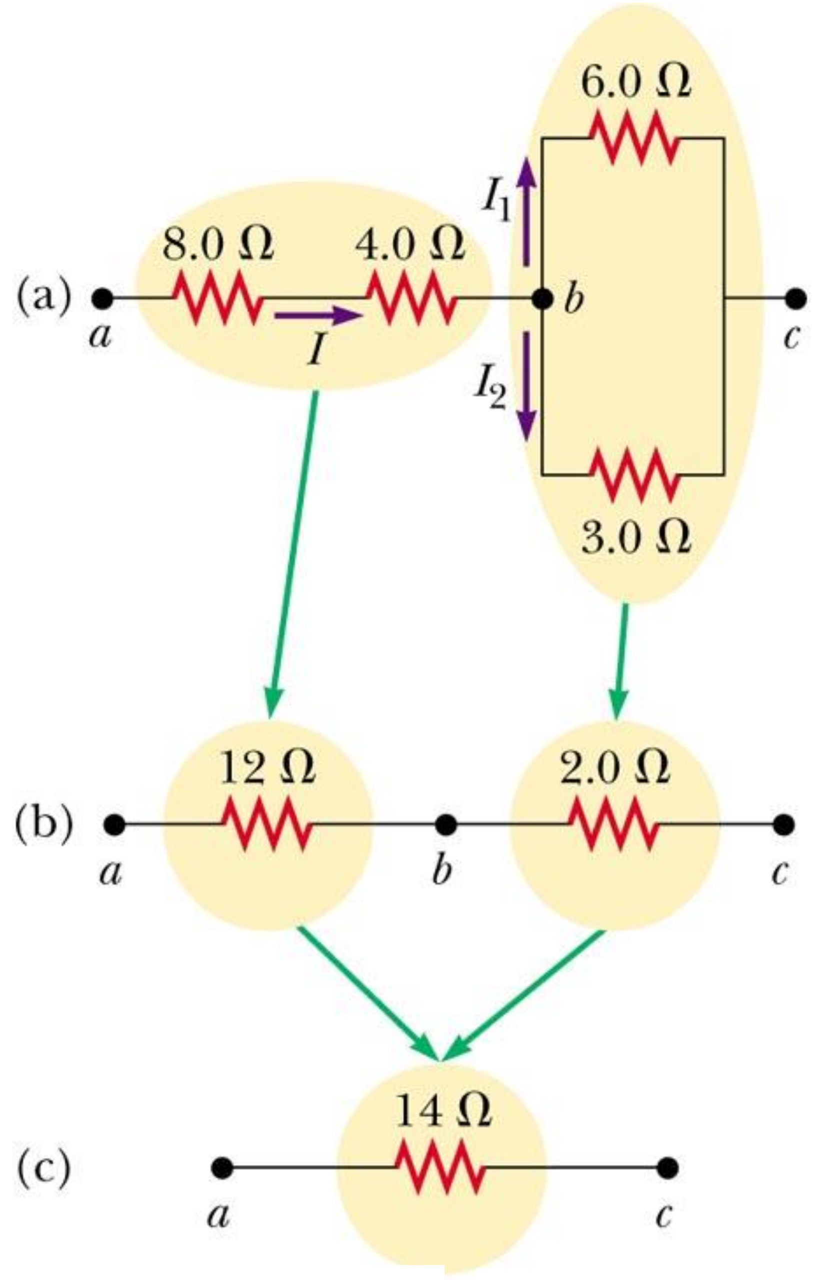
- Resistors in parallel have a more complicated relationship
- Easier to express in terms of conductance
- For two resistors: $R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$

Voltage Divider



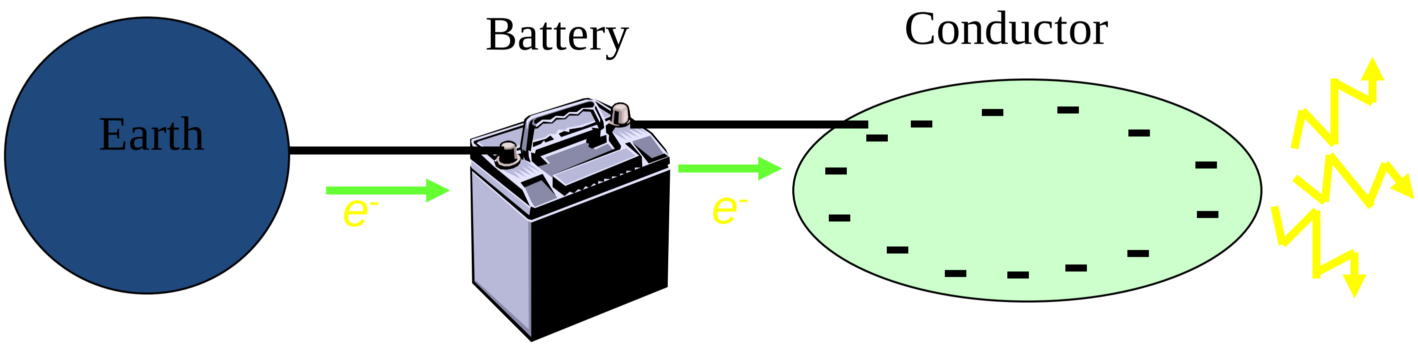
$$
\begin{aligned}
R_{eq} &= R_1 + R_2 \\
I_s &= \frac{V_s}{R_{eq}} \\
&= \frac{V_s}{R_1 + R_2} \\
V_2 &= I_s R_2 \\
&= V_s \frac{R_2}{R_1 + R_2} \\
V_1 &= I_s R_1 \\
&= V_s \frac{R_1}{R_1 + R_2}
\end{aligned}
$$

Equivalent Resistance – Complex Circuit



Maximum Charge on a Conductor

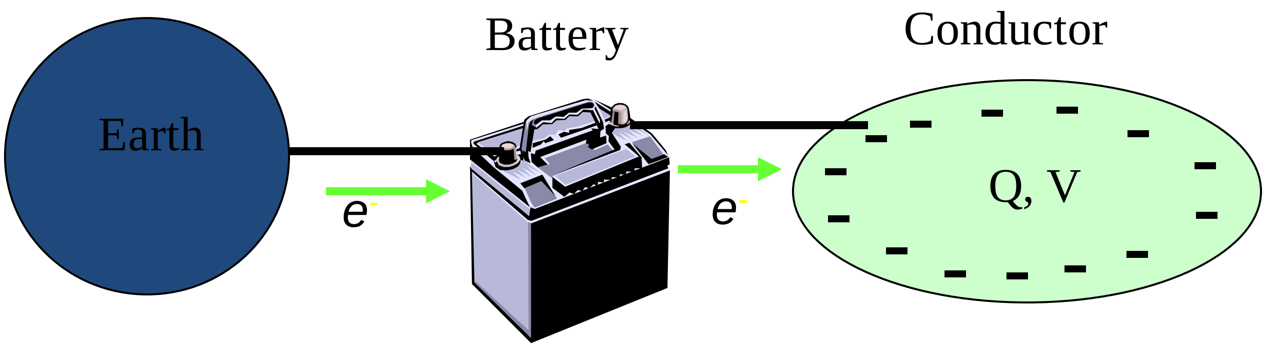
A battery establishes a difference of potential that can pump electrons e^- from a ground (earth) to a conductor



There is a limit to the amount of charge that a conductor can hold without leaking to the air. There is a certain <u>capacity</u> for holding charge.

Capacitance

The capacitance *C* of a conductor is defined as the ratio of the charge Q on the conductor to the potential V produced.



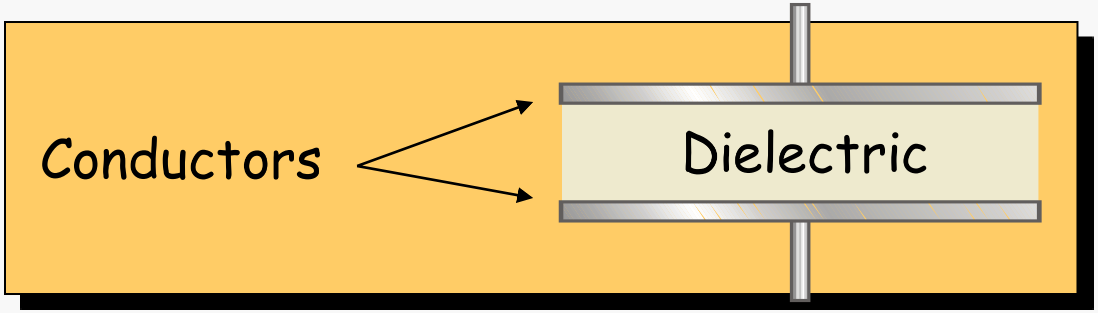
Capacitance:

$$C = \frac{Q}{V}; \quad Units: \; Coulombs \; per \; volt$$

The Capacitor

Capacitors are one of the fundamental passive components. In its most basic form, it is composed of two plates separated by a dielectric.

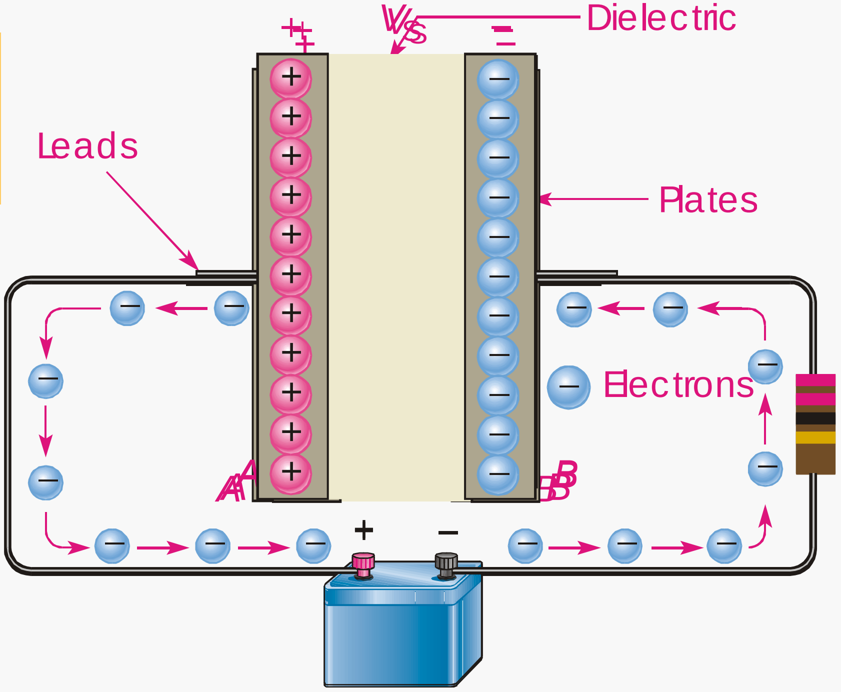
The ability to store charge is the definition of **capacitance**.



$$C = \frac{Q}{V}; \quad Units: \; Coulombs \; per \; volt$$

The Capacitor

The charging process…



A capacitor with stored charge can act as a temporary battery.

Capacitors in Parallel:

$$q_1 = C_1V, \quad q_2 = C_2V, \quad \text{and} \quad q_3 = C_3V.$$

$$q = q_1 + q_2 + q_3 = (C_1 + C_2 + C_3)V.$$

$$C_{eq} = \frac{q}{V} = C_1 + C_2 + C_3,$$

$$\boxed{C_{eq} = \sum_{j=1}^{n} C_j \qquad (n \text{ capacitors in parallel}).}$$

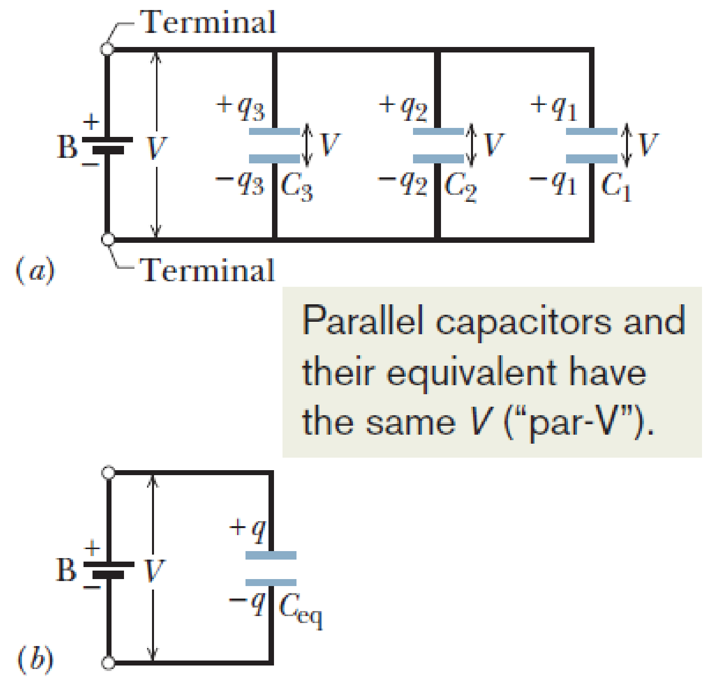


Fig. 25-8 (*a*) Three capacitors connected in parallel to battery B. The battery maintains potential difference V across its terminals and thus across *each* capacitor. (*b*) The equivalent capacitor, with capacitance C_{eq}, replaces the parallel combination.

Capacitors in Series:

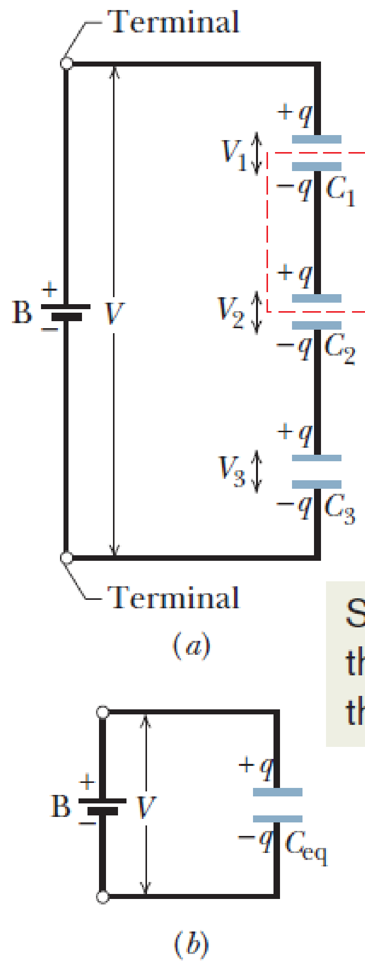
$$V_1 = \frac{q}{C_1}, \quad V_2 = \frac{q}{C_2}, \quad \text{and} \quad V_3 = \frac{q}{C_3}.$$

$$V = V_1 + V_2 + V_3 = q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right).$$

$$C_{eq} = \frac{q}{V} = \frac{1}{1/C_1 + 1/C_2 + 1/C_3},$$

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}.$$

$$\frac{1}{C_{eq}} = \sum_{j=1}^{n} \frac{1}{C_j} \qquad (n \text{ capacitors in series}).$$

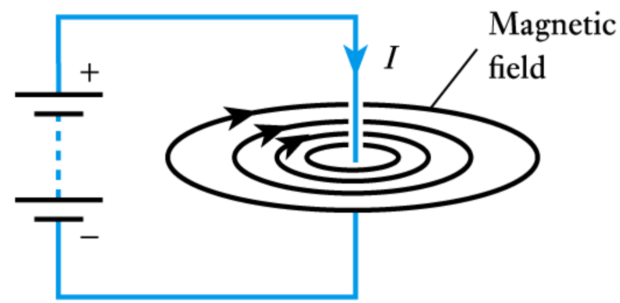


Series capacitors and their equivalent have the same q ("seri-q").

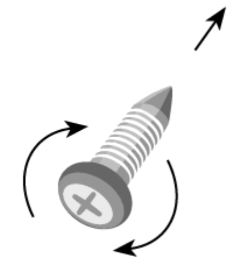
Fig. 25-9 (a) Three capacitors connected in series to battery B. The battery maintains potential difference V between the top and bottom plates of the series combination. (b) The equivalent capacitor, with capacitance C_{eq}, replaces the series combination.

Electromagnetism

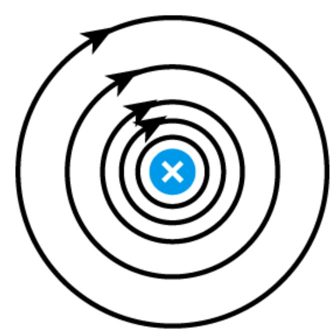
A wire carrying a current I produces a **magnetic field**



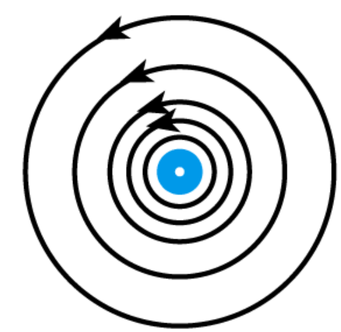
(a) The magnetic field about a current-carrying wire



(b) The direction of rotation and motion of a woodscrew



(c) The magnetic field about a current flowing into the page

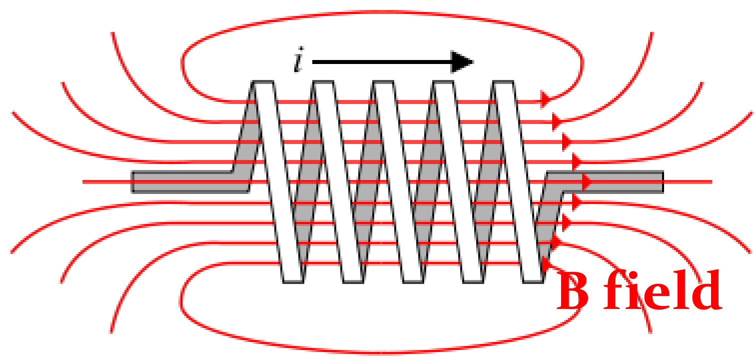


(d) The magnetic field about a current flowing out of the page

Inductance
Energy Storage Devices

Stores energy in an magnetic field created by the electric current flowing through it.

- The flow of current through an inductor creates a magnetic field



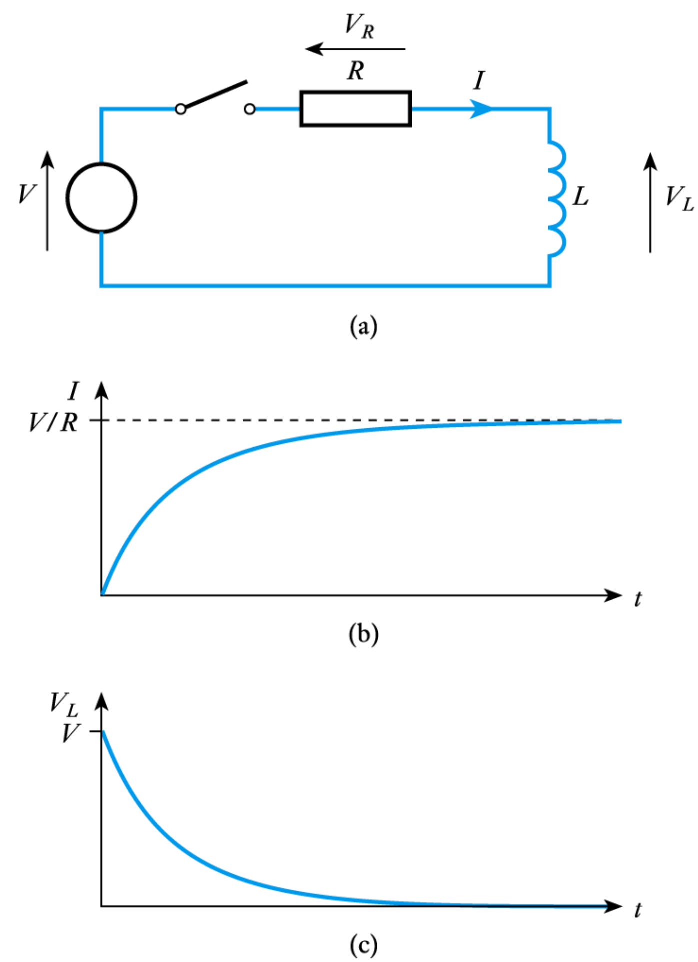
- If the current flowing through the inductor drops, the magnetic field will also decrease and energy is released through the generation of a current.

Inductors

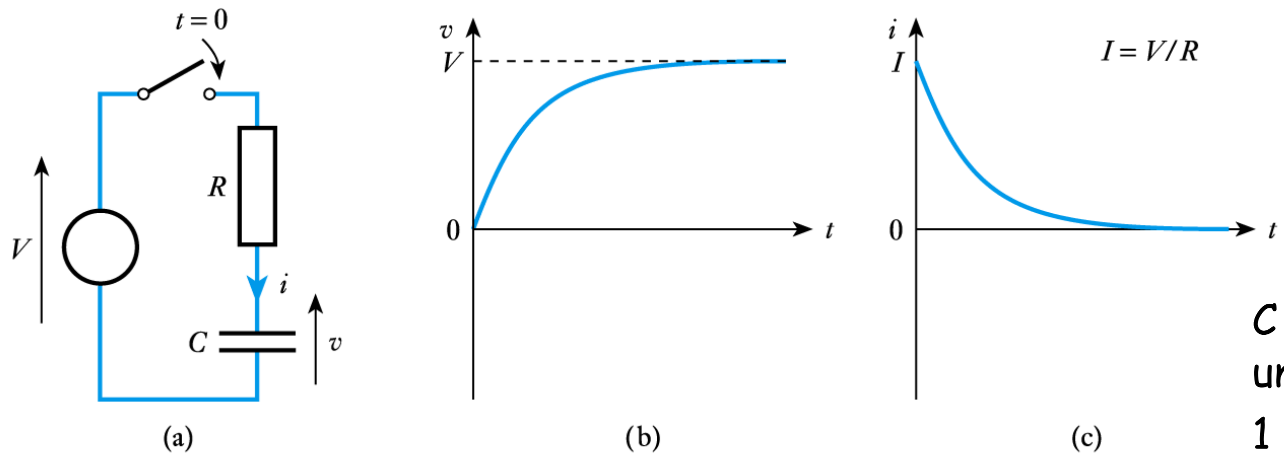
- Generally - coil of conducting wire
  - Usually wrapped around a solid core. If no core is used, then the inductor is said to have an 'air core'.

Voltage and Current Relation

- Consider the circuit shown here
  - inductor is initially un-energised
    - current through it will be zero
  - switch is closed at $t = 0$
  - I is initially zero
    - hence V_R is initially 0
    - hence V_L is initially V
  - as the inductor is energised:
    - I increases
    - V_R increases
    - hence V_L decreases
    - we have exponential behaviour



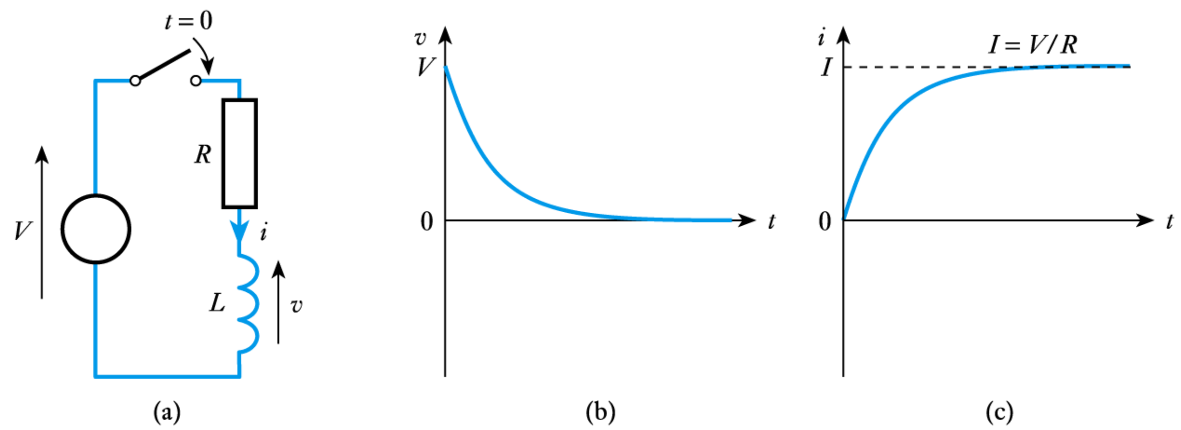
Both the voltage and current have an exponential forms



$$i_C = C\frac{dv}{dt}$$

C , capacitance, has the units of Farad (F)

1 F = 1 A.sn/V

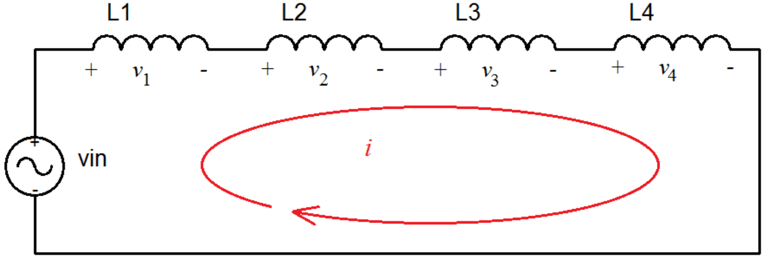


$$v_L = L\frac{di}{dt}$$

L , inductance, has the units of Henries (H)

1 H = 1 V.sn/A

Inductors in Series



$$v_{in} = v_1 + v_2 + v_3 + v_4$$

$$v_1 = L_1 \frac{\mathrm{di}}{\mathrm{dt}} \qquad v_2 = L_2 \frac{\mathrm{di}}{\mathrm{dt}}$$

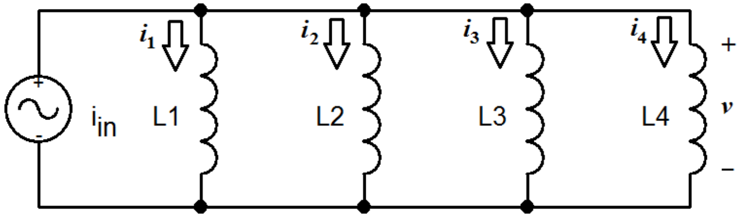
$$v_3 = L_3 \frac{\mathrm{di}}{\mathrm{dt}} \qquad v_4 = L_4 \frac{\mathrm{di}}{\mathrm{dt}}$$

$$v_{in} = L_1 \frac{\mathrm{di}}{\mathrm{dt}} + L_2 \frac{\mathrm{di}}{\mathrm{dt}} + L_3 \frac{\mathrm{di}}{\mathrm{dt}} + L_4 \frac{\mathrm{di}}{\mathrm{dt}}$$

$$v_{in} = L_{eq} \frac{\mathrm{di}}{\mathrm{dt}}$$

$$\mathrm{L}_{\mathrm{eq}} = L_1 + L_2 + L_3 + L_4$$

Inductors in Parallel



$$i_{in} = i_1 + i_2 + i_3 + i_4$$

$$i_1 = \frac{1}{L_1}\int_{t_o}^{t_1} \text{vdt} \qquad i_2 = \frac{1}{L_2}\int_{t_o}^{t_1} \text{vdt}$$

$$i_3 = \frac{1}{L_3}\int_{t_o}^{t_1} \text{vdt} \qquad i_4 = \frac{1}{L_4}\int_{t_o}^{t_1} \text{vdt}$$

$$i_{in} = \frac{1}{L_1}\int_{t_o}^{t_1} \text{vdt} + \frac{1}{L_2}\int_{t_o}^{t_1} \text{vdt} + \frac{1}{L_3}\int_{t_o}^{t_1} \text{vdt} + \frac{1}{L_4}\int_{t_o}^{t_1} \text{vdt}$$

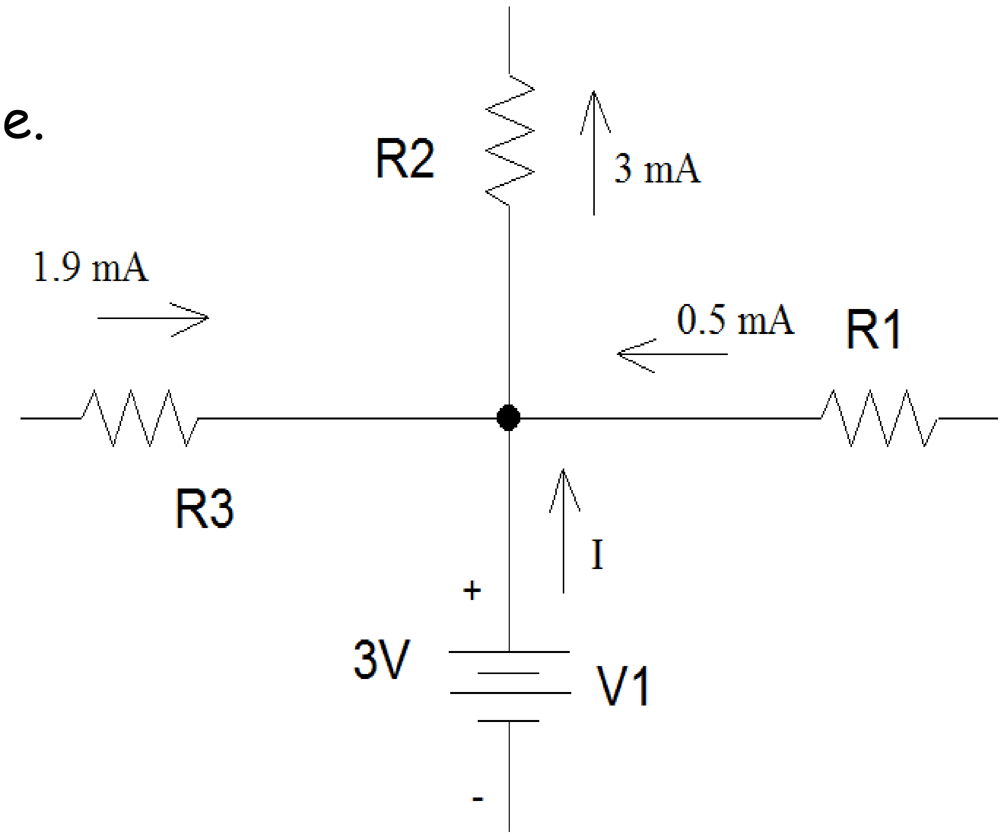
$$i_{in} = \frac{1}{L_{eq}}\int_{t_o}^{t_1} \text{vdt}$$

$$\text{L}_{\text{eq}} = \left[\left(1/L_1\right) + \left(1/L_2\right) + \left(1/L_3\right) + \left(1/L_4\right)\right]^{-1}$$

Example 1

- Determine I, the current flowing out of the voltage source.
  - Use KCL
    - 1.9 mA + 0.5 mA + I are entering the node.
    - 3 mA is leaving the node.

    V1 is generating power.



$$1.9mA + 0.5mA + I = 3mA$$

$$I = 3mA - (1.9mA + 0.5mA)$$

$$I = 0.6mA$$

Example 2

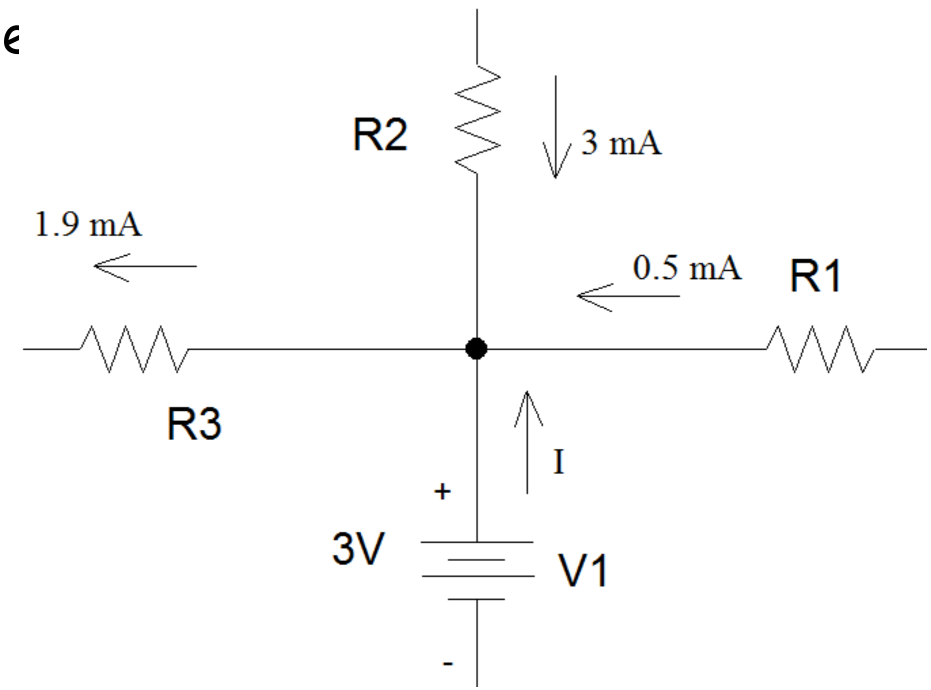
- Suppose the current through R2 was entering the node and the current through R3 was leaving the node.
  - Use KCL
    - 3 mA + 0.5 mA + I are entering the node.
    - 1.9 mA is leaving the node

    V1 is dissipating power.

$$3mA + 0.5mA + I = 1.9mA$$

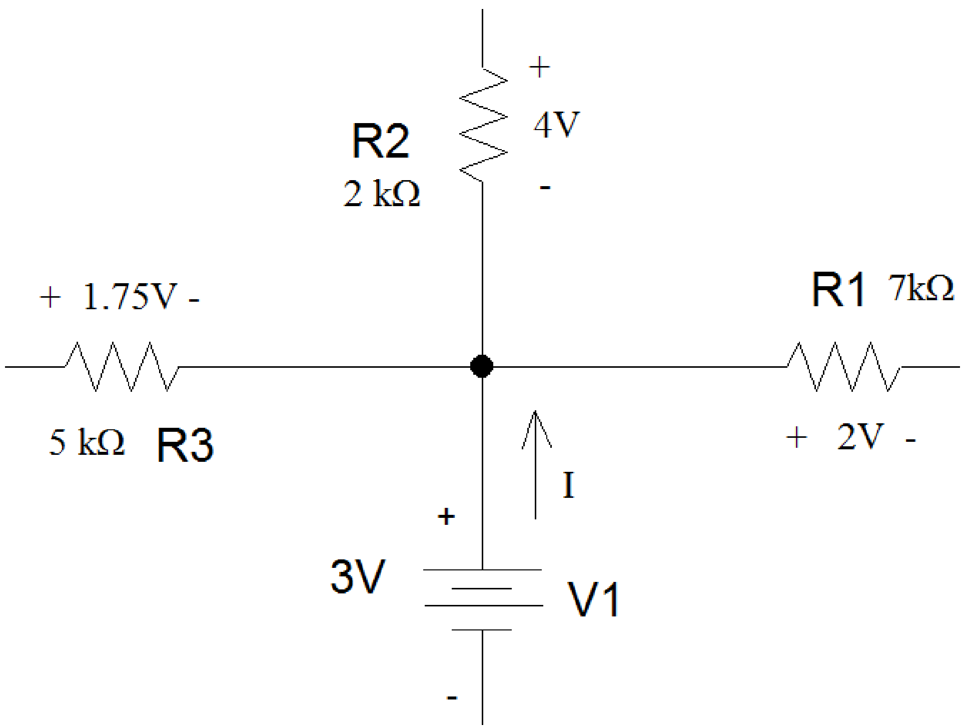
$$I = 1.9mA - (3mA + 0.5mA)$$

$$I = -1.6mA$$



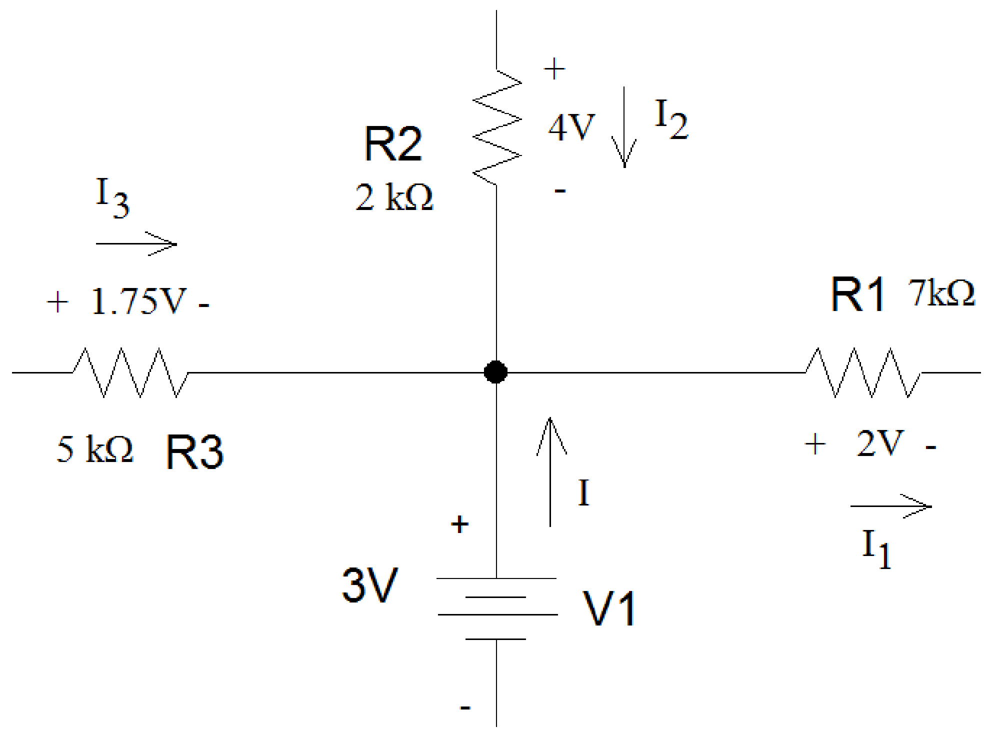
Example 3

- If voltage drops are given instead of currents, you need to apply Ohm's Law to determine the current flowing through each of the resistors before you can find the current flowing out of the voltage supply.



Example 3 (con't)

- For power dissipating components such as resistors, passive sign convention means that current flows into the resistor at the terminal has the + sign on the voltage drop and leaves out the terminal that has the – sign.

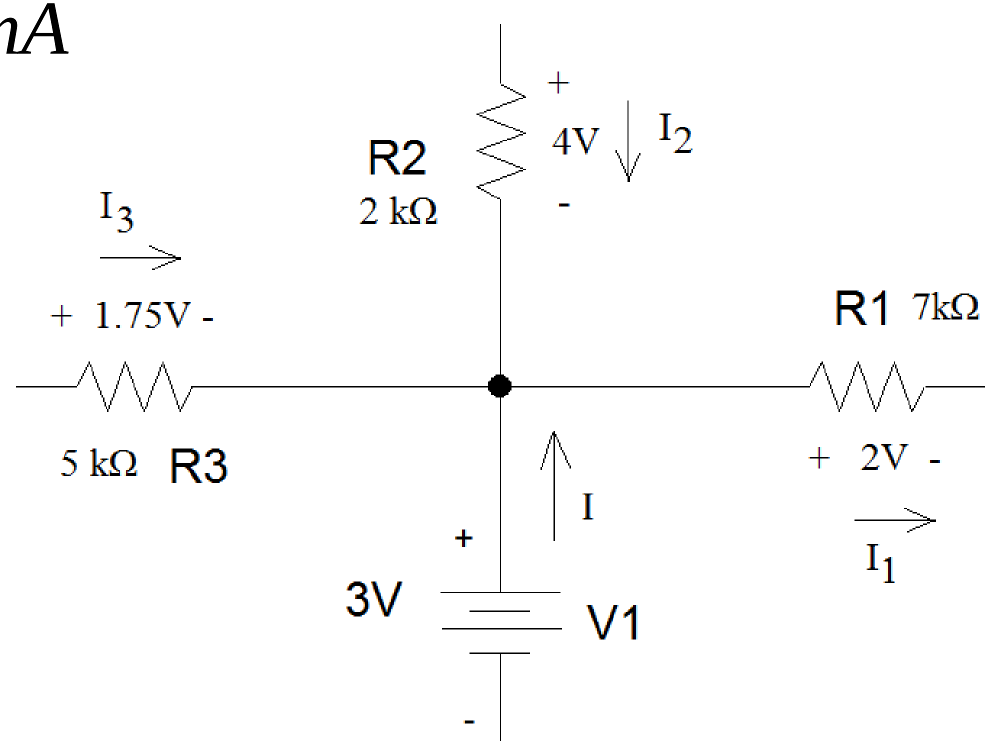


Example 3 (con't)

$$I_1 = 2V / 7k\Omega = 0.286mA$$

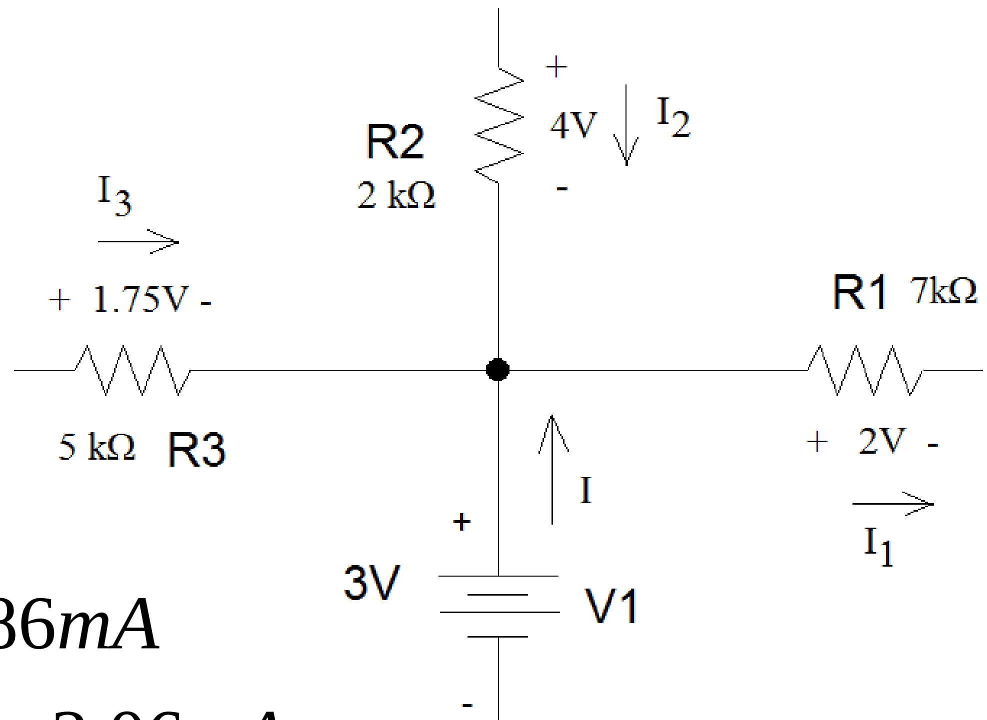
$$I_2 = 4V / 2k\Omega = 2mA$$

$$I_3 = 1.75V / 5k\Omega = 0.35mA$$



Example 3 (con't)

- I1 is leaving the node.
- I2 is entering the node.
- I3 is entering the node.
- I is entering the node.



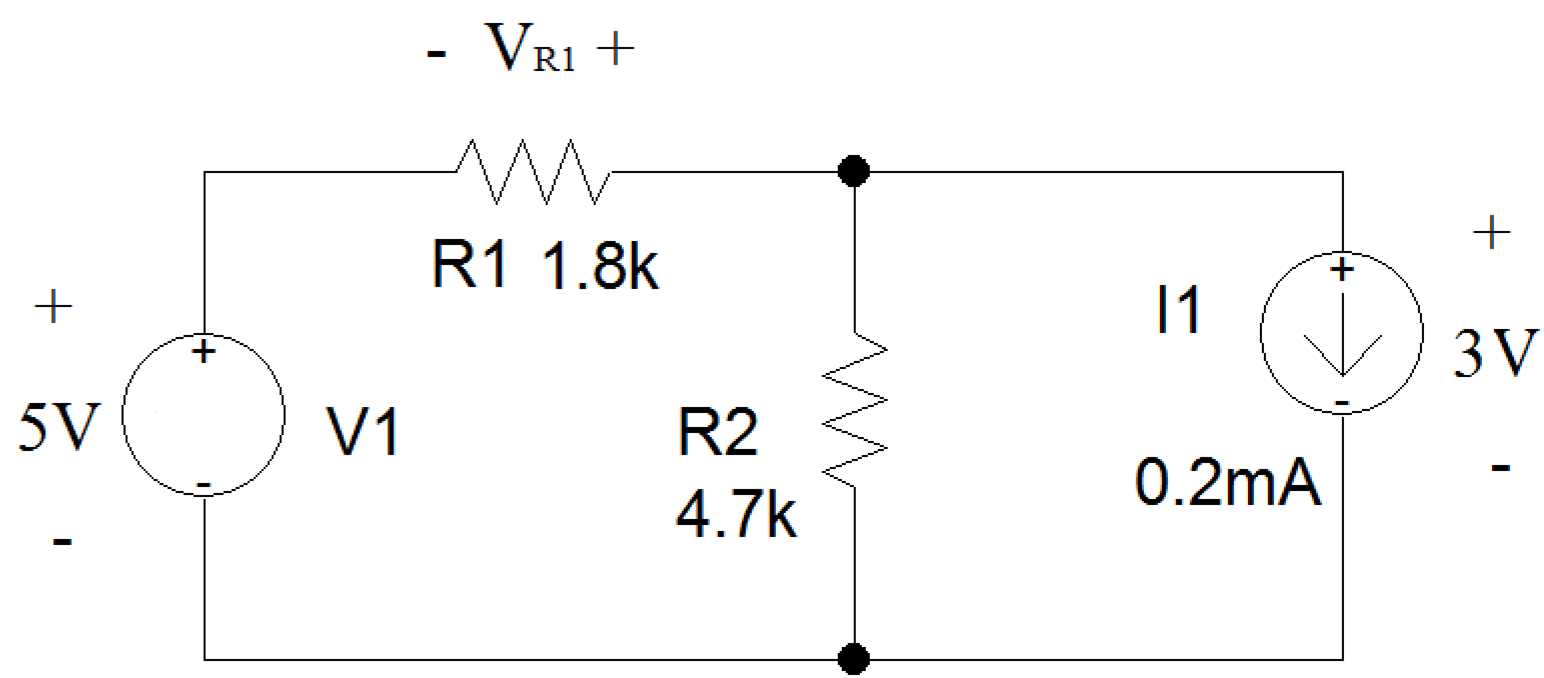
$$I_2 + I_3 + I = I_1$$

$$2mA + 0.35mA + I = 0.286mA$$

$$I = 0.286mA - 2.35mA = -2.06mA$$

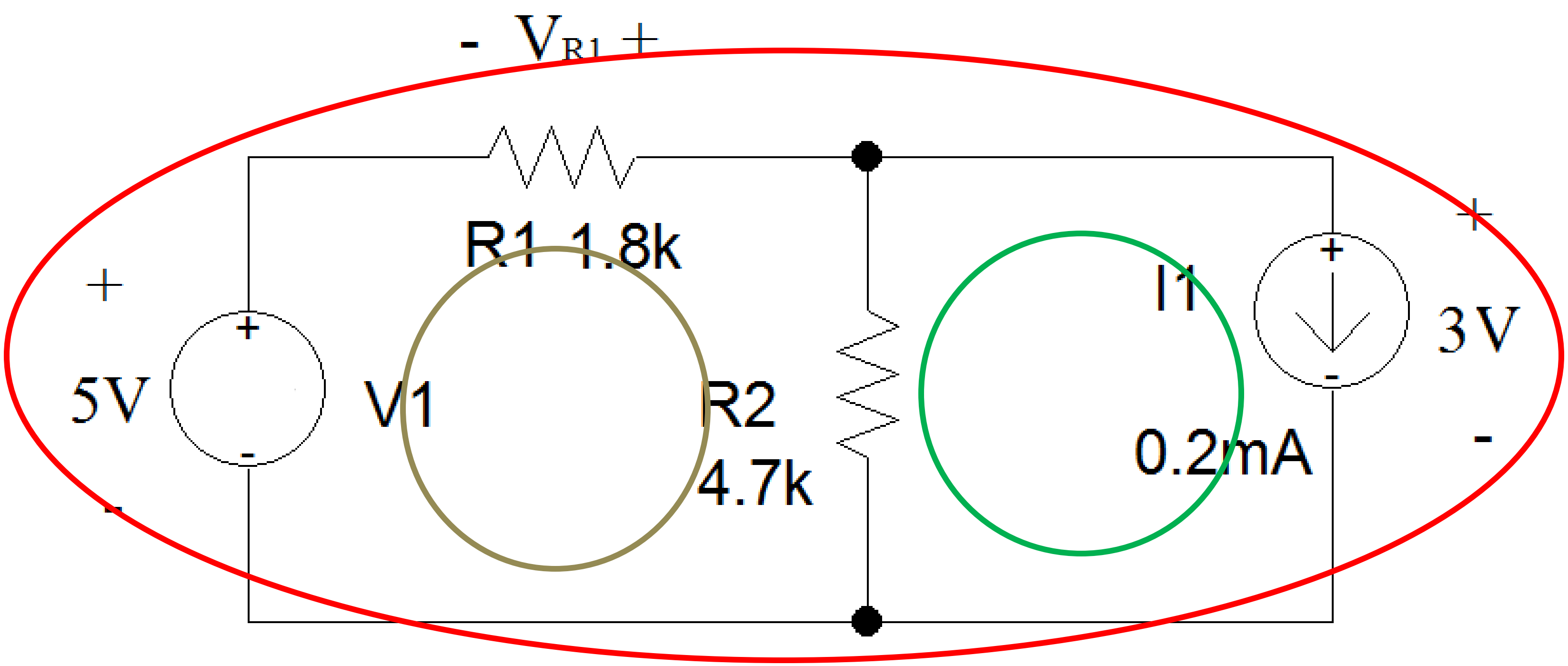
Example 4

- Find the voltage across R1. Note that the polarity of the voltage has been assigned in the circuit schematic.
  - First, define a loop that include R1.



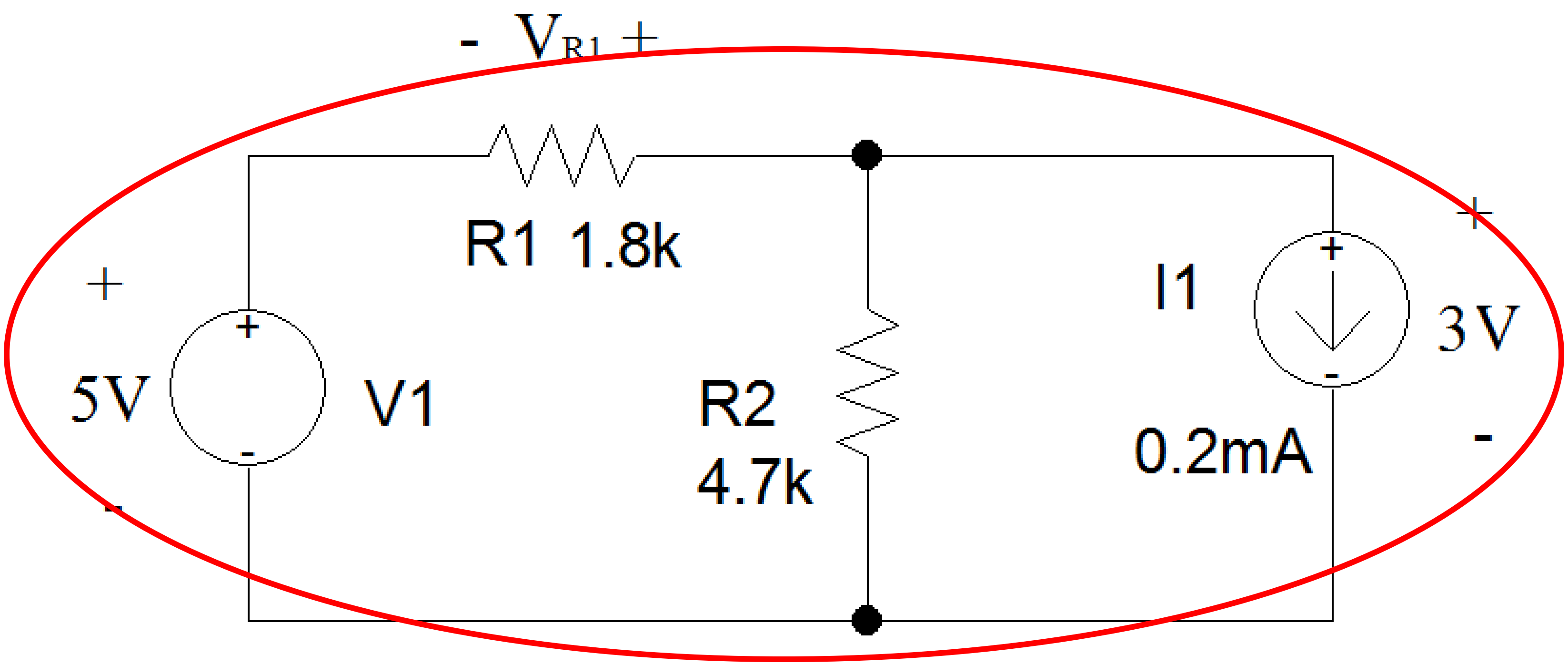
Example 4 (con't)

- There are three possible loops in this circuit – only two include R1.
  - Either loop may be used to determine V_{R1}.



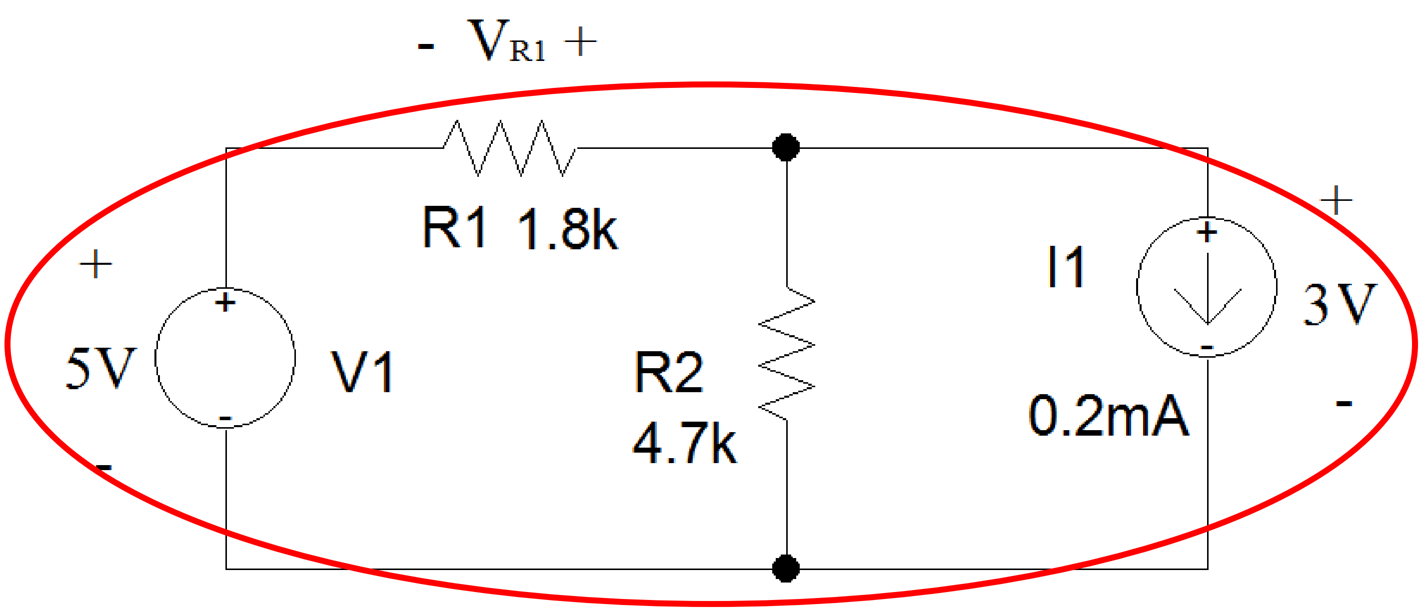
Example 4 (con't)

- If the outer loop is used:
  - Follow the loop clockwise.



Example 4 (con't)

- Follow the loop in a clockwise direction.
- The 5V drop across V1 is a voltage rise.
- V_{R1} should be treated as a voltage rise.
- The loop enters on the positive side of the CURRENT source and exits out the negative side. This is a voltage drop as the voltage becomes less positive as you move through the component.

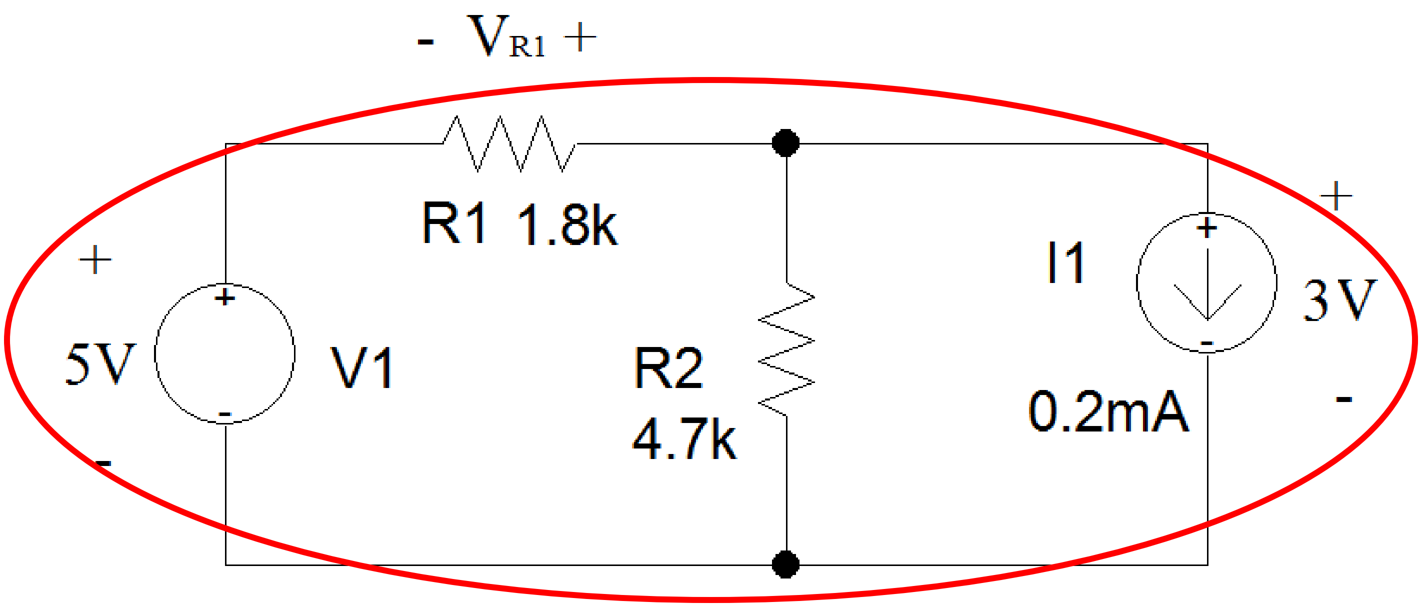


Example 4 (con't)

By convention, voltage drops are added and voltage rises are subtracted in KVL.

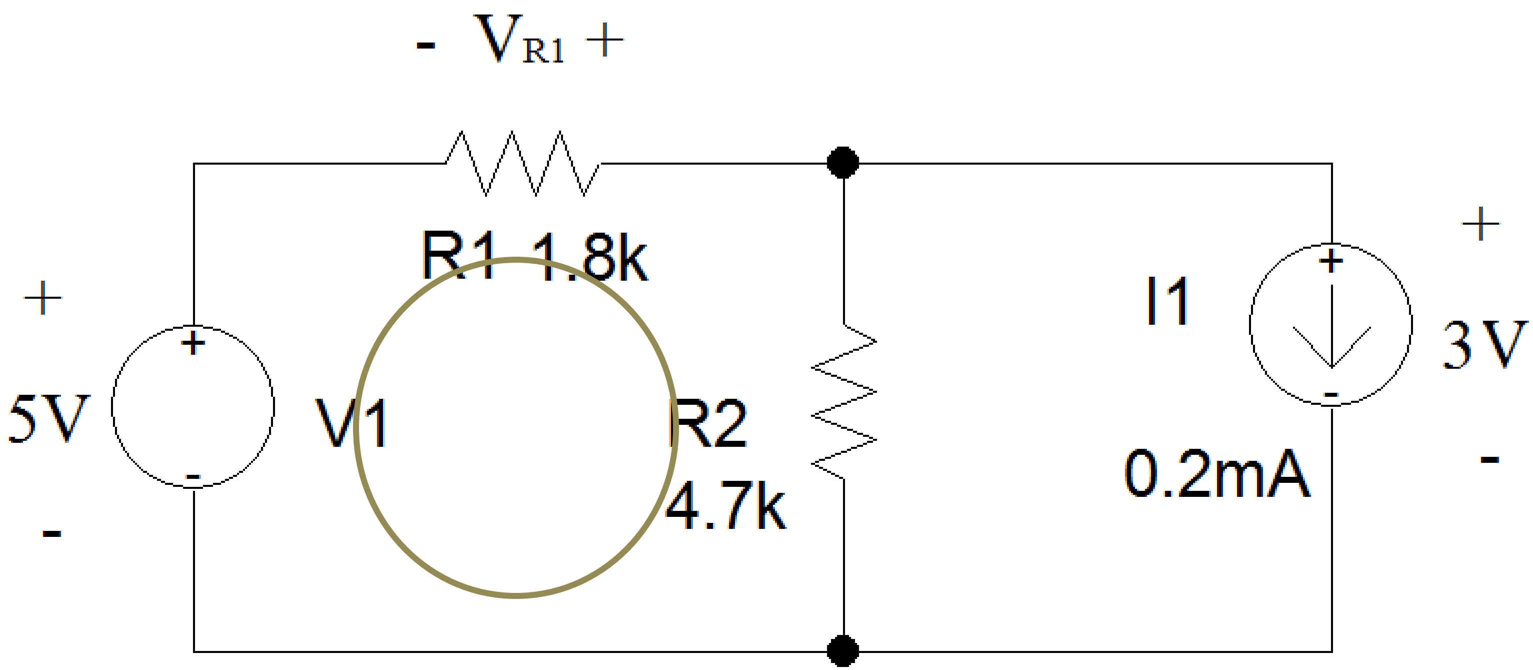
$$-5V - V_{R1} + 3V = 0$$

$$V_{R1} = -2V$$



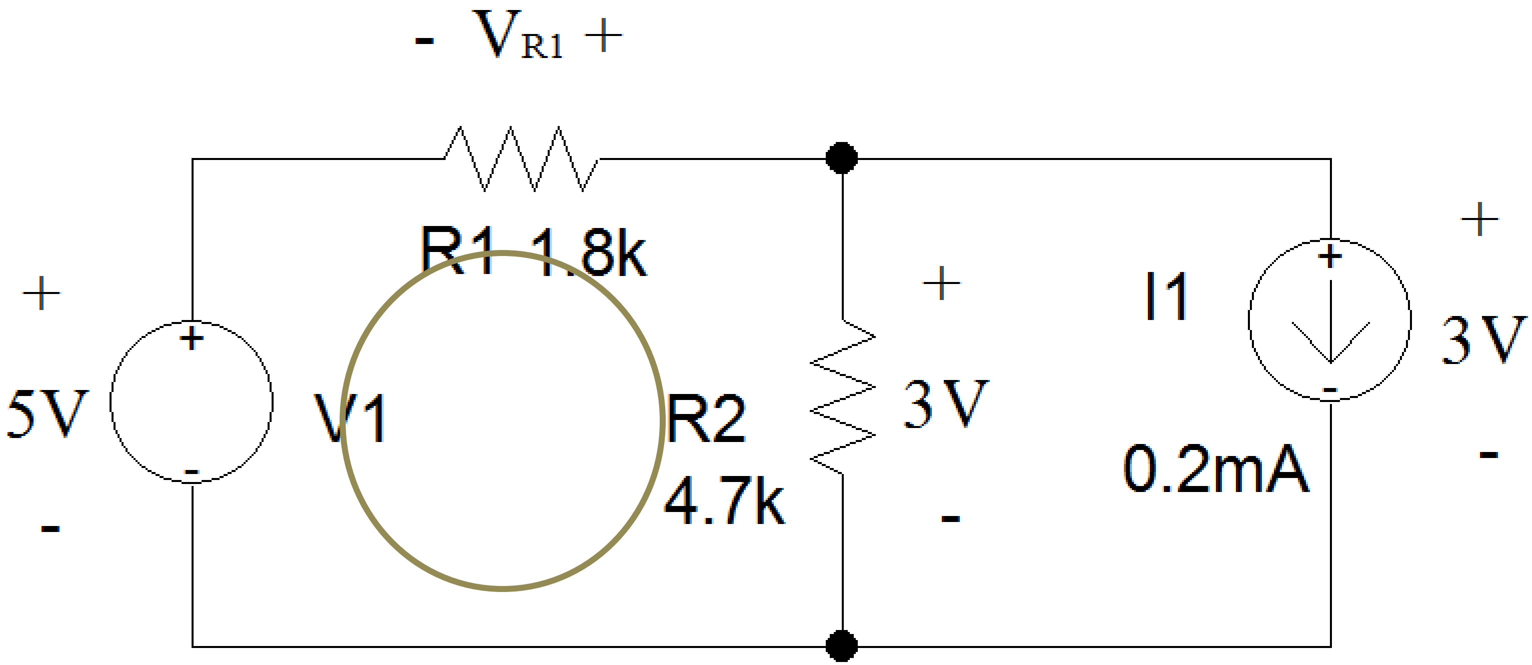
Example 4 (con't)

- Suppose you chose the green loop instead.
  - Since R2 is in parallel with I1, the voltage drop across R2 is also 3V.



Example 4 (con't)

- The 5V drop across V1 is a voltage rise.
- V_{R1} should be treated as a voltage rise.
- The loop enters R2 on the positive side and exits out the negative side. This is a voltage drop as the voltage becomes less positive as you move through the component.

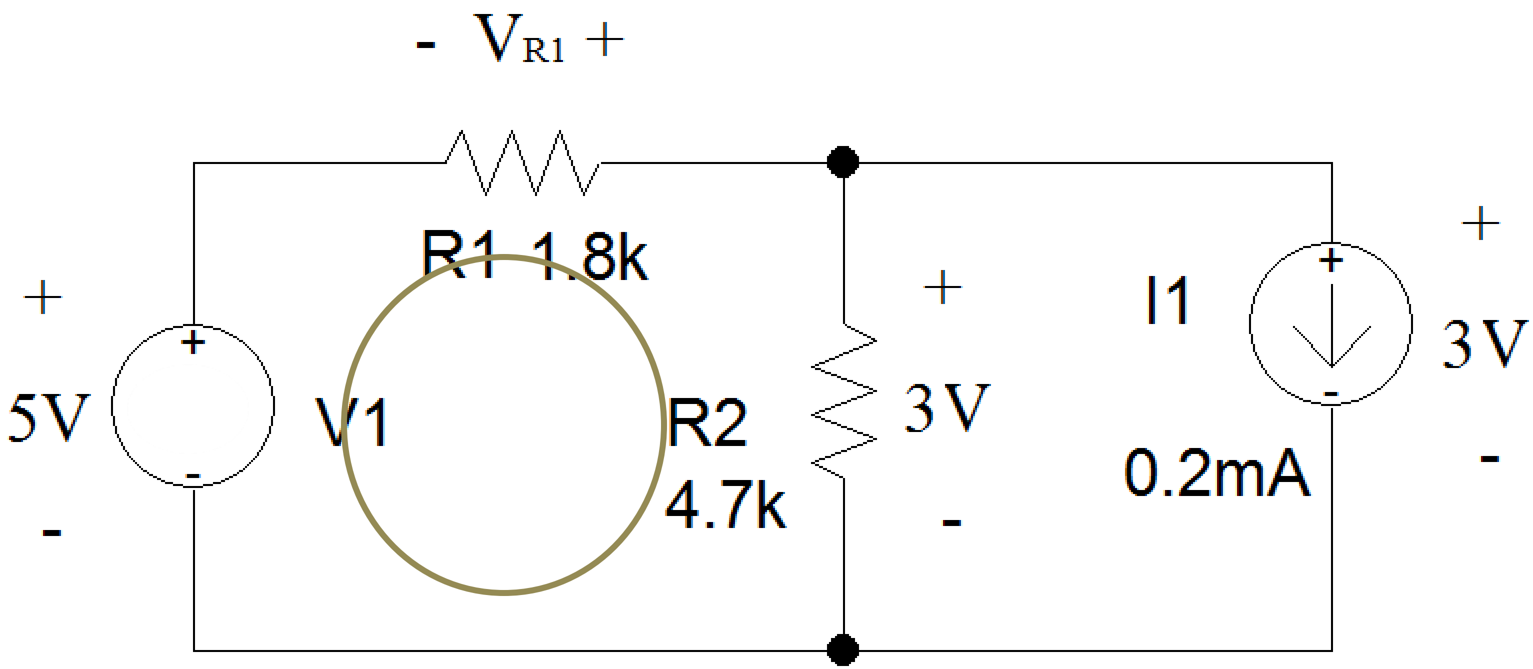


Example 4 (con't)

- As should happen, the answer is the same.

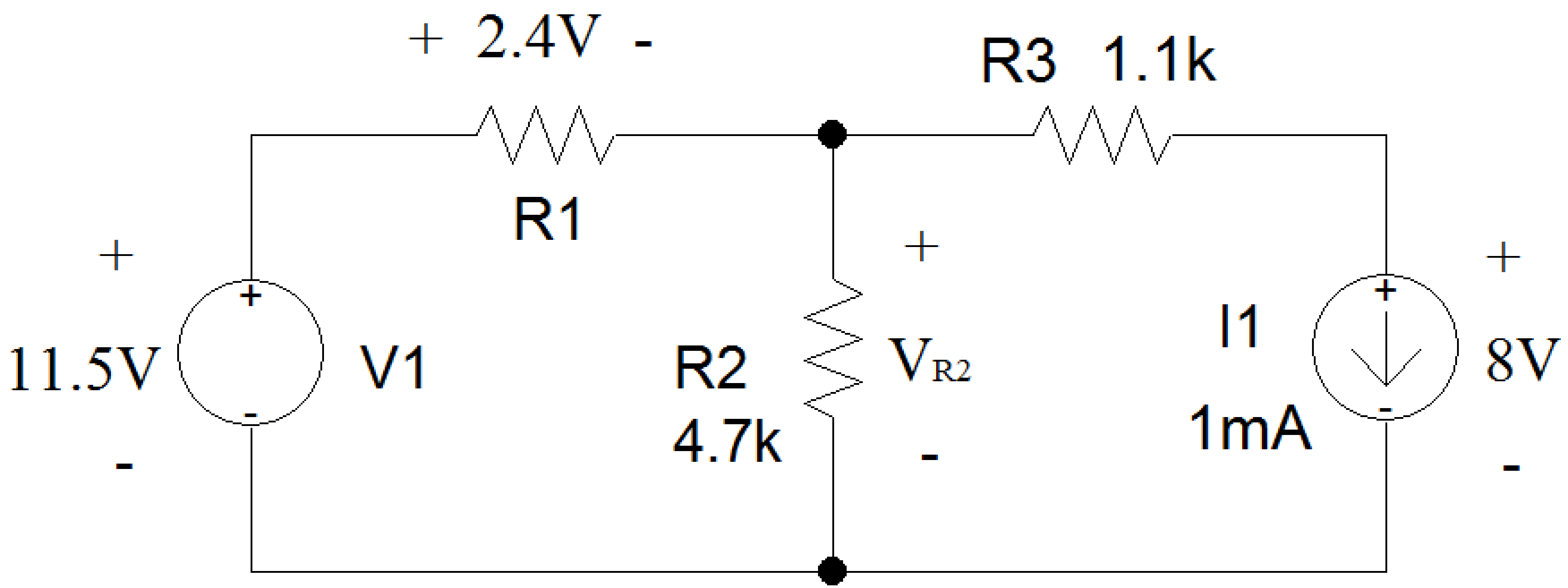
$$-5V - V_{R1} + 3V = 0$$

$$V_{R1} = -2V$$



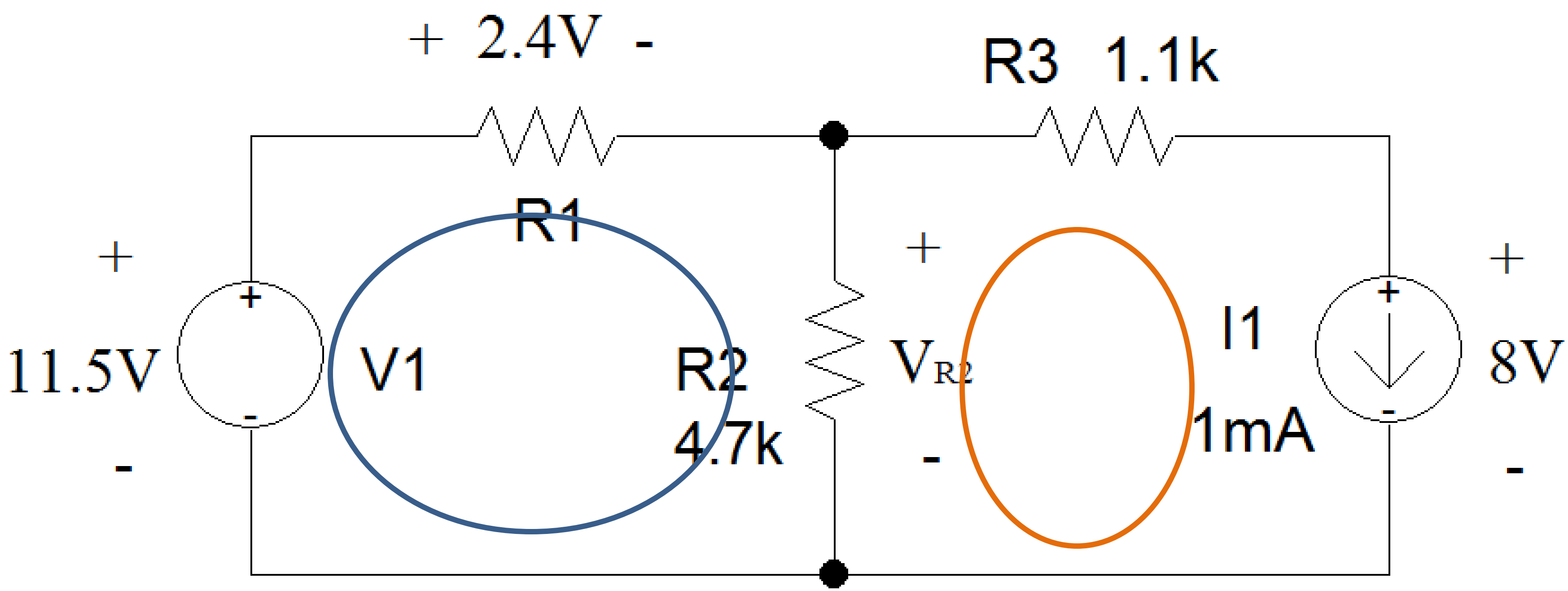
Example 5

- Find the voltage across R2 and the current flowing through it.
  - First, draw a loop that includes R2.



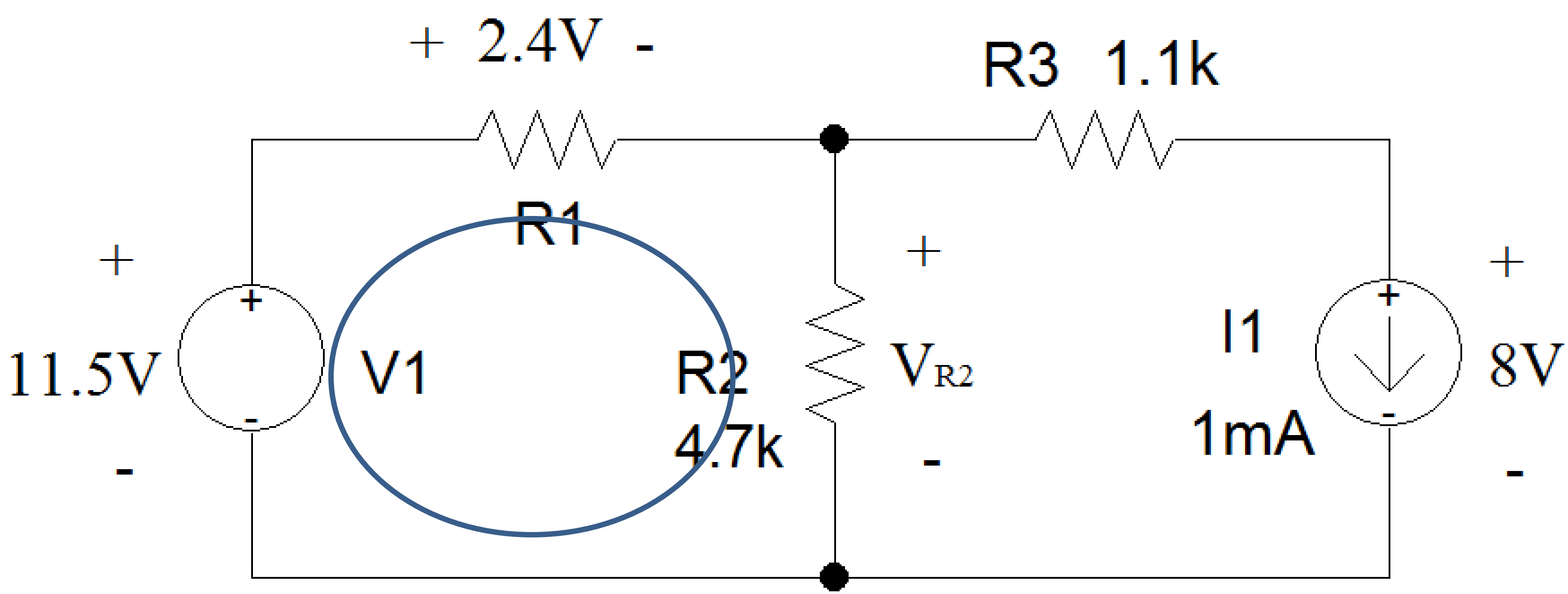
Example 5 (con't)

- There are two loops that include R2.
  - The one on the left can be used to solve for V_{R2} immediately.



Example 5 (con't)

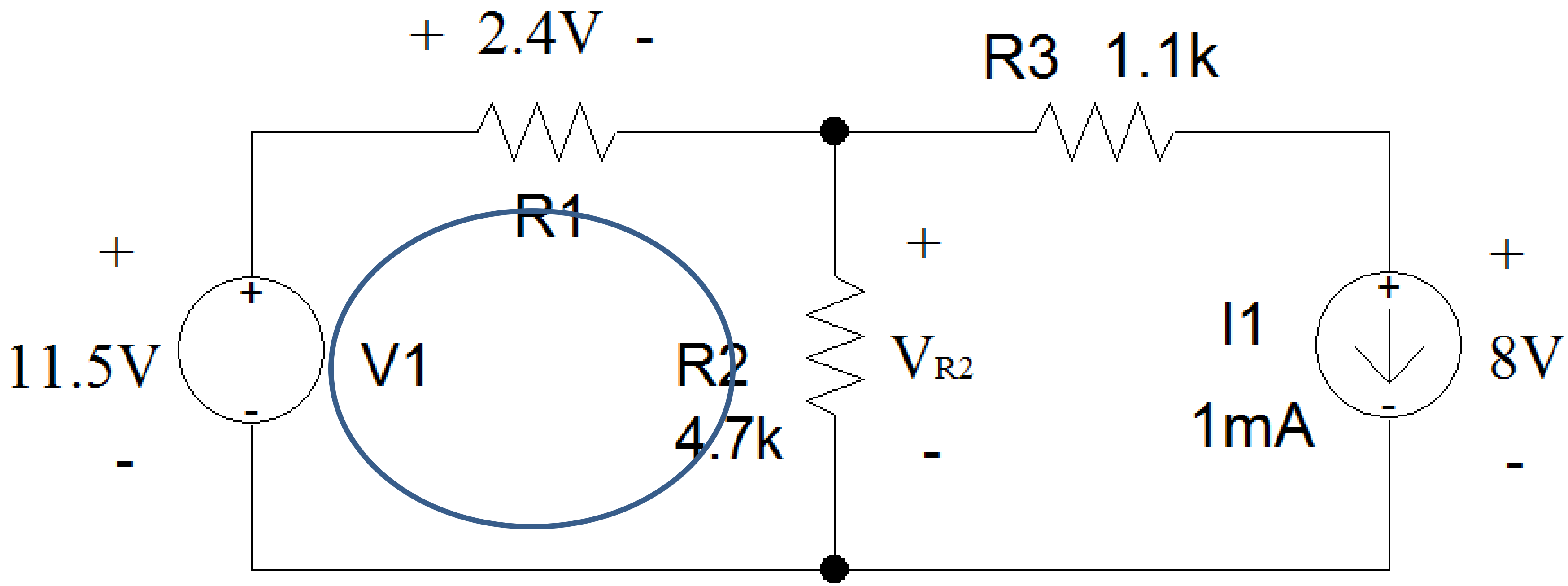
- Following the loop in a clockwise direction.
  - The 11.5V drop associated with V1 is a voltage rise.
  - The 2.4V associated with R1 is a voltage drop.
  - V_{R2} is treated as a voltage drop.



Example 5 (con't)

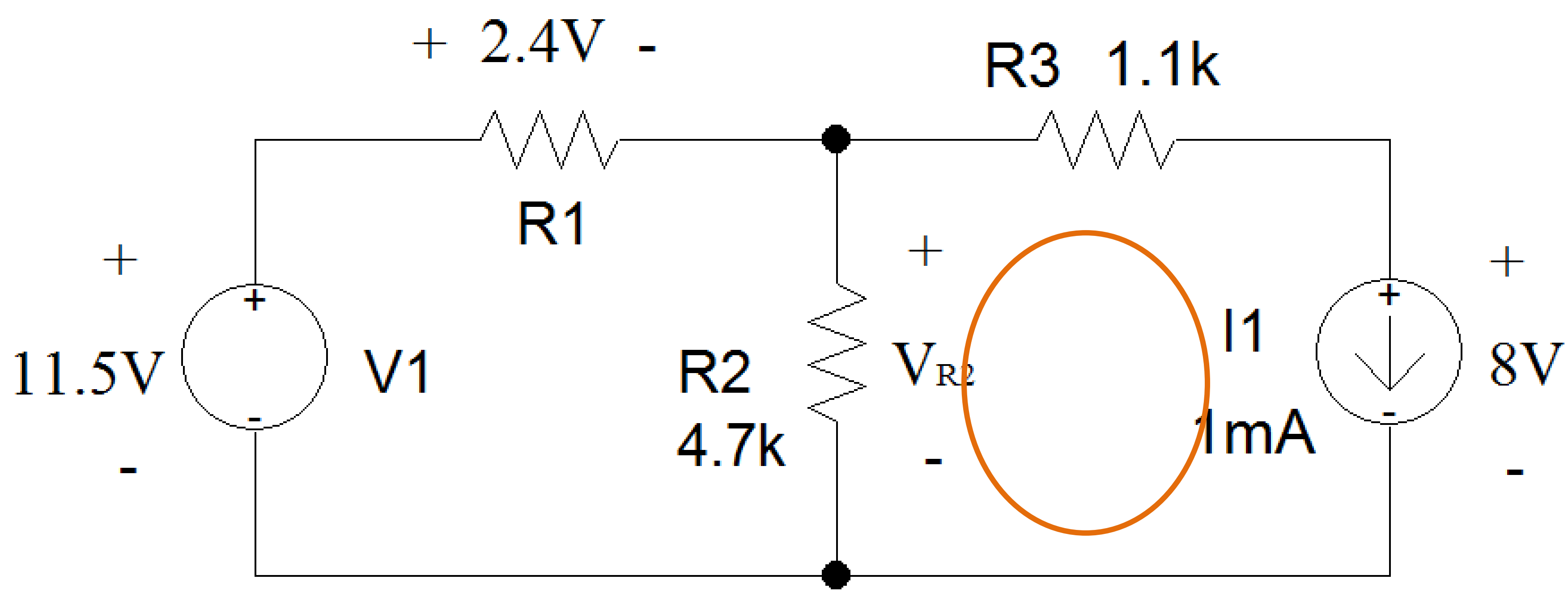
$$-11.5V + 2.4V + V_{R2} = 0$$

$$V_{R2} = 9.1V$$



Example 5 (con't)

- If you used the right-hand loop, the voltage drop across R3 must be calculated using Ohm's Law.



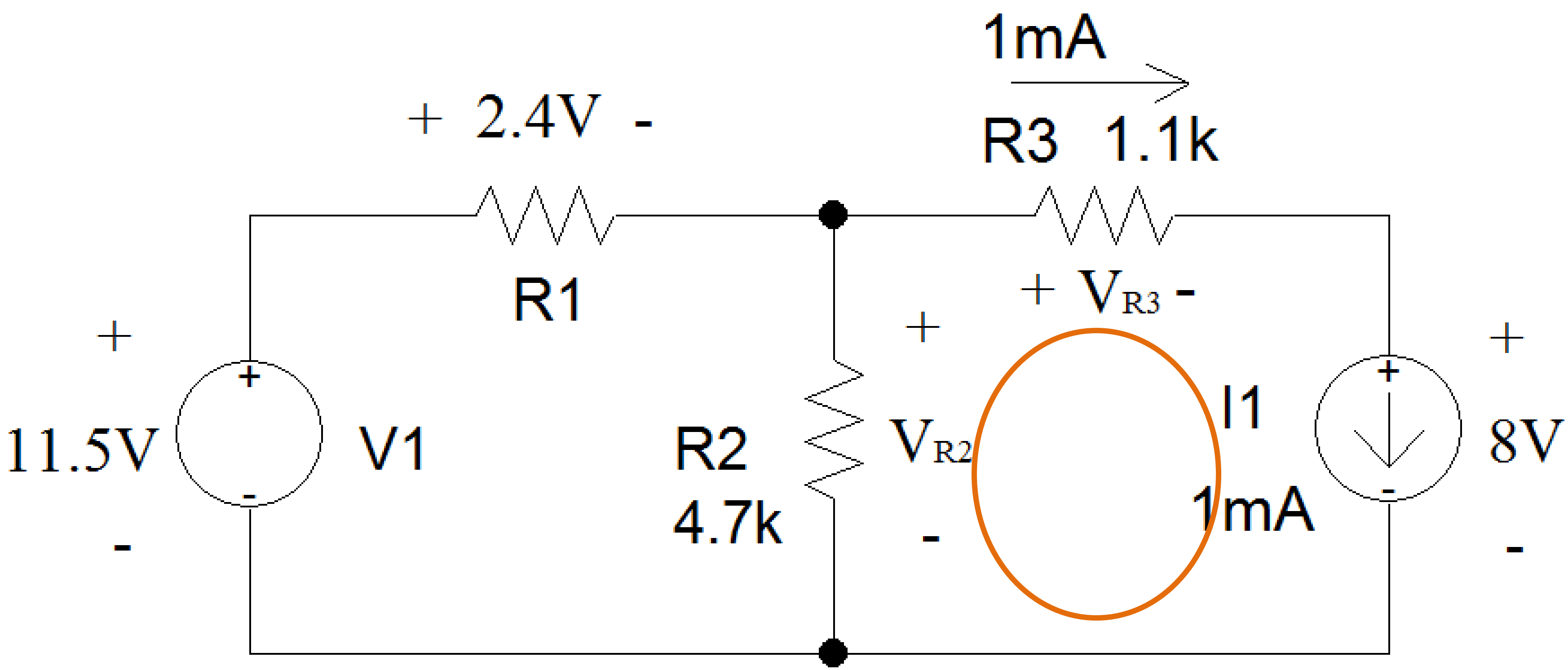
Example 5 (con't)

- Since R3 is a resistor, passive convention means that the positive sign of the voltage drop will be assigned to the end of R3 where current enters the resistor.
- As I1 is in series with R3, the direction of current through R3 is determined by the direction of current flowing out of the current source.
- Because I1 and R3 are in series, the magnitude of the current flowing out of I1 must be equal to the magnitude of the current flowing out of R3.

Example 5 (con't)

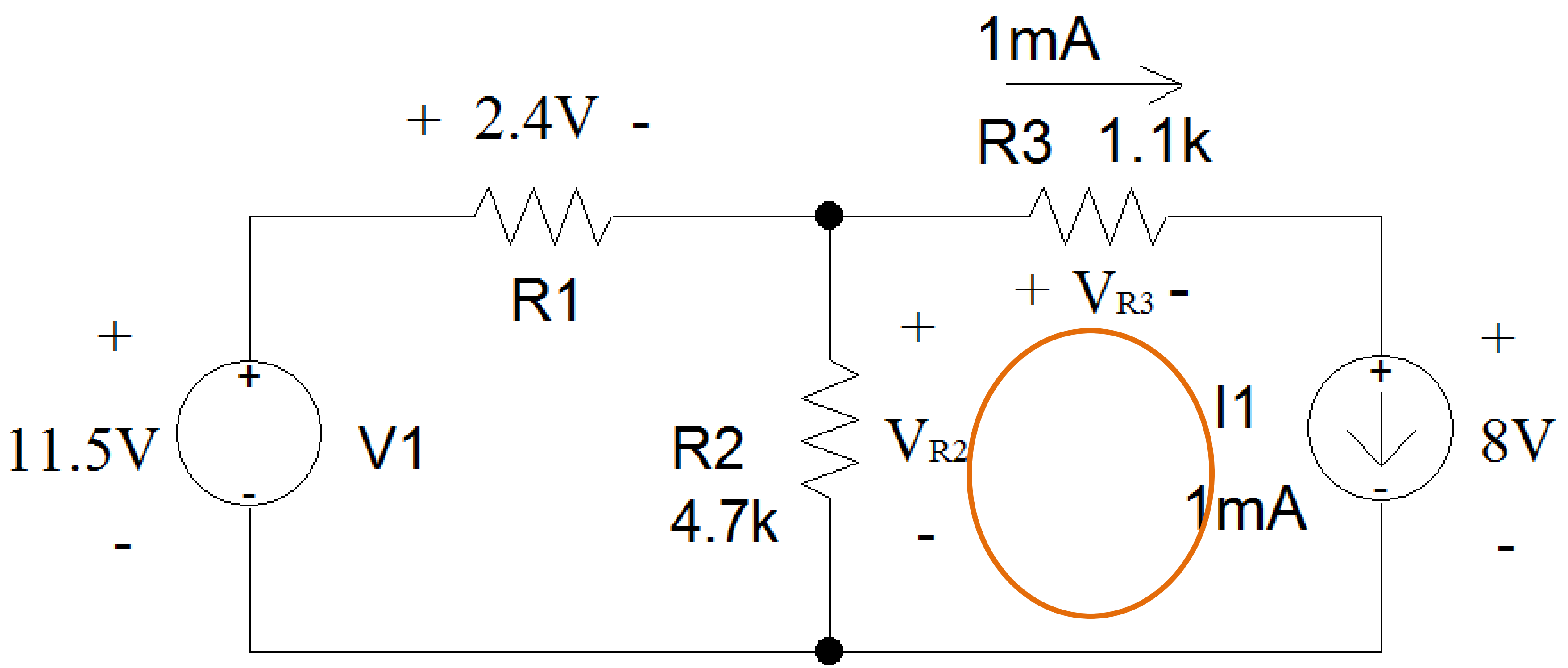
- Use Ohm's Law to find V_{R3}.

$$V_{R3} = 1mA(1.1k\Omega) = 1.1V$$



Example 5 (con't)

- Moving clockwise around the loop:
  - V_{R3} is a voltage drop.
  - The voltage associated with I1 is a voltage drop.
  - **V_{R2} is a voltage rise.**

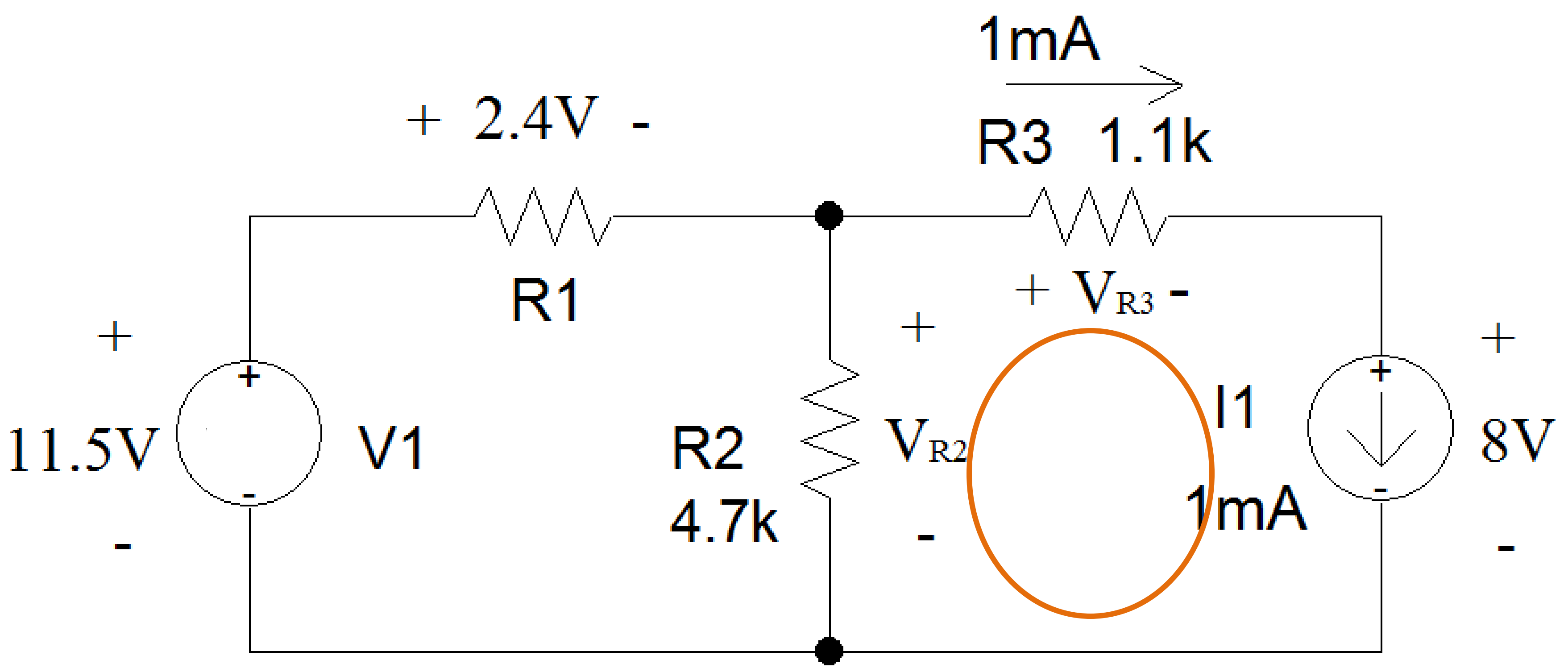


Example 5 (con't)

Again, the same answer is found.

$$1.1V + 8V - V_{R2} = 0$$

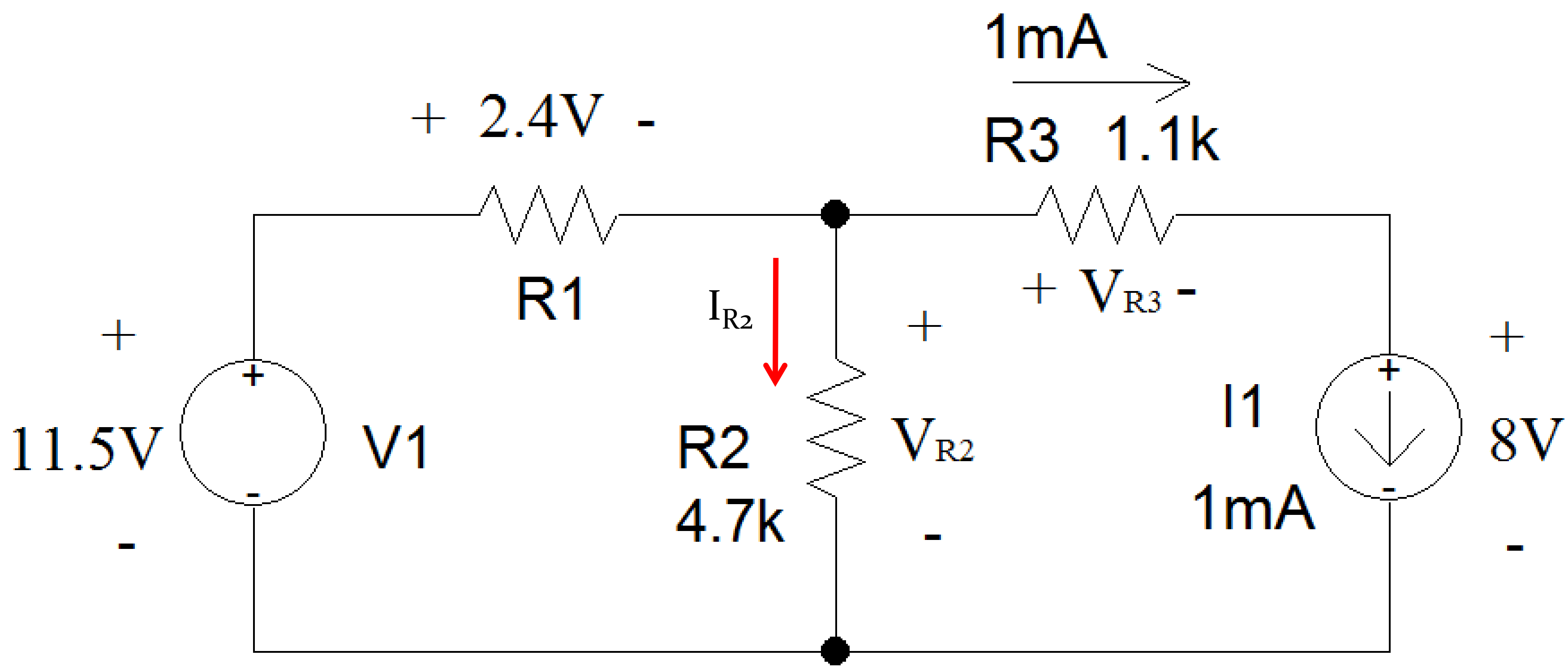
$$V_{R2} = 9.1V$$



Example 5 (con't)

Once the voltage across R2 is known, Ohm's Law is applied to determine the current.

The direction of positive current flow, based upon passive sign convention is shown in red.



Example 5 (con't)

$$I_{R2} = 9.1V / 4.7k\Omega$$

$$I_{R2} = 1.94mA$$