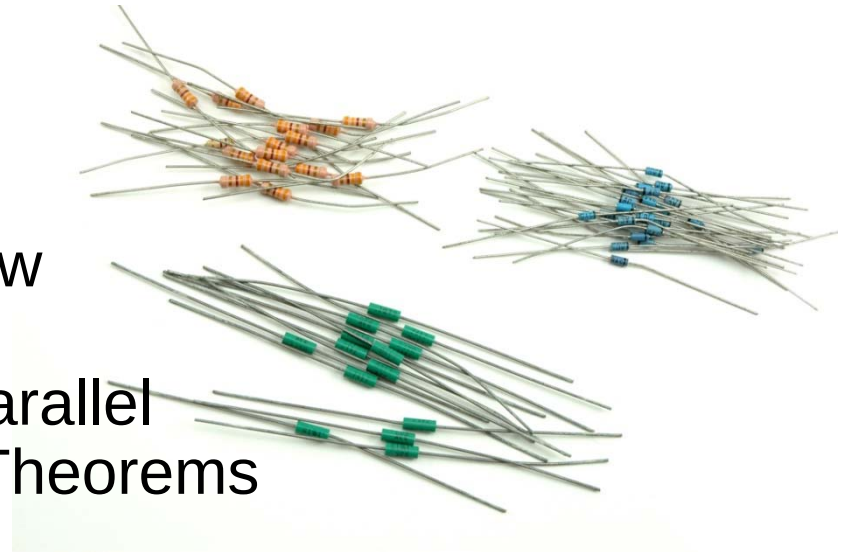




Resistance and DC Circuits

- Introduction
- Current and Charge
- Voltage Sources
- Current Sources
- Resistance and Ohm's Law
- Kirchhoff's Laws
- Resistors in Series and Parallel
- Thévenin's and Norton's Theorems
- Superposition
- Nodal Analysis
- Mesh Analysis
- Solving Simultaneous Circuit Equations
- Choice of Techniques





3.1

Introduction

- Many circuits can be analysed, and in some cases designed, using little more than Ohm's law
- However, in some cases we need some additional techniques and these are discussed in this lecture.
- We begin by reviewing some of the basic elements that we use to describe our circuits

3.2

Current and Charge

- An electric **current** is a flow of electric **charge**

$$I = \frac{dQ}{dt}$$

- At an atomic level a current is a flow of **electrons**
 - each electron has a charge of 1.6×10^{-19} coulombs
 - conventional current shown in the opposite direction
- Rearranging above expression gives

$$Q = \int I dt$$

- For constant current

$$Q = I \times t$$



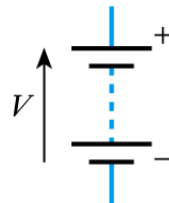
3.3

Voltage Sources

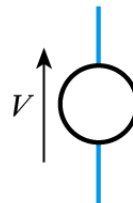
- A voltage source produces an **electromotive force (e.m.f.)** which causes a current to flow within a circuit
 - unit of e.m.f. is the **volt**
 - a volt is the potential difference between two points when a joule of energy is used to move one coulomb of charge from one point to the other
- Real voltage sources, such as batteries have resistance associated with them
 - in analysing circuits we use **ideal voltage sources**
 - **No internal resistance = ideal voltage source**
 - we also use **controlled** or **dependent voltage sources**

3.4

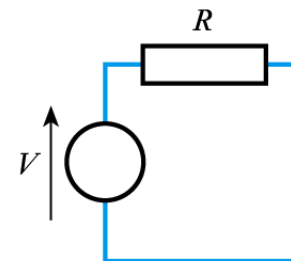
■ Voltage sources



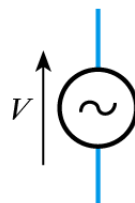
(a) A battery



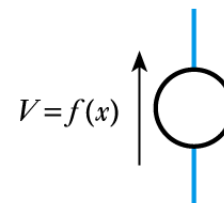
(b) An ideal voltage source



(c) Modelling a battery using an ideal voltage source



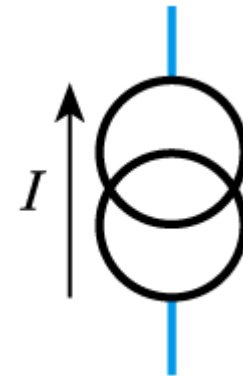
(d) An alternating voltage source



(e) A controlled voltage source

Current Sources

- We also sometimes use the concept of an **ideal current source**
 - unrealisable, but useful in circuit analysis
 - can be a fixed current source, or a **controlled** or **dependent current source**
 - while an ideal voltage source has zero output resistance, an
 - An ideal current source has *infinite* output resistance



Resistance and Ohm's Law

■ Ohm's law

$$V \propto I$$

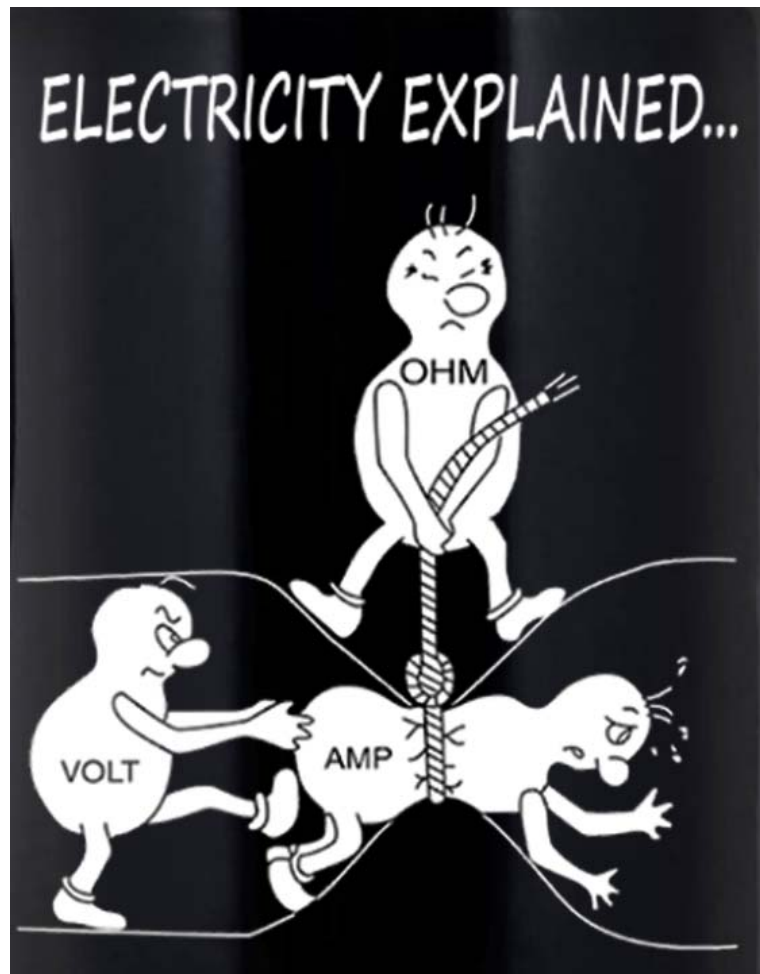
- constant of proportionality is the resistance R
- hence

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

- current through a resistor causes power dissipation

$$P = IV \qquad P = \frac{V^2}{R} \qquad P = I^2 R$$

Summary of passive electronics





Video 3A



3.7

Kirchhoff's Laws

■ Node

- a point in a circuit where two or more circuit components are joined

■ Loop

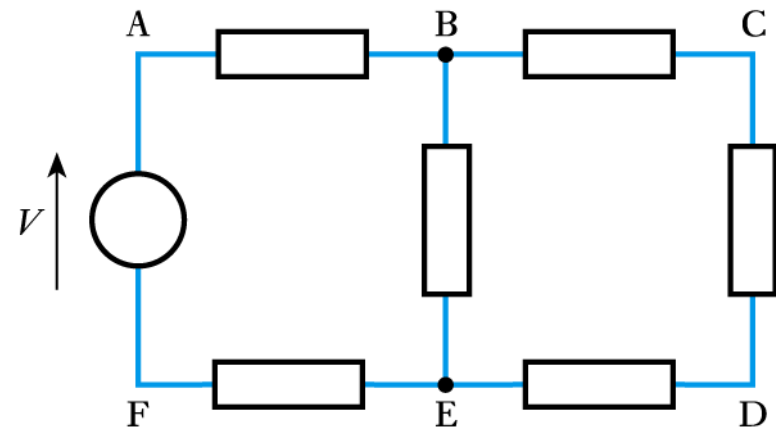
- any closed path that passes through no node more than once

■ Mesh

- a loop that contains no other loop

■ Examples:

- A, B, C, D, E and F are *nodes*
- the paths ABEFA, BCDEB and ABCDEFA are *loops*
- ABEFA and BCDEB are *meshes*

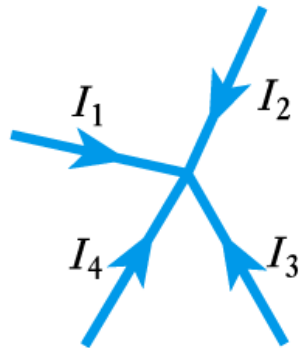


3.9

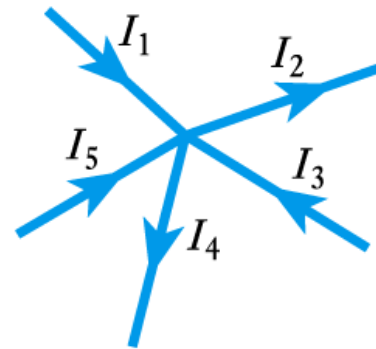
■ Current Law

At any instant, the algebraic sum of all the currents flowing into any node in a circuit is zero

- if currents flowing into the node are positive, currents flowing out of the node are negative, then $\sum I = 0$



$$I_1 + I_2 + I_3 + I_4 = 0$$



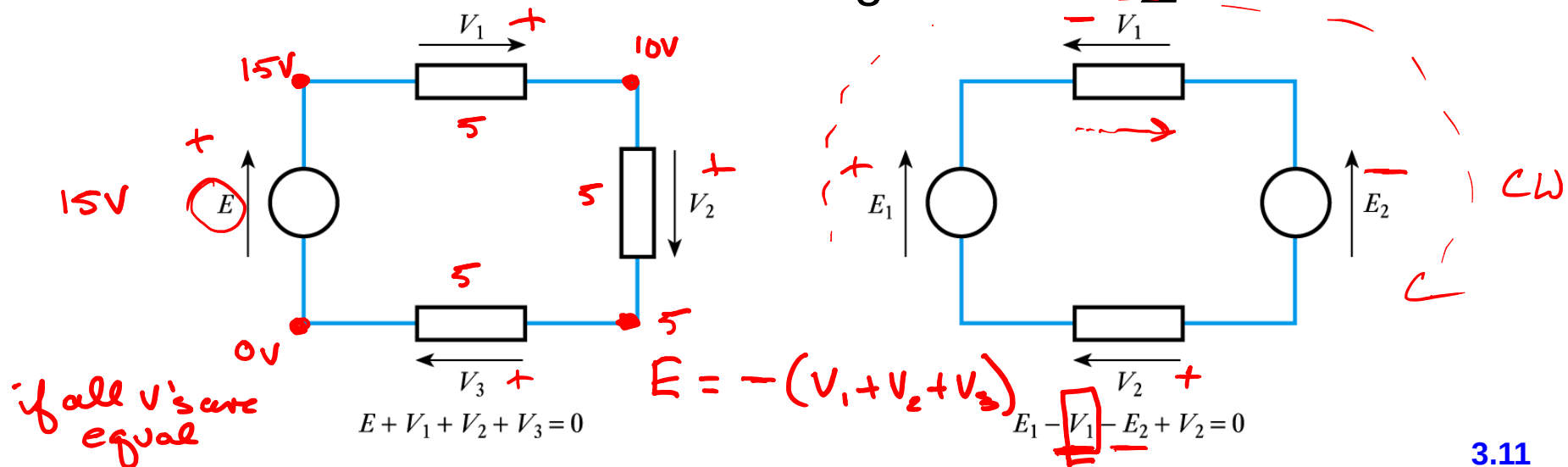
$$I_1 - I_2 + I_3 - I_4 + I_5 = 0$$

Convention

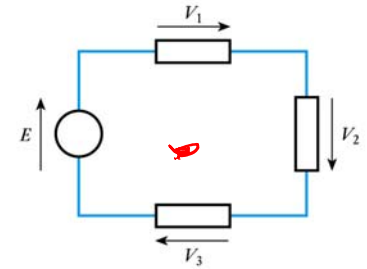
■ Voltage Law

At any instant the algebraic sum of all the voltages around any loop in a circuit is zero

- if clockwise voltage arrows are positive and anticlockwise arrows are negative then $\sum V = 0$



In General: Single Loop Voltage Law



- The current I is:

$$I = \frac{\sum V_{Si}}{\sum R_j} = \frac{\text{sum of voltage sources}}{\text{sum of resistances}} = \frac{E}{\sum R_j}$$

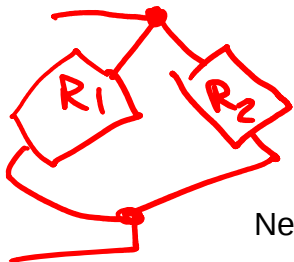
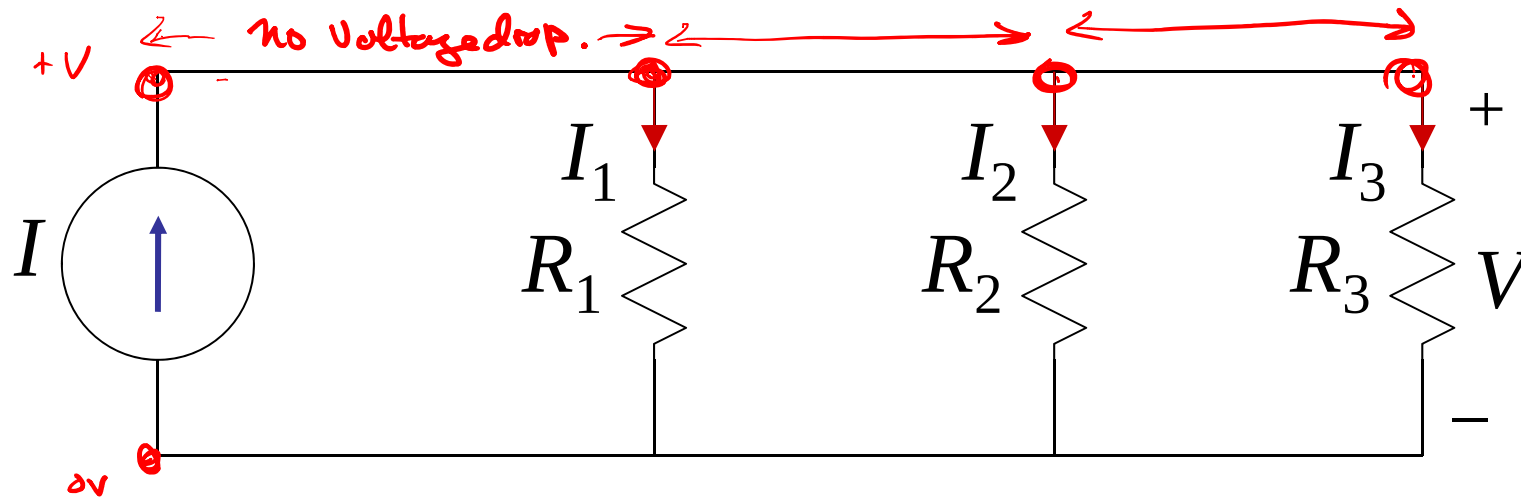
- This approach works for any single loop circuit with voltage sources and resistors.
- Resistors in series can be replaced by:

$$\frac{\sum V_s}{R_{\text{series}}} = I$$

$$R_{\text{series}} = \underline{R_1} + \underline{R_2} + \cdots + \underline{R_N} = \underline{\sum R_j}$$

Resistors in Parallel-Current Law

Same voltage across all the elements (have the same node)- the elements are in **parallel**

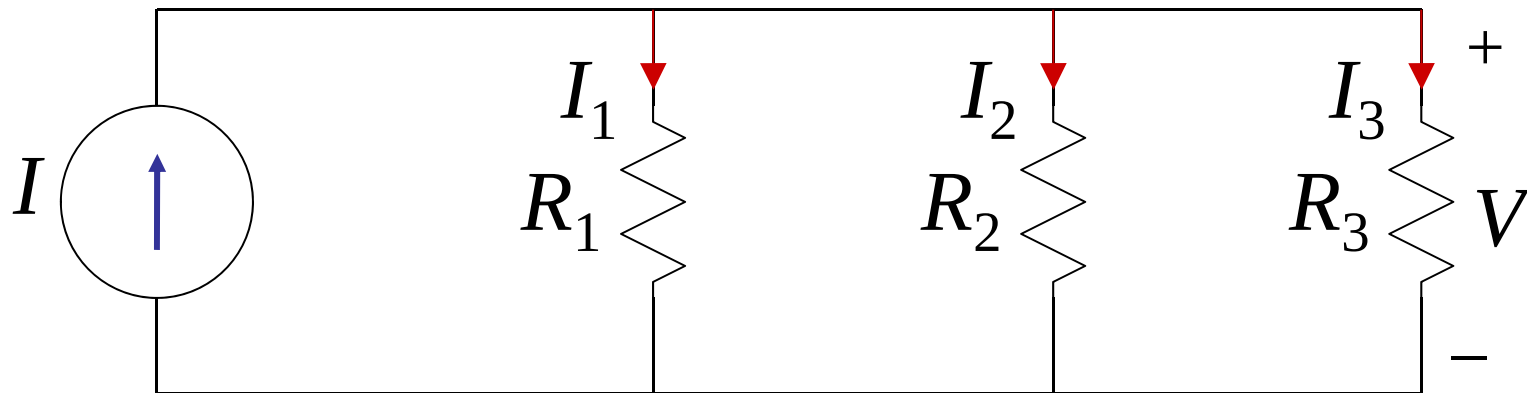


How do we find I_1 , I_2 , and I_3 ?

Apply KCL at the Top Node

$$I = I_1 + I_2 + I_3$$

But Ohm's Law: $I_1 = \frac{V}{R_1}$ $I_2 = \frac{V}{R_2}$ $I_3 = \frac{V}{R_3}$



Solve for V

$$I = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} = V \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)$$

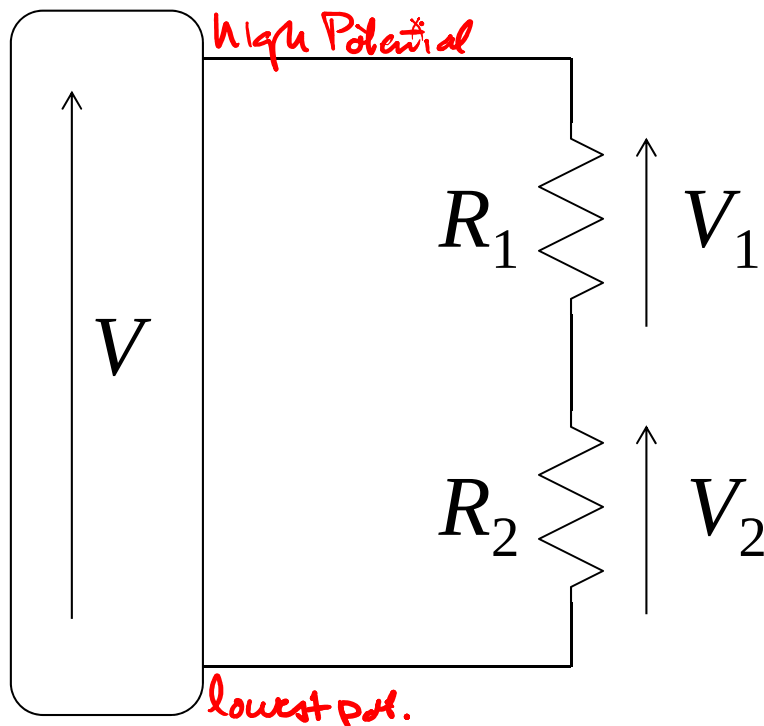
$$V = \frac{I}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \quad \text{Ohm's Law: } \underline{R_{eq}} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Definition: *Parallel* - the elements share the same two end nodes (Voltage is the same across all the elements)

Voltage Division

Two resistors **in series** with a voltage V across them

KVL: $V - V_1 - V_2 = 0$ Ohms Law: $I = V / (R_1 + R_2)$



$$V_1 = I \cdot R_1$$

Req.

$$V_1 = V \frac{R_1}{R_1 + R_2}$$

$$V_2 = I \cdot R_2 = V - V_1$$

$$V_2 = V \frac{R_2}{R_1 + R_2}$$

In General: Voltage Division

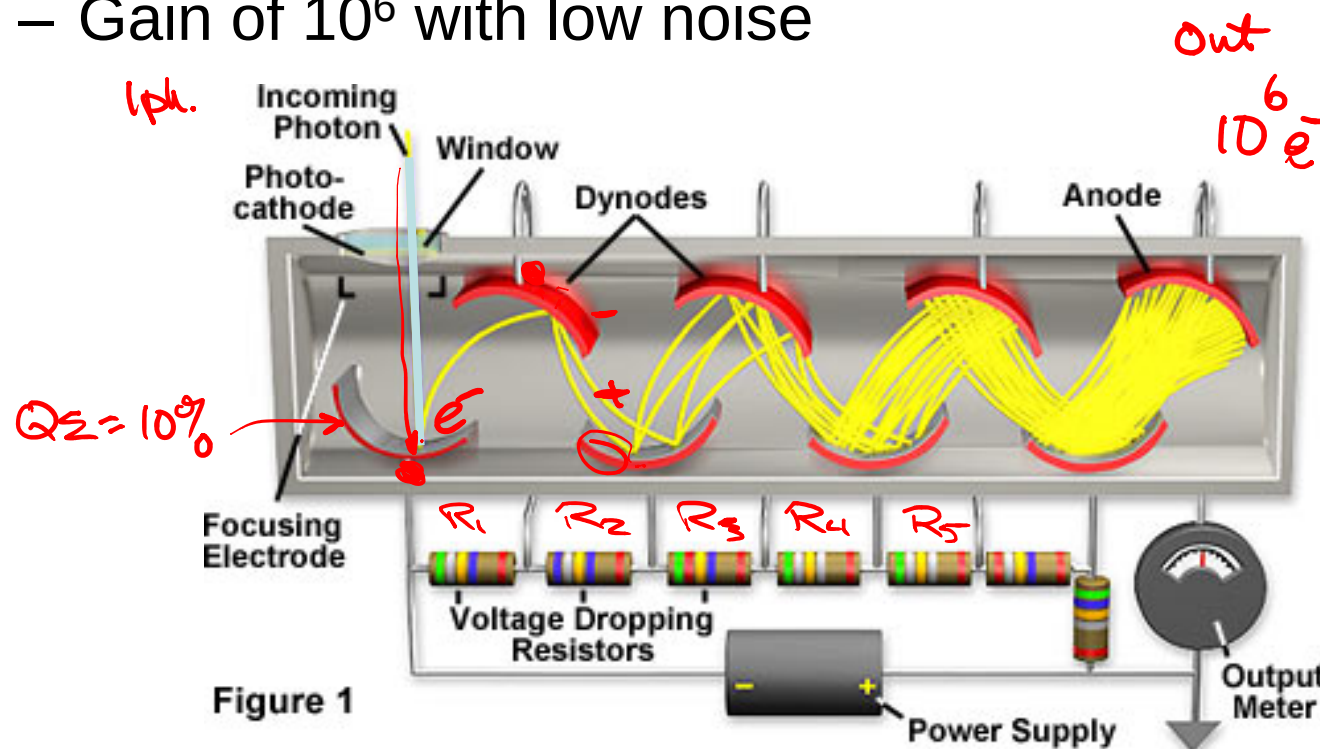
Consider N resistors **in series**:

$$V_{R_i}(t) = \frac{R_i}{\sum R_j} \sum V_{S_k}(t)$$

Source voltage(s) are divided between the resistors in direct proportion to their resistances

Application of Voltage Divider

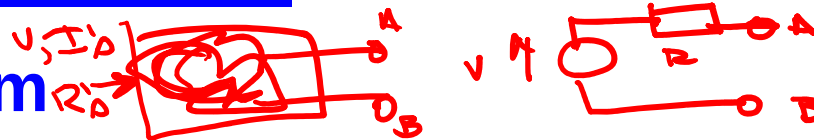
- Photomultiplier Tube
 - ~3000 V Potential Difference in 10-14 steps
 - Gain of 10^6 with low noise



$$V_{R_i} = V_T \frac{R_i}{\sum R_i}$$

Thévenin's and Norton's Theorems

■ Thévenin's Theorem



As far as its appearance from outside is concerned, any two terminal network of resistors and energy sources can be replaced by a series combination of an ideal voltage source V and a resistor R , where V is the open-circuit voltage of the network and R is the resistance that would be measured between the output terminals if the energy sources were removed and replaced by their internal resistance

Thevenin's Theorem 2

- Any linear circuit with sources (dependent and/or independent) and resistors **can be replaced by an equivalent circuit containing a single voltage source and a single resistor.**



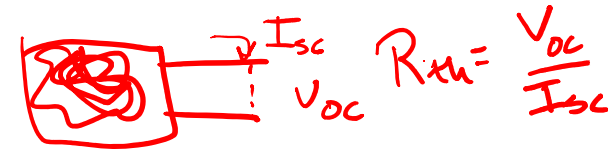
- Thevenin's theorem implies that we can replace arbitrarily complicated networks with simple networks for purposes of analysis.

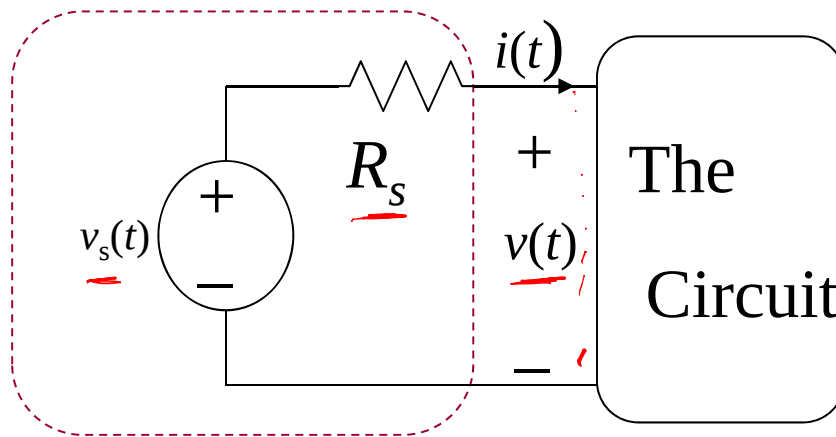
$$V_{th} \quad R_{th}$$

$$V_L = V_{th} \frac{R_L}{R_{th} + R_L}$$

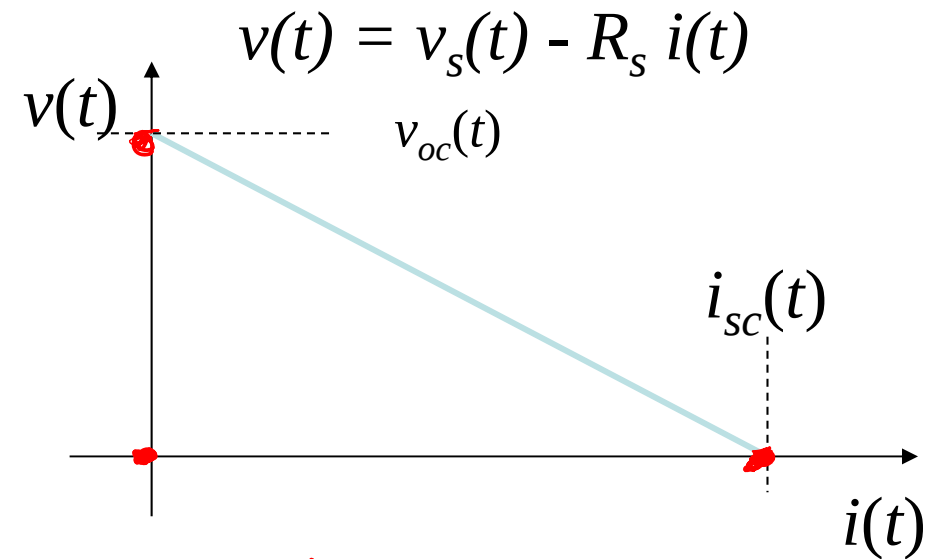
- If we have a single “load” resistor which is subject to change, we simplify circuit to a simple Thevenin equivalent with a single resistor and can recalculate easily for many different loads

A Realistic Source Model

 $R_{th} = \frac{V_{oc}}{I_{sc}}$

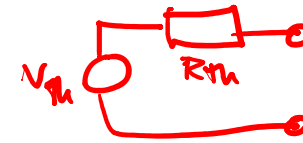


The Source

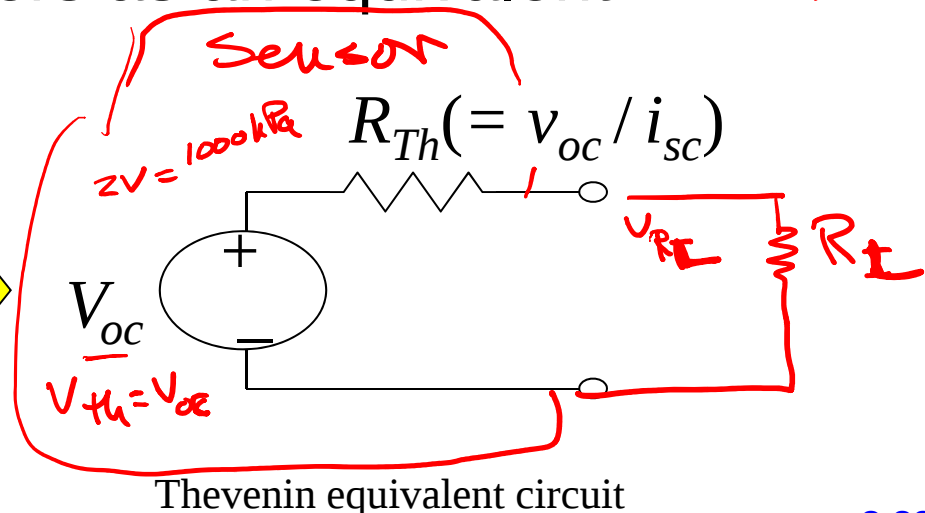
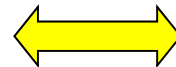
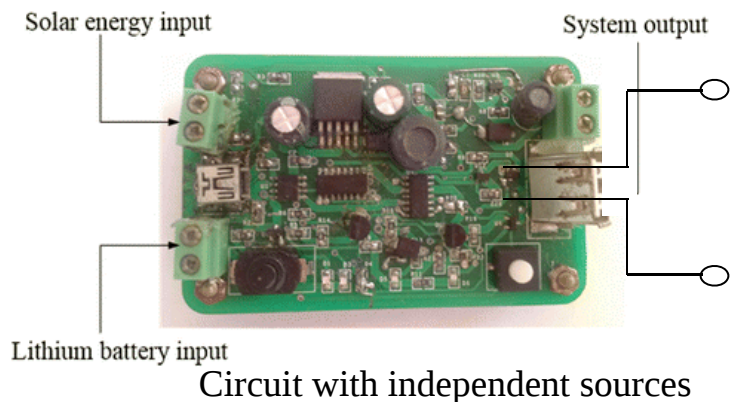


- Since the $i(t) = 0$ **open circuit voltage** and the $v(t) = 0$ **short circuit current** determine where the I-V line crosses both axes, they completely define the line.
- Any circuit that has the same I-V characteristics is an equivalent circuit.

Implications Sensor $\rightarrow$ Thev. eq. circuit



- We use Thevenin's theorem to justify the concept of input and output resistance for amplifier circuits.
- We model transducers as equivalent sources and resistances.
- We model stereo speakers as an equivalent resistance.



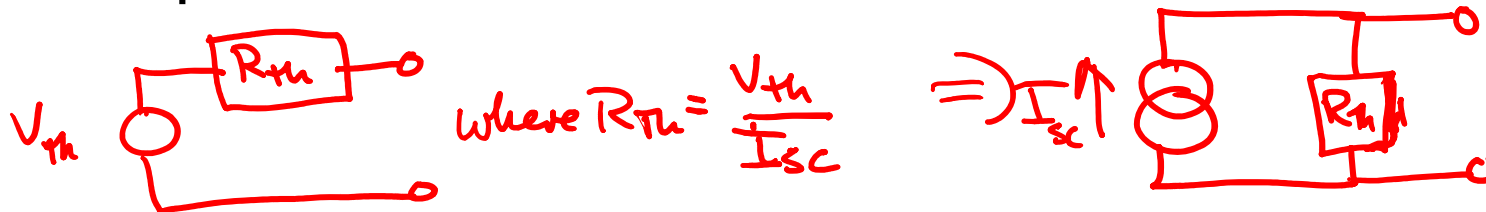
3.22

■ Norton's Theorem

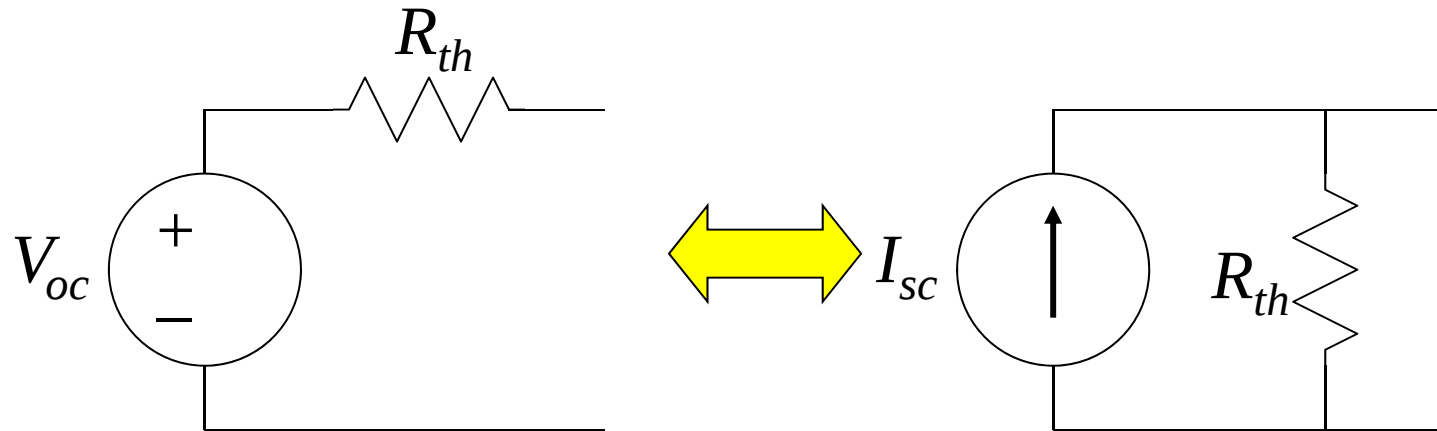
As far as its appearance from outside is concerned, any two terminal network of resistors and energy sources can be replaced by a parallel combination of an ideal current source I and a resistor R , where I is the short-circuit current of the network and R is the resistance that would be measured between the output terminals if the energy sources were removed and replaced by their internal resistance

Norton's Theory 2

- Any Thevenin equivalent circuit is in turn equivalent to a current source in parallel with a resistor [source transformation].
- A current source in parallel with a resistor is called a Norton equivalent circuit.
- Finding a Norton equivalent circuit requires essentially the same process as finding a Thevenin equivalent circuit.



Source Transformation

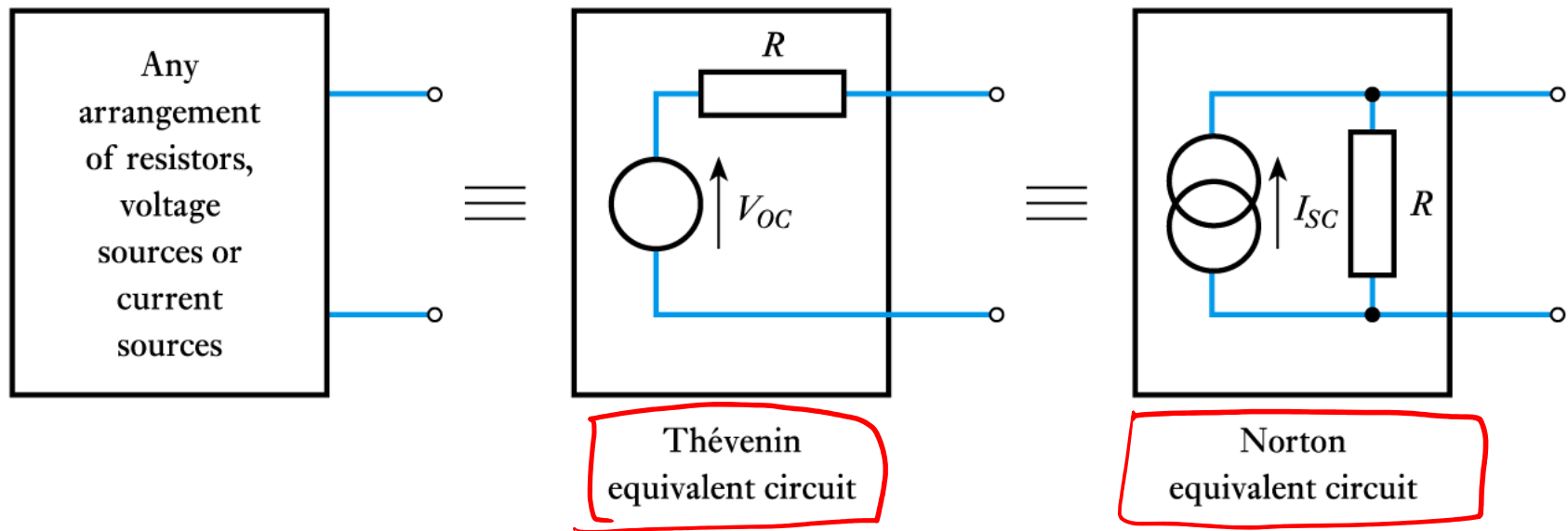


$$V_{oc} = R_{th} \cdot I_{sc}$$

$$I_{sc} = \frac{V_{oc}}{R_{th}}$$

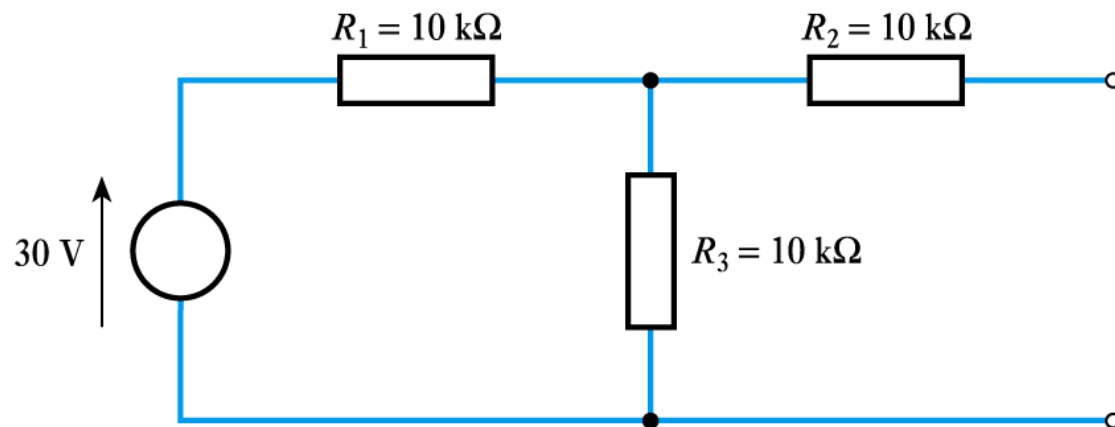
R_{th} is the real internal resistance of the real voltage source ($R_{\text{ideal voltage source}} = 0$)
Limits voltage at the load $\propto$ load resistance

R_{th} is the real internal resistance of the real current source ($R_{\text{ideal current source}} = \infty$)
Limits the current to the load $\propto$ load resistance



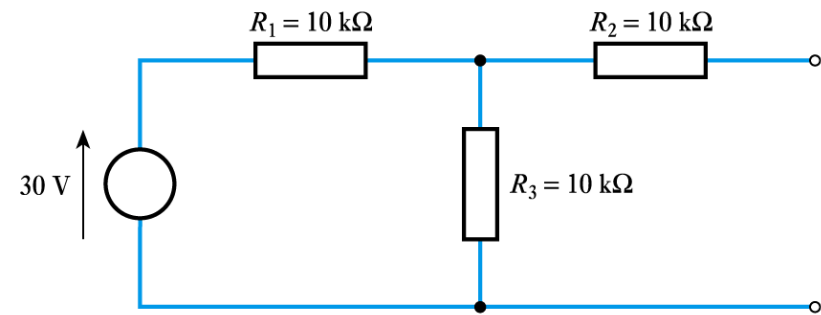
- from the Thévenin equivalent circuit $I_{SC} = \frac{V_{OC}}{R}$
- hence for *either* circuit $R = \frac{V_{OC}}{I_{SC}}$

-
- **Example** – see **Example 3.3** from course text
Determine Thévenin and Norton equivalent circuits of the following circuit



Example (continued)

- if nothing is connected across the output no current will flow in R_2 so there will be no voltage drop across it. Hence V_o is determined by the voltage source and the potential divider formed by R_1 and R_3 . Hence
- if the output is shorted to ground, R_2 is in parallel with R_3 and the current taken from the source is $30\text{V}/15\text{ k}\Omega = 2\text{ mA}$. This will divide equally between R_2 and R_3 so the output current, and so
- the resistance in the equivalent circuit is therefore given by



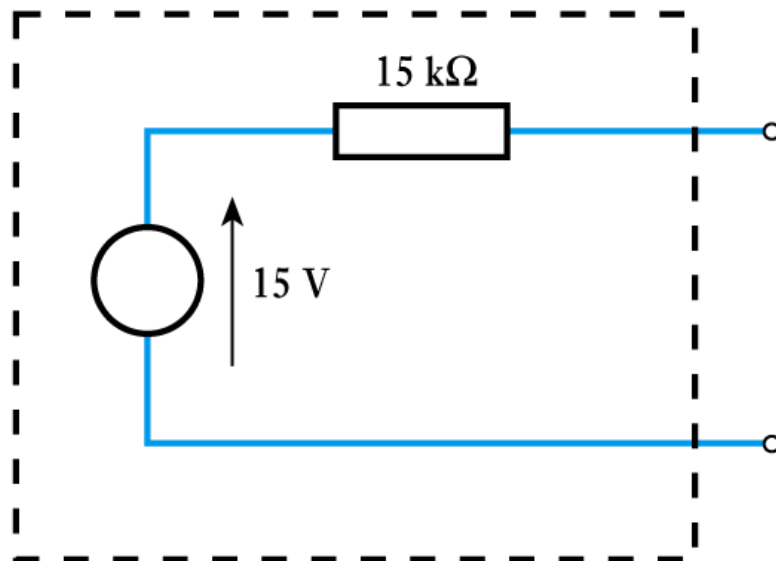
$$V_{OC} = \frac{30}{2} = 15\text{ V}$$

$$I_{SC} = 1\text{ mA}$$

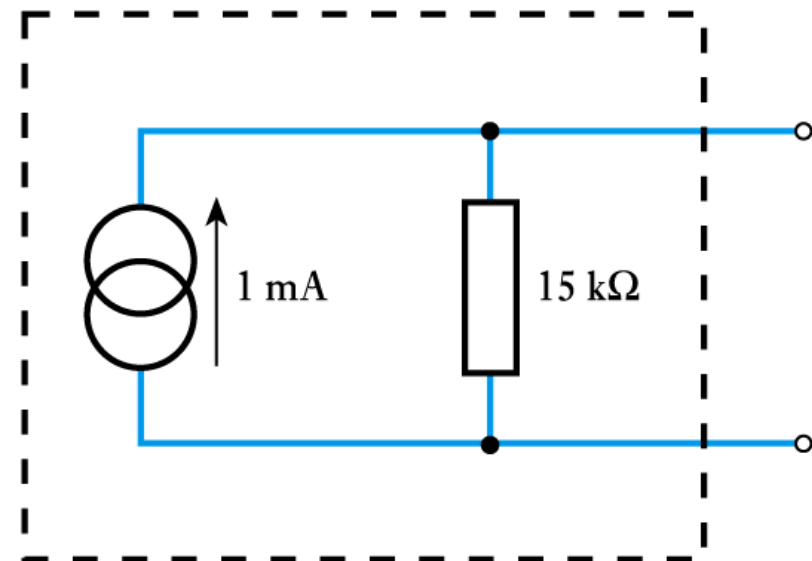
$$R = \frac{V_{OC}}{I_{SC}} = \frac{15\text{ V}}{1\text{ mA}} = 15\text{ k}\Omega$$

Example (continued)

- hence equivalent circuits are:



Thévenin
equivalent circuit



Norton
equivalent circuit

Method 2: Thevenin/Norton Analysis

Compute the Thevenin equivalent resistance, R_{Th} (or impedance, Z_{Th}).

(a) Remove load. If there are only independent sources, then short circuit all the voltage sources and open circuit the current sources

(b) Calculate the equivalent resistance between the terminals

This is then the Thevenin Resistance, R_{th}

(c) Reconnect all the voltage and current sources

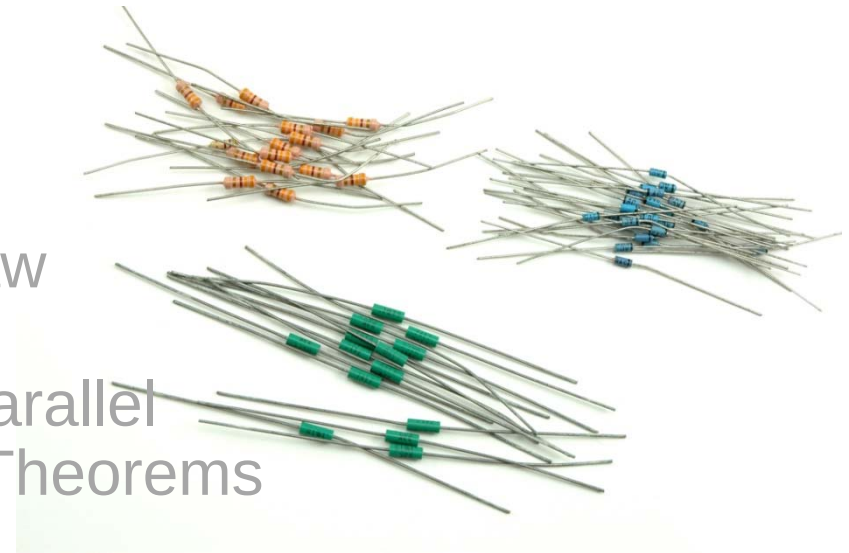
(d) Then compute either V_{OC} or I_{SC} (Whichever is easier) across the terminals

(e) Then compute the other from $V_{OC} = I_{SC} \cdot R_{th}$



Next time: Resistance and DC Circuits

- Introduction
- Current and Charge
- Voltage Sources
- Current Sources
- Resistance and Ohm's Law
- Kirchhoff's Laws
- Resistors in Series and Parallel
- Thévenin's and Norton's Theorems
- **Superposition**
- **Nodal Analysis**
- **Mesh Analysis**
- **Solving Simultaneous Circuit Equations**
- **Choice of Techniques**



Solving circuits



3.9

Superposition

- **Principle of superposition**

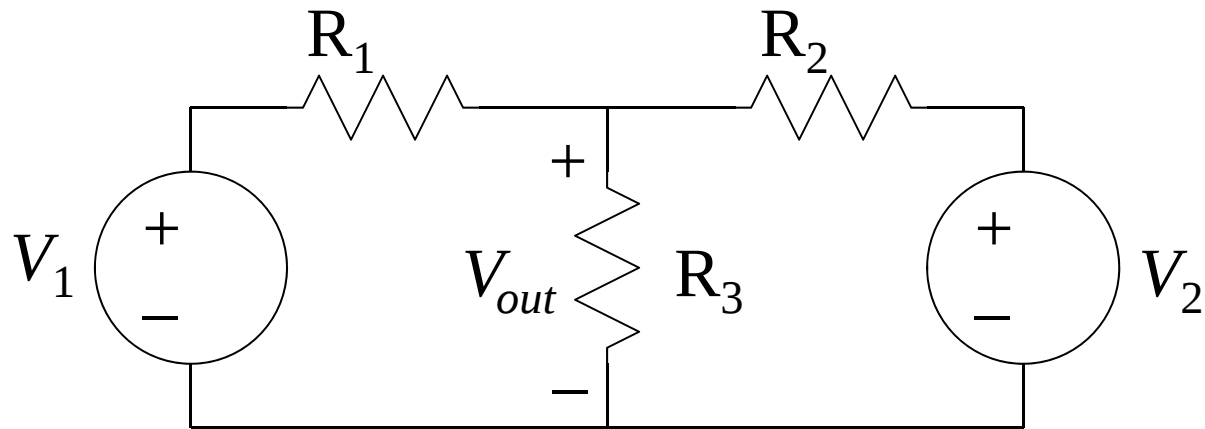
In any linear network of resistors, voltage sources and current sources, each voltage and current in the circuit is equal to the algebraic sum of the voltages or currents that would be present if each source were to be considered separately. When determining the effects of a single source the remaining sources are replaced by their internal resistance

3.33

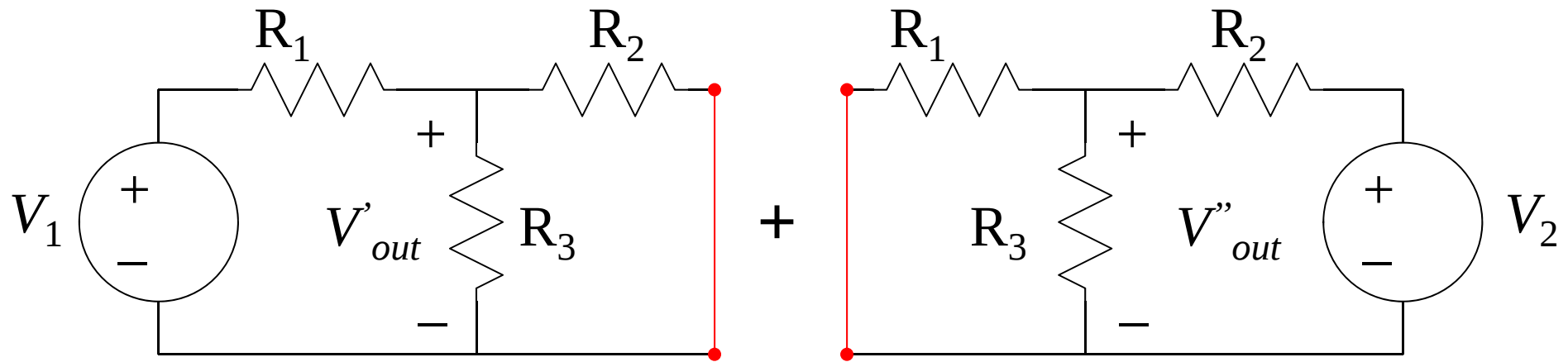
How to Apply Superposition

- To find the contribution due to an individual independent source, zero out the other independent sources in the circuit.
 - Voltage source $\Rightarrow$ short circuit.
 - Current source $\Rightarrow$ open circuit.
- Solve the resulting circuit using your favorite technique(s).

The Summing Circuit



Superposition



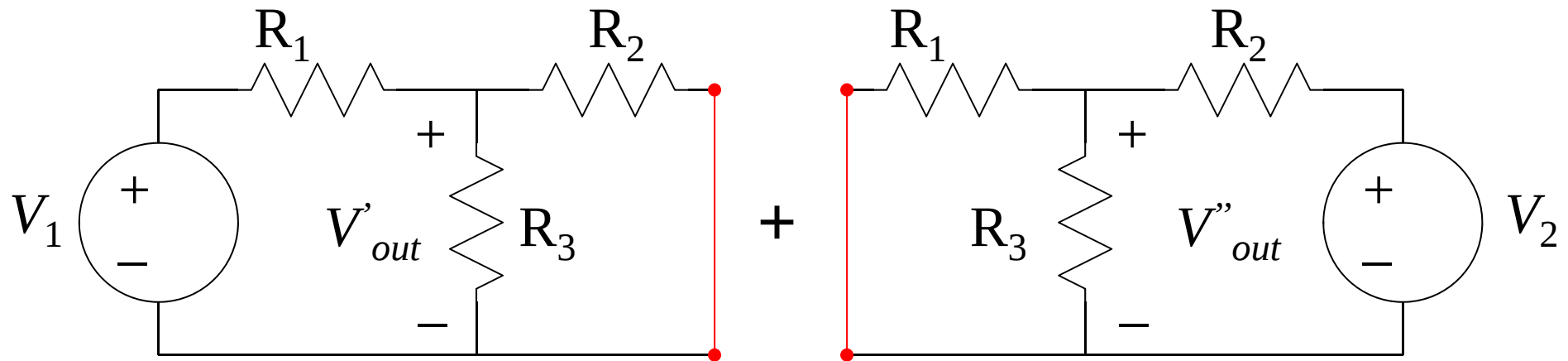
$$I' = V_1 / (R_1 + R_{2//3})$$

$$V'_{out} = I' R_{2//3}$$

Where

$$R_{2//3} = R_2 R_3 / (R_2 + R_3)$$

Superposition



$$I' = V_1 / (R_1 + R_{2//3})$$

$$V'_{out} = I' R_{2//3}$$

Where

$$R_{2//3} = R_2 R_3 / (R_2 + R_3)$$

$$I'' = V_2 / (R_2 + R_{1//3})$$

$$V''_{out} = I'' R_{1//3}$$

Where

$$R_{1//3} = R_1 R_3 / (R_1 + R_3)$$

3.37

Use of Superposition

$$V_{out} = V'_{out} + V''_{out}$$

If $R_1=R_2=R_3=1\text{k}\Omega$

then

$$V'_{out} = V_1/3$$

$$V''_{out} = V_2/3$$

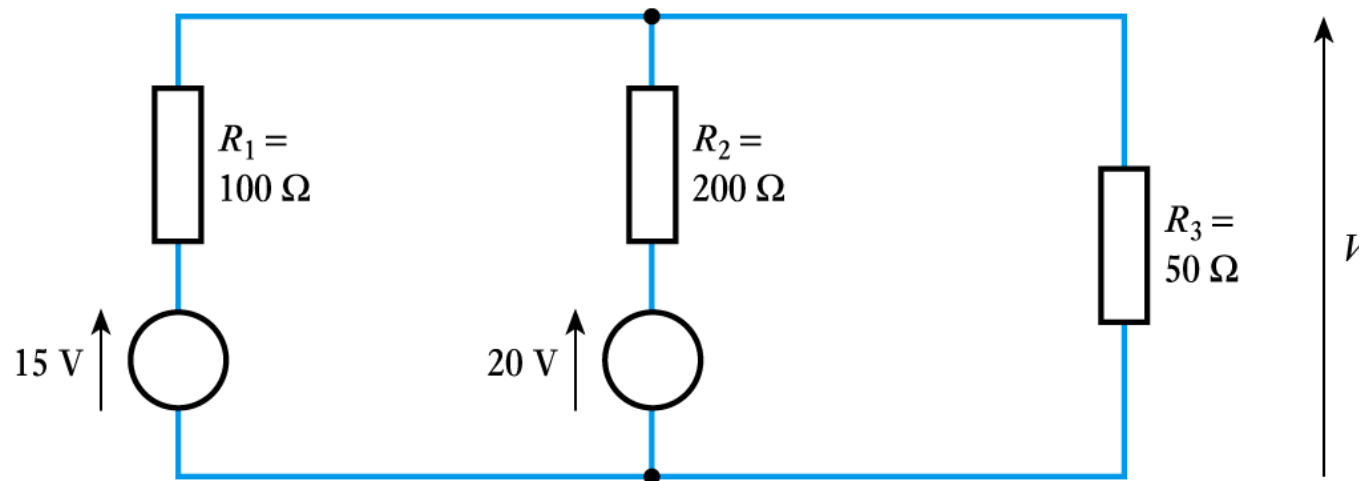
$$V_{out} = V'_{out} + V''_{out} = V_1/3 + V_2/3$$

Summary and next time

- Nomenclature and symbols
- Circuit analysis using:
 - Ohms Law
 - Kirchoff's voltage law
 - Kirchoff's current law
- Further analysis using Thevenin and Norton theorems
- Superposition
- Next time
 - Further example of Superposition, Thevenin and Norton theorems
 - Mesh and Nodal analysis
 - AC circuits

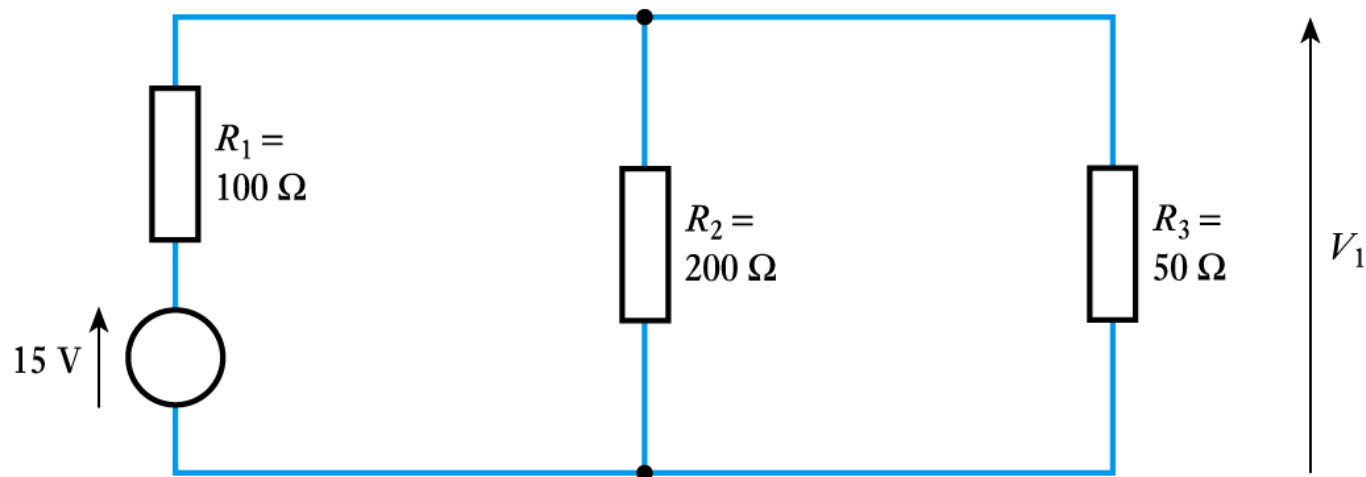
Further example of Superposition, Thevenin and Norton theorems

- **Example** – see **Example 3.5** from course text
Determine the output voltage V of the following circuit



Example (continued)

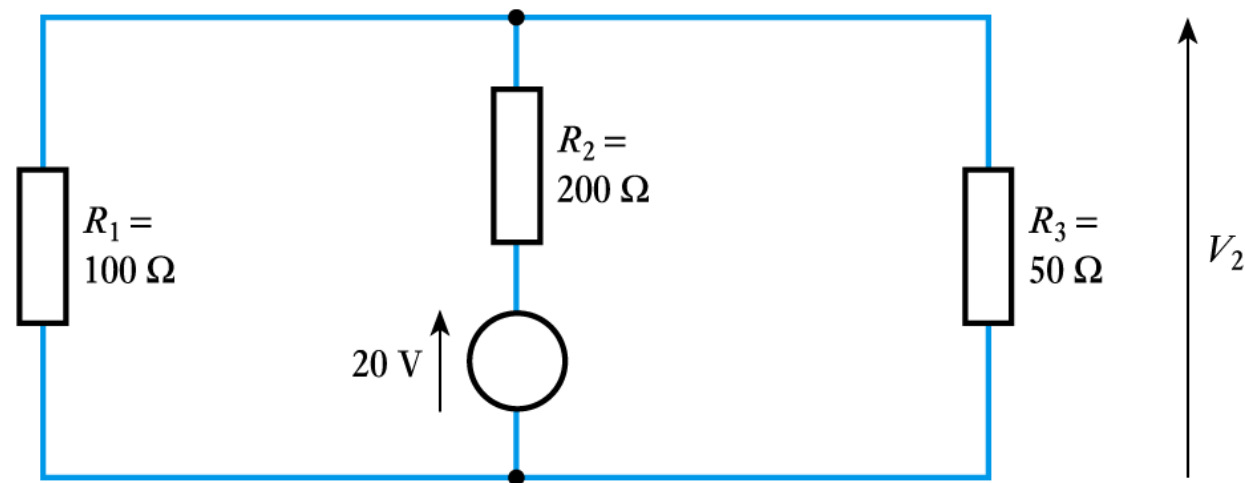
- first consider the effect of the 15V source alone



$$V_1 = 15 \frac{200 // 50}{100 + 200 // 50} = 15 \frac{40}{100 + 40} = 4.29\text{ V}$$

Example (continued)

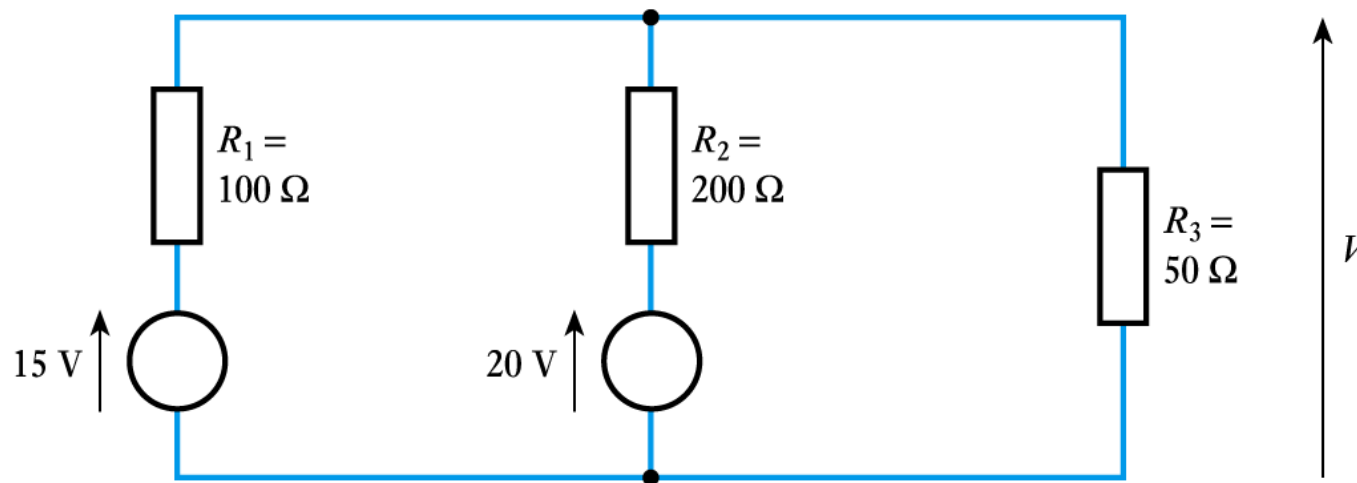
- next consider the effect of the 20V source alone



$$V_2 = 20 \frac{100 // 50}{200 + 100 // 50} = 20 \frac{33.3}{200 + 33.3} = 2.86\text{ V}$$

Example (continued)

- so, the output of the complete circuit is the sum of these two voltages



$$V = V_1 + V_2 = 4.29 + 2.86 = 7.15\text{ V}$$

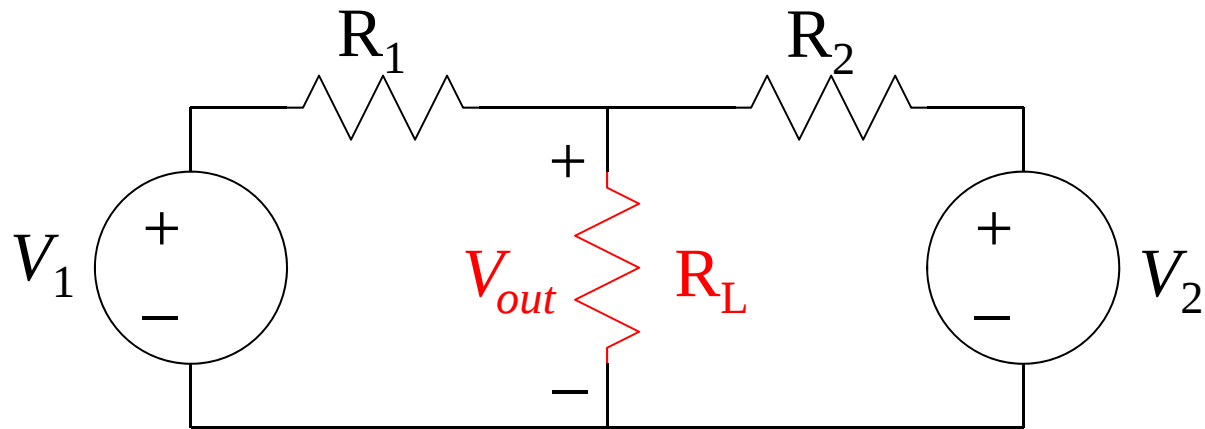
Generalized Thevenin/Norton Analysis

1. Pick a good breaking point in the circuit (cannot split a dependent source and its control variable).
Example of a good break point, remove the load resistor.

2. **Thevenin:** Compute the open circuit voltage, V_{OC} .
Norton: Compute the short circuit current, I_{SC} .

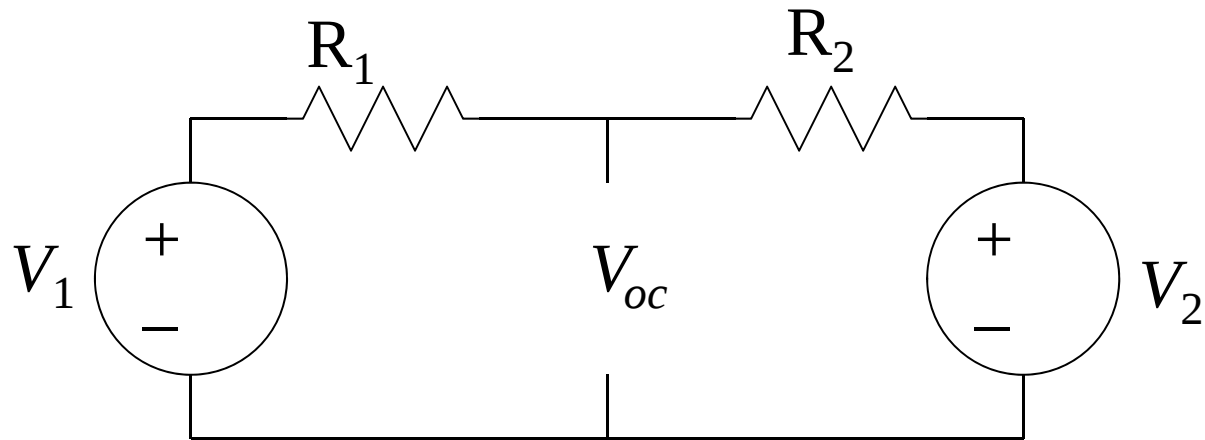
[If there are only dependent sources both $V_{OC}=0$ and $I_{SC}=0$,
so skip step 2]

The Summing Circuit



Break the circuit at the load and remove resistor

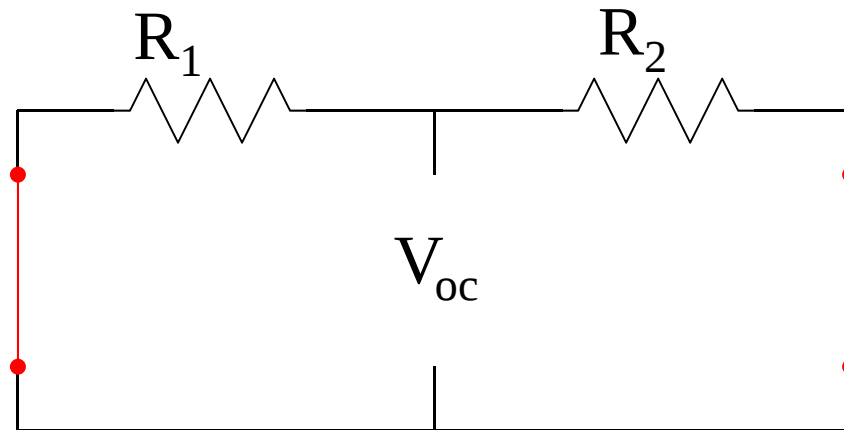
Now compute the Thevenin open circuit voltage



Here it is just 2 voltage dividers.

$$V_{oc} = V_1 R_2 / (R_1 + R_2) + V_2 R_1 / (R_1 + R_2)$$

Now compute the Thevenin equivalent resistance across the voltage

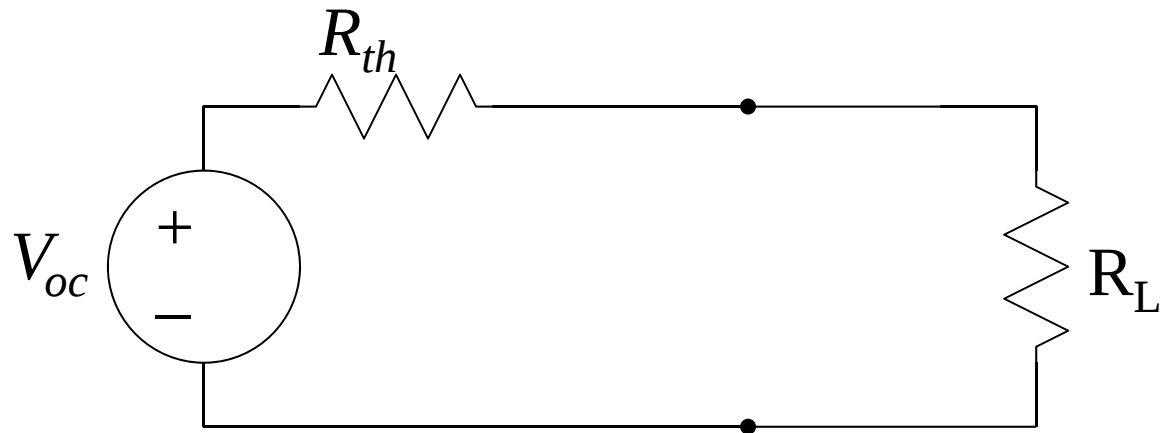


Here it is just R_1 paralleled with R_2 .

$$R_{th} = R_1 R_2 / (R_1 + R_2)$$

If needed, calculate Thevenin current, $I_{th} = V_{oc} / R_{th}$

Now compute the Thevenin equivalent circuit for calculations



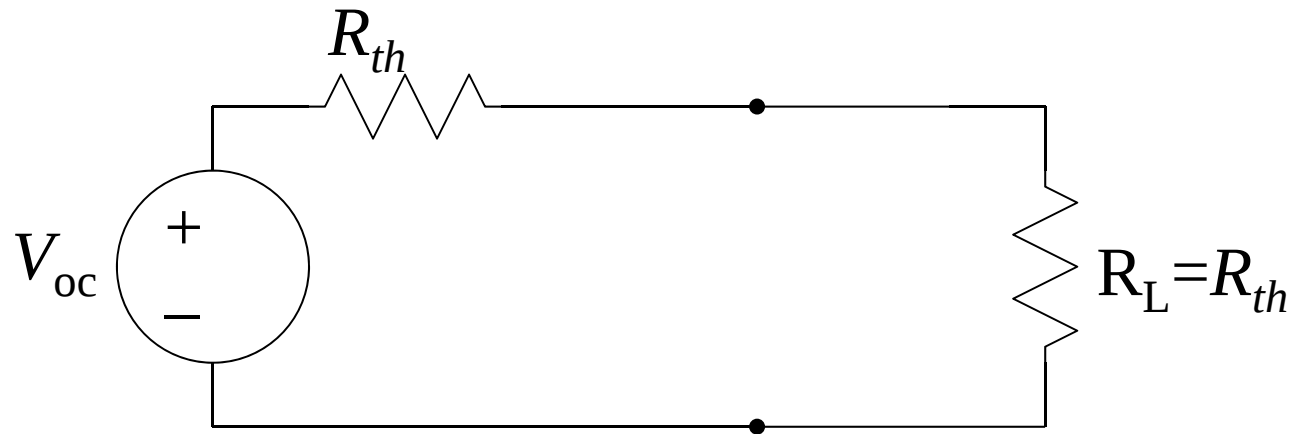
$$I_L = V_{oc} / (R_{th} + R_L) \text{ and } V_L = R_L V_{oc} / (R_{th} + R_L)$$

Note, Power dissipated in the load is :

$$P_L = R_L I^2 = R_L [V_{oc} / (R_{th} + R_L)]^2$$

Differentiate with respect to R_L to find that the maximum energy transfer is when $R_L = R_{th}$

Impedance Matched Circuit



This circuit will dissipate the maximum energy in the load

E.g. audio circuit or heating circuit



Video 3B



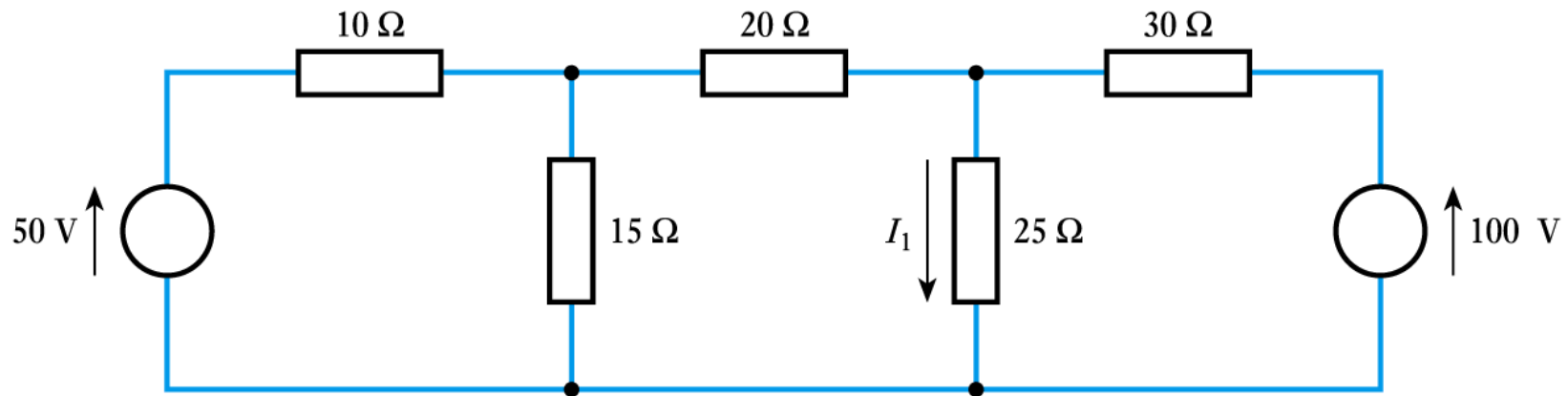
3.10

Nodal Analysis

- Six steps:
 1. Chose one node as the reference node
 2. Label remaining nodes V_1 , V_2 , etc.
 3. Label any known voltages
 4. Apply Kirchhoff's current law to each unknown node
 5. Solve simultaneous equations to determine voltages
 6. If necessary calculate required currents

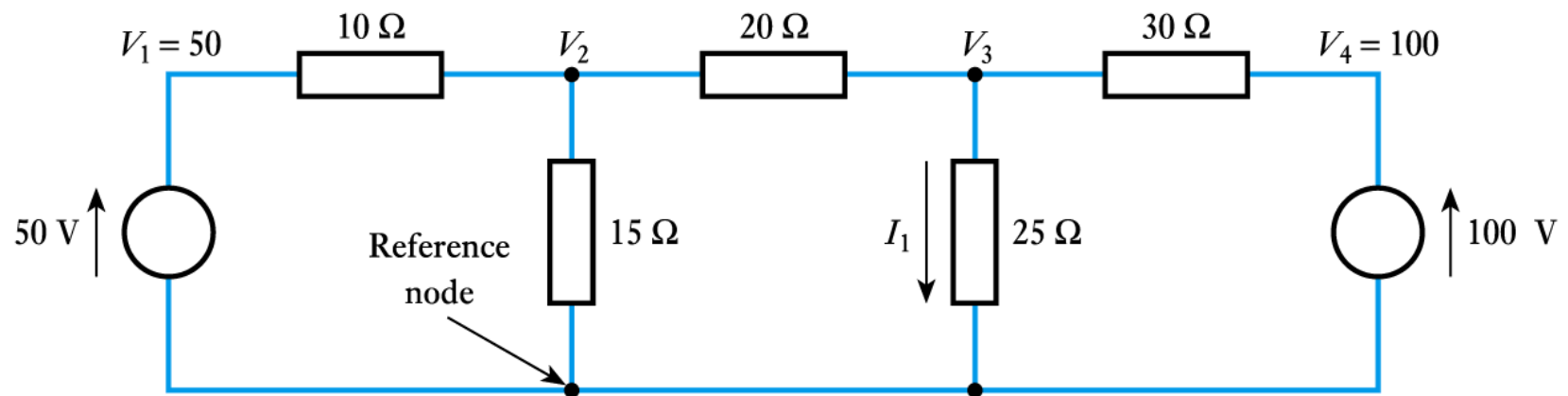
3.50

- **Example** – see **Example 3.7** from course text
Determine the current I_1 in the following circuit



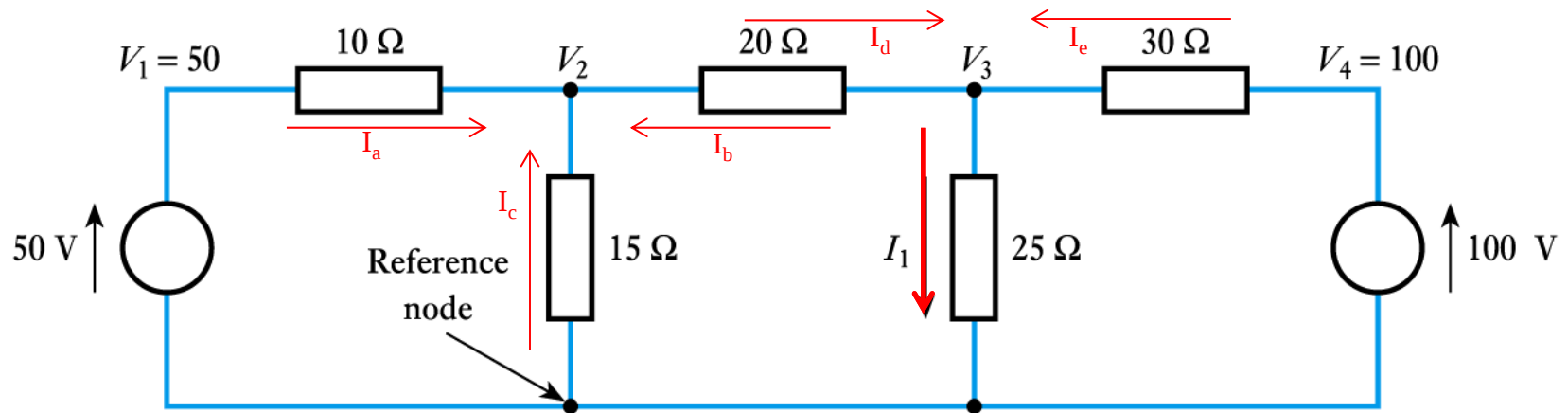
Example (continued)

- first we pick a reference node and label the various node voltages, assigning values where these are known



Example (continued)

- Next, assign a current into or out of each node with an unknown voltage and apply KCL



- So KCL gives $I_a + I_b + I_c = 0$, and $I_d + I_e - I_1 = 0$

Example (continued)

- next we take the sum of the currents flowing into the nodes with unknown voltages and apply Ohms law:

$$\frac{50 - V_2}{10} + \frac{V_3 - V_2}{20} + \frac{0 - V_2}{15} = 0 \quad \frac{V_2 - V_3}{20} + \frac{100 - V_3}{30} + \frac{0 - V_3}{25} = 0$$

- solving these two equations gives

$$V_2 = 32.34 \text{ V}$$

$$V_3 = 40.14 \text{ V}$$

- and the required current, I_1 , is given by

$$I_1 = \frac{V_3 - 0}{25 \Omega} = \frac{40.14 \text{ V}}{25 \Omega} = 1.6 \text{ A}$$

Mesh Analysis



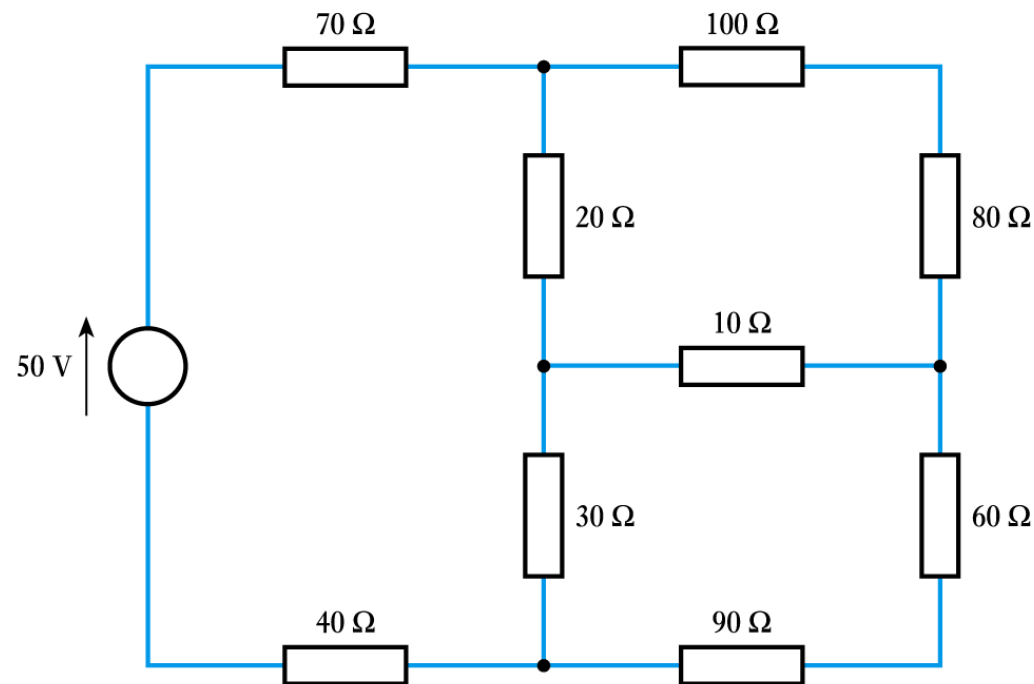
Video 3C



3.11

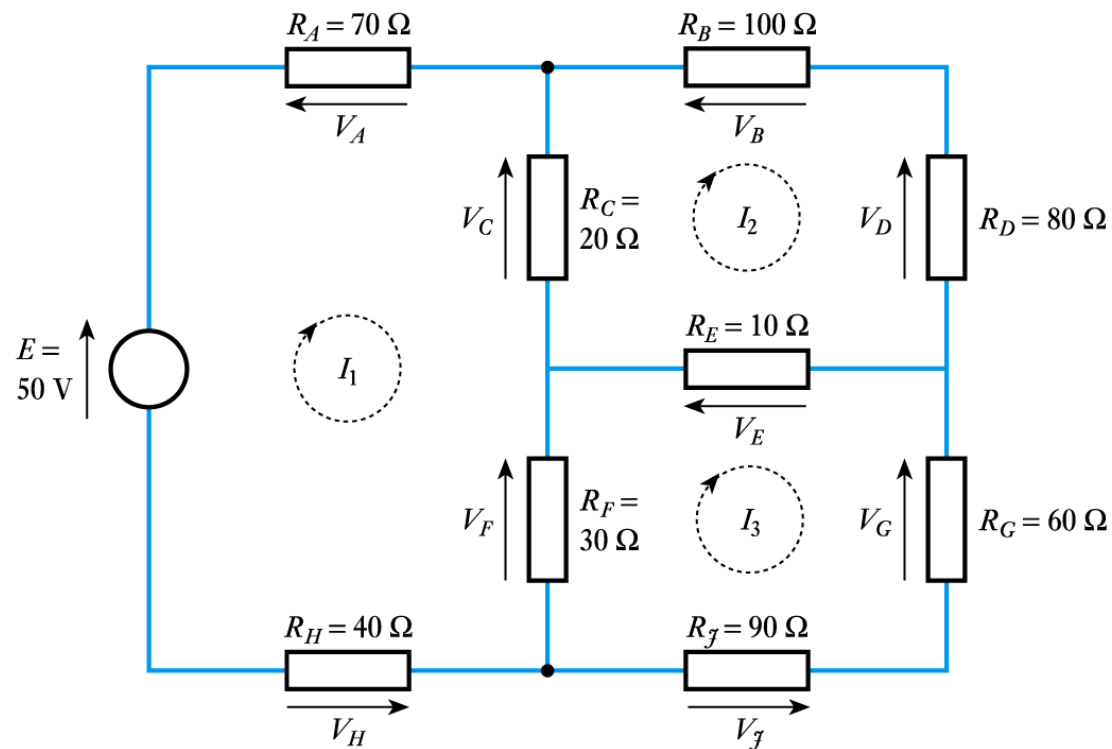
- Four steps:
 1. Identify the meshes and assign a clockwise-flowing current to each. Label these I_1 , I_2 , etc.
 2. Apply Kirchhoff's voltage law to each mesh
 3. Solve the simultaneous equations to determine the currents I_1 , I_2 , etc.
 4. Use these values to obtain voltages if required

- **Example** – see **Example 3.8** from course text
Determine the voltage across the $10\ \Omega$ resistor



Example (continued)

- first assign loops currents and label voltages



Example (continued)

- next apply Kirchhoff's law to each loop. This gives

$$E - V_A - V_C - V_F - V_H = 0$$

$$V_C - V_B - V_D + V_E = 0$$

$$V_F - V_E - V_G - V_J = 0$$

- which gives the following set of simultaneous equations

$$50 - 70I_1 - 20(I_1 - I_2) - 30(I_1 - I_3) - 40I_1 = 0$$

$$20(I_1 - I_2) - 100I_2 - 80I_2 + 10(I_3 - I_2) = 0$$

$$30(I_1 - I_3) - 10(I_3 - I_2) - 60I_3 - 90I_3 = 0$$

Example (continued)

- these can be rearranged to give

$$50 - 160I_1 + 20I_2 + 30I_3 = 0$$

$$20I_1 - 210I_2 + 10I_3 = 0$$

$$30I_1 + 10I_2 - 190I_3 = 0$$

- which can be solved to give

$$I_1 = 326 \text{ mA}$$

$$I_2 = 34 \text{ mA}$$

$$I_3 = 53 \text{ mA}$$

Example (continued)

- the voltage across the $10\ \Omega$ resistor is therefore given by

$$\begin{aligned}V_E &= R_E (I_3 - I_2) \\&= 10(0.053 - 0.034) \\&= 0.19\ \text{V}\end{aligned}$$

- since the calculated voltage is positive, the polarity is as shown by the arrow with the left hand end of the resistor more positive than the right hand end

Solving Simultaneous Circuit Equations

- Both nodal analysis and mesh analysis produce a series of **simultaneous equations**

- can be solved ‘by hand’ or by using matrix methods

- e.g. $50 - 160I_1 + 20I_2 + 30I_3 = 0$

$$20I_1 - 210I_2 + 10I_3 = 0$$

$$30I_1 + 10I_2 - 190I_3 = 0$$

- can be rearranged as as

$$160I_1 - 20I_2 - 30I_3 = 50$$

$$20I_1 - 210I_2 + 10I_3 = 0$$

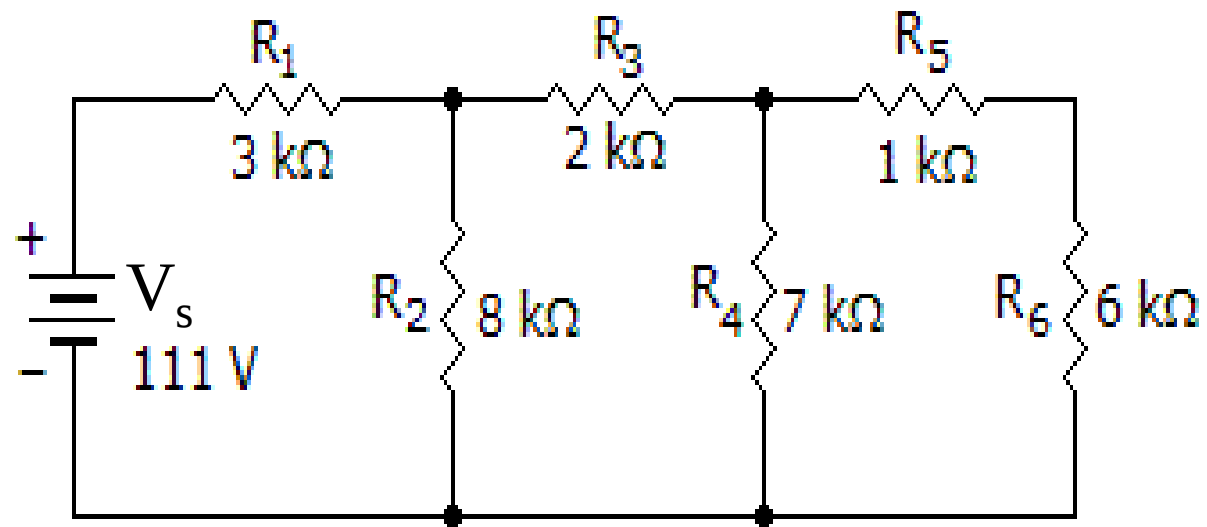
$$30I_1 + 10I_2 - 190I_3 = 0$$

Solving Simultaneous Circuit Equations

- these equations can be expressed as

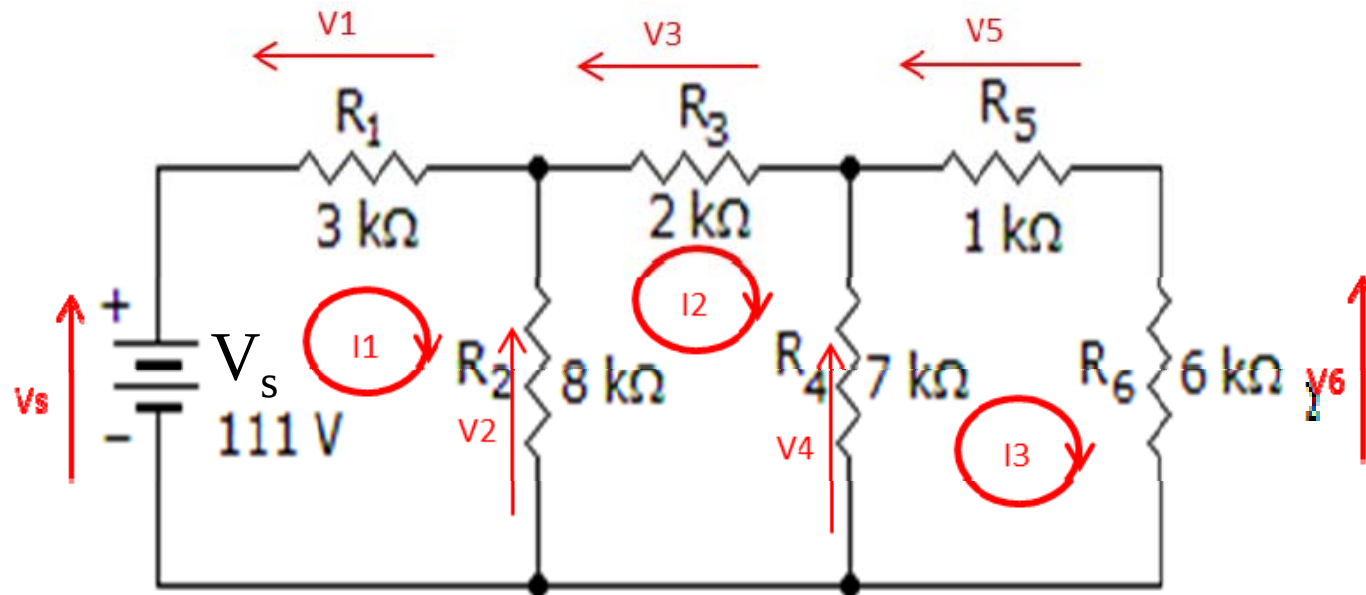
$$\begin{bmatrix} 160 & -20 & -30 \\ 20 & -210 & 10 \\ 30 & 10 & -190 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} 50 \\ 0 \\ 0 \end{bmatrix}$$

- which can be solved by hand (e.g. **Cramer's rule**)
- or can use automated tools
 - e.g. scientific calculators
 - computer-based packages such as **MATLAB** or **Mathcad**



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Mesh analysis



KVL around each mesh gives

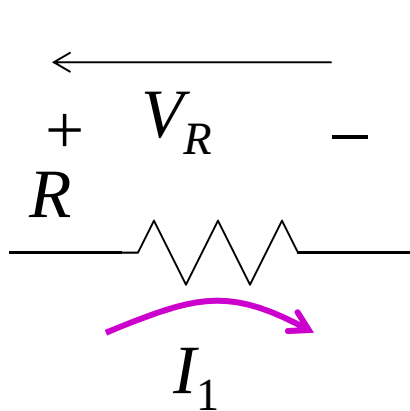
$$V_s - V_1 - V_2 = 0$$

$$V_2 - V_3 - V_4 = 0$$

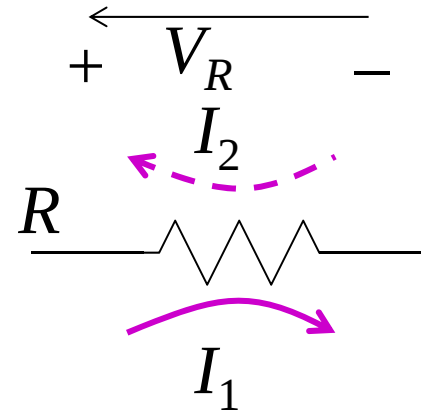
$$V_4 - V_5 - V_6 = 0$$

And want to apply
Ohms law to each
voltage drop

Voltages from Mesh Currents



$$V_R = I_1 R$$



$$V_R = (I_1 - I_2) R$$

Note Sign Convention: I_1 is anti-parallel to $V_R \Rightarrow V_{R1} = I_1 \cdot R$

I_2 parallel to $V_R \Rightarrow V_{R2} = -I_2 \cdot R$

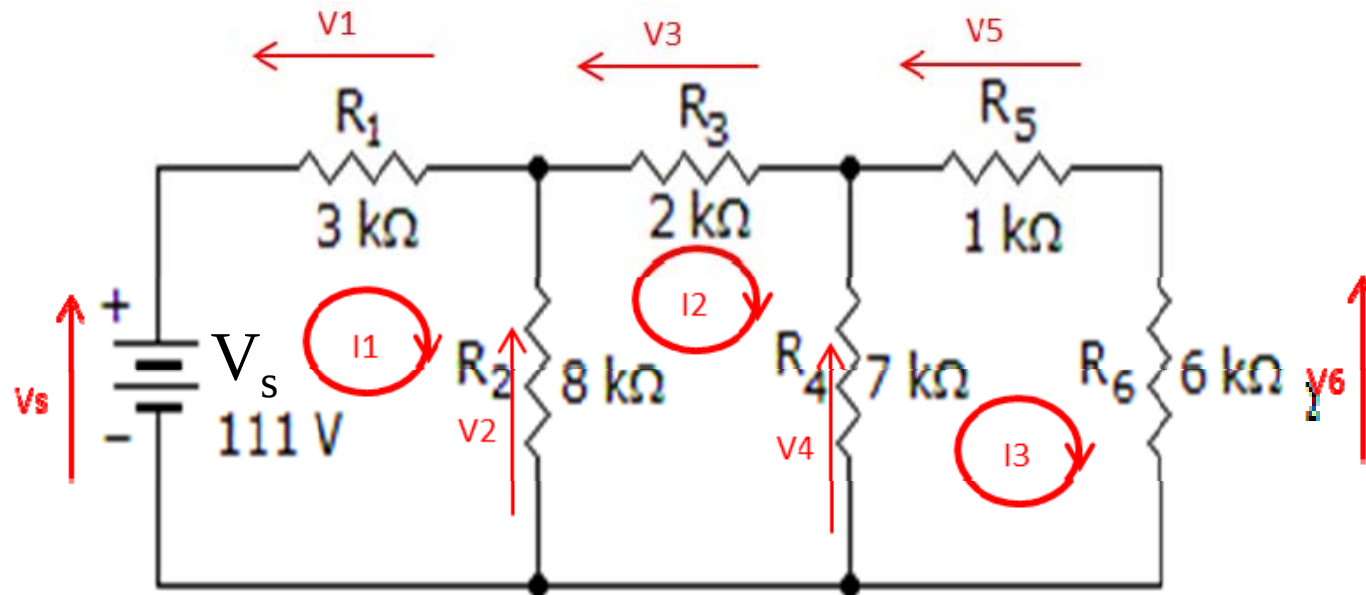
total voltage is the sum $V_R = (I_1 - I_2) \cdot R$

6.65

$$V_S - \textcircled{V1} - V2 = 0$$

$$V2 - V3 - V4 = 0$$

$$V4 - V5 - V6 = 0$$



Using Ohms law gives

$$111\text{V} - \textcircled{R_1 \cdot I_1} - R_2 \cdot (I_1 - I_2) = 0$$

$$R_2 \cdot (I_1 - I_2) - R_3 \cdot I_2 - R_4 \cdot (I_2 - I_3) = 0$$

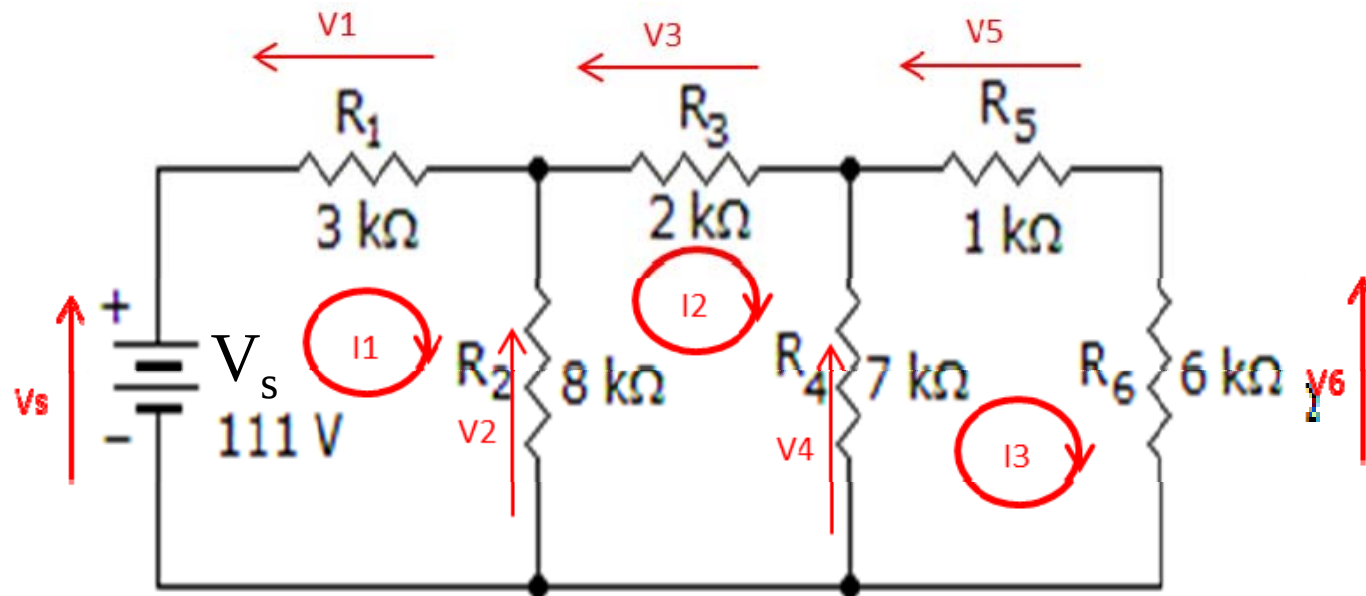
$$R_4 \cdot (I_2 - I_3) - R_5 \cdot I_3 - R_6 \cdot I_3 = 0$$

3.66

$$V_S - V_1 - \textcircled{V_2} = 0$$

$$V_2 - V_3 - V_4 = 0$$

$$V_4 - V_5 - V_6 = 0$$



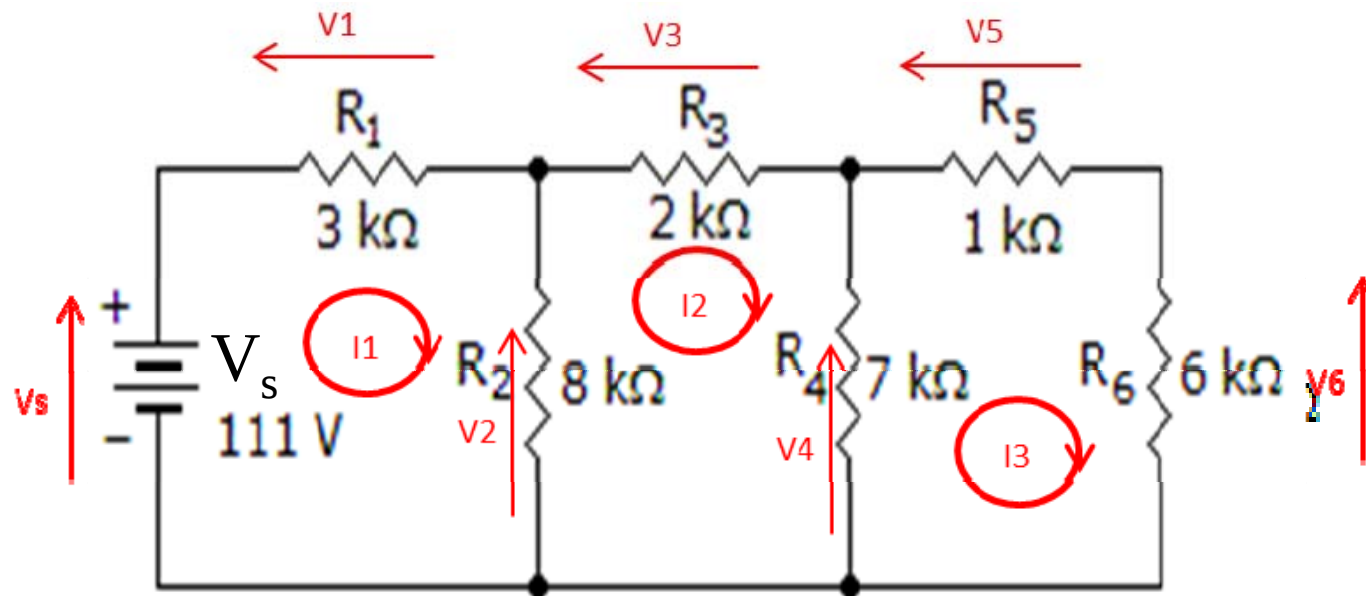
Using KVL gives

$$111V - R_1 \cdot I_1 - \textcircled{R_2 \cdot (I_1 - I_2)} = 0$$

$$R_2 \cdot (I_1 - I_2) - R_3 \cdot I_2 - R_4 \cdot (I_2 - I_3) = 0$$

$$R_4 \cdot (I_2 - I_3) - R_5 \cdot I_3 - R_6 \cdot I_3 = 0$$

3.67



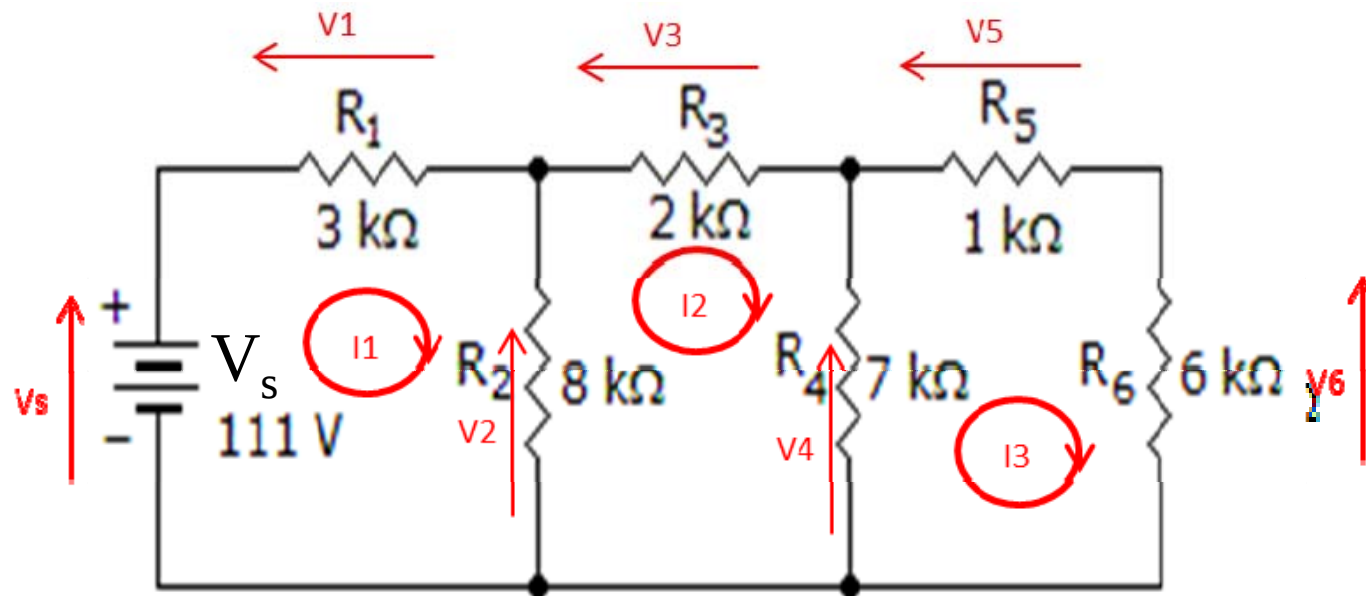
Using KVL gives

$$111V - R_1 \cdot I_1 - R_2 \cdot (I_1 - I_2) = 0$$

$$R_2 \cdot (I_1 - I_2) - R_3 \cdot I_2 - R_4 \cdot (I_2 - I_3) = 0$$

$$R_4 \cdot (I_2 - I_3) - R_5 \cdot I_3 - R_6 \cdot I_3 = 0$$

3.68



Expand to:

$$\begin{array}{rcl}
 111\text{V} - (R_1 + R_2) \cdot I_1 + & (R_2) & \cdot I_2 & 0 & \cdot I_3 = 0 \\
 (R_2) \cdot I_1 - (R_2 + R_3 + R_4) \cdot I_2 + & (R_4) & \cdot I_3 = 0 \\
 0 & \cdot I_1 & (R_4) \cdot I_2 - (R_4 + R_5 + R_6) \cdot I_3 = 0
 \end{array}$$

3.69

Mesh gives simultaneous equations

$$\begin{aligned} -(R_1+R_2) \cdot I_1 + (R_2) \cdot I_2 + 0 \cdot I_3 &= -111 \text{ V} \\ (R_2) \cdot I_1 - (R_2+R_3+R_4) \cdot I_2 + (R_4) \cdot I_3 &= 0 \\ 0 \cdot I_1 + (R_4) \cdot I_2 - (R_4+R_5+R_6) \cdot I_3 &= 0 \end{aligned}$$

Which in matrix form become

$$\begin{aligned} &-(R_1+R_2) && (R_2) && 0 \\ &(R_2) &- (R_2+R_3+R_4) && (R_4) \\ &0 && (R_4) &- (R_4+R_5+R_6) \end{aligned}$$



3.13

Choice of Techniques

- How do we choose the right technique?
 - nodal and mesh analysis will work in a wide range of situations but are not necessarily the simplest methods
 - no simple rules
 - often involves looking at the circuit and seeing which technique seems appropriate

3.71



Video 3D Further Study

Further Study

- The Further Study section at the end of Chapter 3 investigates the choice of circuit analysis techniques.
- A circuit is presented which could be analysed in a number of ways.
- Have a look and see which you think is best, then watch the video.



Key Points

- An electric current is a flow of charge
- A voltage source produces an e.m.f. which can cause a current to flow
- Current in a conductor is directly proportional to voltage
- At any instant the sum of the currents into a node is zero
- At any instant the sum of the voltages around a loop is zero
- Any two terminal network of resistors and energy sources can be replaced by a Thévenin or Norton equivalent circuit
- Nodal and mesh analysis provide systematic methods of applying Kirchhoff's laws