Fundamental quantities

Voltage — potential difference bet. 2 points
“across” quantity
analogous to ‘pressure’ between two points

Current — flow of charge through a material
“through” quantity
analogous to fluid flowing along a pipe

\[ I = \lim_{\delta t \to 0} \frac{\delta q}{\delta t} = \frac{dq}{dt} \]
Units of measurement

- Voltage: volt (V)
- Current: ampere (A)

- NOT Volt, Ampere!!

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Multiplier (abbreviation)</th>
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<tbody>
<tr>
<td>Peta</td>
<td>$\times 10^{15}$ (P)</td>
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<tr>
<td>Tera</td>
<td>$\times 10^{12}$ (T)</td>
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<tr>
<td>Giga</td>
<td>$\times 10^{9}$ (G)</td>
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<td>Mega</td>
<td>$\times 10^{6}$ (M)</td>
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<td>Kilo</td>
<td>$\times 10^{3}$ (k)</td>
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<td>Hecto</td>
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<td>Deca</td>
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<td>milli</td>
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<td>micro</td>
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<td>pico</td>
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<td>femto</td>
<td>$\times 10^{-15}$ (f)</td>
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Power and energy

Work done in moving a charge $\Delta q$ from A to B having a potential difference of $V$ is

$$W = V \Delta q$$

Power is work done per unit time, i.e.,

$$P = \lim_{\delta t \to 0} V \frac{\delta q}{\delta t} = V \frac{dq}{dt} = VI$$
Direction and polarity

- Current direction indicates the direction of flow of positive charge.
- Voltage polarity indicates the relative potential between 2 points: + assigned to a higher potential point; and – assigned to a lower potential point.

**NOTE:** Direction and polarity are arbitrarily assigned on circuit diagrams. Actual direction and polarity will be governed by the sign of the value.

\[ 3A = -3A \quad \text{and} \quad 4V = -4V \]
Independent sources

- Voltage sources
- Current sources

Independent — stubborn! never change!

Maintains a voltage/current (fixed or varying) which is not affected by any other quantities.

An independent voltage source can never be shorted.
An independent current source can never be opened.
Dependent sources

- Dependent sources — values depend on some other variables

![Diagram of dependent voltage and current sources with equations: $v(v_x, i_y, ..)$ and $i(v_x, i_y, ..)$]
Circuit

- Collection of devices such as sources and resistors in which terminals are connected together by conducting wires.
  - These wires converge in NODES
  - The devices are called BRANCHES of the circuit

Circuit Analysis Problem:
To find all currents and voltages in the branches of the circuit when the intensities of the sources are known.
Kirchhoff’s laws

- Kirchhoff’s current law (KCL)
  - The algebraic sum of the currents in all branches which converge to a common node is equal to zero.

- Kirchhoff’s voltage law (KVL)
  - The algebraic sum of all voltages between successive nodes in a closed path in the circuit is equal to zero.
Overview of analysis

- Ad hoc methods (not general)
  - Series/parallel reduction
  - Ladder circuit
  - Voltage/current division
  - Star-delta conversion

- More general
  - Mesh and nodal methods

- Completely general
  - Loop and cutset approach (requires graph theory)

Done in Basic Electronics!
Series/parallel reduction

- **Series circuit** — each node is incident to just two branches of the circuit

KVL gives

\[ V_{1,n+1} = V_{12} + V_{23} + \cdots + V_{n,n+1} = (R_1 + R_2 + \cdots + R_n)I \]

Hence, the equivalent resistance is:

\[ R = R_1 + R_2 + \cdots + R_n \]
Series/parallel reduction

- Parallel circuit — one terminal of each element is connected to a node of the circuit while other terminals of the elements are connected to another node of the circuit.

KCL gives

\[ I = (G_1 + G_2 + \cdots + G_n)V \]

Hence, the equivalent resistance is:

\[ G = G_1 + G_2 + \cdots + G_n \]
Note on algebra

- For algebraic brevity and simplicity:
  - For series circuits, R is preferably used.
  - For parallel circuits, G is preferably used.

For example, if we use R for the parallel circuit, we get the equivalent resistance as

\[ R = \frac{R_1 R_2 R_3 \cdots R_n}{R_2 R_3 \cdots R_n + R_1 R_3 R_4 \cdots R_n + \cdots + R_1 R_2 \cdots R_{n-1}} \]

which is more complex than the formula in terms of G:

\[ G = G_1 + G_2 + \ldots + G_n \]
Ladder circuit

- We can find the resistance looking into the terminals 0 and 1, by applying the series/parallel reduction successively.

First, lumping everything beyond node 2 as $G_2$, we have

$$\frac{V}{I} = R_{12} + \frac{1}{G_2}$$

Then, we focus on this $G_2$, which is just $G_{20}$ in parallel with another subcircuit, i.e.,

$$G_2 = G_{20} + \frac{1}{R_2'}$$

We continue to focus on the remaining subcircuit. Eventually we get
Voltage/current division

For the series circuit, we can find the voltage across each resistor by the formula:

\[ V_{i,i+1} = R_i I = \frac{R_i V}{R_1 + R_2 + \cdots + R_n} \]

Note the choice of R and G in the formulae!

For the parallel circuit, we can find the voltage across each resistor by the formula:

\[ I_i = G_i V = \frac{G_i I}{G_1 + G_2 + \cdots + G_n} \]
Example (something that can be done with series/parallel reduction)

Consider this circuit, which is created deliberately so that you can solve it using series/parallel reduction technique. **Find \( V_2 \).**

Solution:
Resistance seen by the voltage source is

\[
R = \frac{V_1}{I_1} = R_1 + \frac{1}{\frac{1}{R_2} + \frac{1}{R_3 + R_4}} = R_1 + \frac{R_2(R_3 + R_4)}{R_2 + R_3 + R_4}
\]

Hence,

\[
I_1 = \frac{(R_2 + R_3 + R_4)V_1}{(R_3 + R_4)(R_1 + R_2) + R_1R_2}
\]

Current division gives:

\[
I_4 = I_1 \times \frac{\left(\frac{1}{R_3 + R_4}\right)}{\left(\frac{1}{R_3 + R_4}\right) + \frac{1}{R_2}} = \frac{R_2I_1}{R_2 + R_3 + R_4}
\]

Then, using \( V_2 = I_4R_4 \), we get

\[
V_2 = \frac{R_2R_4V_1}{(R_1 + R_2)(R_3 + R_4) + R_1R_2}
\]
Oops!

Series/parallel reduction *fails* for this bridge circuit!

Is there some *ad hoc* solution?
Equivalence of star and delta

Problems:
1. Given a star circuit, find the delta equivalence. That means, suppose you have all the G’s in the star. Find the G’s in the delta such that the two circuits are “equivalent” from the external viewpoint.
2. The reverse problem.
For the Y circuit, we consider summing up all currents into the centre node: $I_1 + I_2 + I_3 = 0$, where

\[ I_1 = G_{10}(V_1 - V_0) \]
\[ I_2 = G_{20}(V_2 - V_0) \]
\[ I_3 = G_{30}(V_3 - V_0) \]

Thus,

\[ V_0 = \frac{G_{10}V_1 + G_{20}V_2 + G_{30}V_3}{G_{10} + G_{20} + G_{30}} \]

And

\[ I_1 = \frac{(G_{20} + G_{30})V_1 - G_{20}V_2 - G_{30}V_3}{G_{10} + G_{20} + G_{30}} \times G_{10} \]
\[ I_2 = \frac{-G_{10}V_1 + (G_{30} + G_{10})V_2 - G_{30}V_3}{G_{10} + G_{20} + G_{30}} \times G_{20} \]
\[ I_3 = \frac{-G_{10}V_1 - G_{20}V_2 + (G_{10} + G_{20})V_3}{G_{10} + G_{20} + G_{30}} \times G_{30} \]
Star-to-delta conversion

For the □ circuit, we have

\[
\begin{align*}
I_1 &= (G_{12} + G_{31})V_1 - G_{12}V_2 - G_{31}V_3 \\
I_2 &= -G_{12}V_1 + (G_{12} + G_{23})V_2 - G_{23}V_3 \\
I_3 &= -G_{31}V_1 - G_{23}V_2 + (G_{31} + G_{23})V_3
\end{align*}
\]
Star-to-delta conversion

Now, equating the two sets of $I_1$, $I_2$ and $I_3$, we get

\[
G_{12} = \frac{G_{10}G_{20}}{G_{10} + G_{20} + G_{30}}
\]

\[
G_{23} = \frac{G_{20}G_{30}}{G_{10} + G_{20} + G_{30}}
\]

\[
G'_{31} = \frac{G_{10}G_{30}}{G_{10} + G_{20} + G_{30}}
\]

The first problem is solved.
Delta-to-star conversion

This problem is more conveniently handled in terms of R. The answer is:

\[
\begin{align*}
R_{10} &= \frac{R_{12}R_{31}}{R_{23} + R_{31} + R_{12}} \\
R_{20} &= \frac{R_{23}R_{12}}{R_{23} + R_{31} + R_{12}} \\
R_{30} &= \frac{R_{31}R_{23}}{R_{23} + R_{31} + R_{12}}
\end{align*}
\]
Example — the bridge circuit again

We know that the series/parallel reduction method is not useful for this circuit!

The star-delta transformation may solve this problem.

The question is how to apply the transformation so that the circuit can become solvable using the series/parallel reduction or other ad hoc methods.
Example — the bridge circuit again

After we do the conversion from Y to D, we can easily solve the circuit with parallel/series reduction.
Useful/important theorems

- Thévenin Theorem
- Norton Theorem
- Maximum Power Transfer Theorem
Thévenin and Norton theorems

Problem:
Find the simplest equivalent circuit model for \( \mathcal{N} \), such that the external circuit \( \mathcal{N}^* \) would not feel any difference if \( \mathcal{N} \) is replaced by that equivalent model.

The solution is contained in two theorems due to Thévenin and Norton.
Thévenin and Norton theorems

Let’s look at the logic behind these theorems (quite simple really).

If we write down KVL, KCL, and Ohm’s law equations correctly, we will have a number of equations with the same number of unknowns. Then, we can try to solve them to get what we want.

Now suppose everything is linear. We are sure that we can get the following equation after elimination/substitution (some high school algebra):

\[ aV + bI - c = 0 \]

Case 1: \( a \neq 0 \)

\[ V = \frac{-b}{a} I + \frac{c}{a} = -R_T I + V_T \]

Case 2: \( b \neq 0 \)

\[ I = \frac{-a}{b} V + \frac{c}{b} = -\frac{V}{R_N} + I_N \]

Thévenin  Norton
Equivalent models

Thévenin equiv. ckt
Voltage source in series with a resistor
i.e., $V + IR_T = V_T$
which is consistent with case 1 equation

Norton equiv. ckt
Current source in parallel with a resistor
i.e., $I = I_N + V/R_N$
which is consistent with case 2 equation
How to find $V_T$ and $I_N$

**Thévenin equiv. ckt**
Open-circuit the terminals ($I=0$), we get $V_T$ as the observed value of $V$.

Easy! $V_T$ is just the open-circuit voltage!

**Norton equiv. ckt**
Short-circuit the terminals ($V=0$), we get $I_N$ as the observed current $I$.

Easy! $I_N$ is just the short-circuit current!
How to find $R_T$ and $R_N$ (they are equal)

**Thévenin equiv. ckt**
Short-circuit the terminals ($V=0$), find $I$ which is equal to $V_T/R_T$. Thus, $R_T = V_T / I_{sc}$

**Norton equiv. ckt**
Open-circuit the terminals ($I=0$), find $V$ which is equal to $I_N R_N$. Thus, $R_N = V_{oc} / I_N$.

For both cases,

\[ R_T = R_N = V_{oc} / I_{sc} \]
Simple example

Step 1: open-circuit
The o/c terminal voltage is

\[ v_{o/c} = 2 \times \frac{1}{1+1} = 1V \]

Step 2: short-circuit
The s/c current is

\[ i_{s/c} = \frac{2}{1+0.5} \times \frac{1}{2} = \frac{2}{3}A \]

Step 3: Thévenin or Norton resistance

\[ R_T = R_N = \frac{v_{o/c}}{i_{s/c}} = \frac{1}{2/3} = \frac{3}{2} \Omega \]

Hence, the equiv. ckt is:

[Diagram of equivalent circuit with 1V source, 1.5Ω, and 0.667A source with 1.5Ω]
Example — the bridge again

**Problem:** Find the current flowing in $R_5$.

One solution is by delta-star conversion (as done before).

Another simpler method is to find the Thévenin equivalent circuit seen from $R_5$. 
Example — the bridge again

Step 1: open circuit
The o/c voltage across A and B is
\[ v_{o/c} = V \times \left( \frac{R_4}{R_1 + R_4} - \frac{R_3}{R_2 + R_3} \right) = V_T \]

Step 2: short circuit
The s/c current is
\[ i_{s/c} = (\text{current in } R_1) - (\text{current in } R_4) \]
\[ = I \times \left( \frac{G_1}{G_1 + G_2} - \frac{G_4}{G_3 + G_4} \right) \]

Step 3: \( R_T \)
\[ R_T = \frac{v_{o/c}}{i_{s/c}} \]
\[ = \frac{G_1 + G_2 + G_3 + G_4}{(G_1 + G_4)(G_2 + G_3)} \]
\[ = \frac{1}{(R_1||R_4) + (R_2||R_3)} \]
Example — the bridge again

Current in R5 = \frac{V_T}{R_5 + R_T}
Maximum power transfer theorem

We consider the power dissipated by $R_L$. The current in $R_L$ is

$$I = \frac{V_T}{R_T + R_L}$$

Thus, the power is

$$P_L = I^2 R_L$$

$$= \frac{V_T^2 R_L}{(R_T + R_L)^2}$$

This power has a maximum, when plotted against $R_L$.

$$\frac{dp_L}{dR_L} = 0 \text{ gives } R_L = R_T.$$
A misleading interpretation

It seems counter-intuitive that the MPT theorem suggests a maximum power at $R_L = R_T$.

Shouldn’t maximum power occur when we have all power go to the load? That is, when $R_T = 0$!

**Is the MPT theorem wrong?**

Discussion: what is the condition required by the theorem?
Systematic analysis techniques

So far, we have solved circuits on an *ad hoc* manner. We are able to treat circuits with parallel/series reduction, star-delta conversion, with the help of some theorems.

How about very *general arbitrary circuit styles*?

In *Basic Electronics*, you have learnt the use of MESH and NODAL methods.

MESH — planar circuits only; solution in terms of *mesh currents*.  
NODAL — any circuit; solution in terms of *nodal voltages*.

**BUT THEY ARE NOT EFFICIENT!**
Mesh analysis (for planar circuits only)

**Mesches — windows**

![Diagram of meshes and planar circuits](image-url)
Mesh analysis

**Step 1: Define meshes and unknowns**
Each window is a mesh. Here, we have two meshes. For each one, we “imagine” a current circulating around it. So, we have two such currents, $I_1$ and $I_2$ — unknowns to be found.

**Step 2: Set up KVL equations**

Mesh 1: \[-42 + 6I_1 + 3(I_1 - I_2) = 0\]

Mesh 2: \[3(I_2 - I_1) + 4I_2 - 10 = 0\]

**Step 3: Simplify and solve**

\[
\begin{align*}
9I_1 - 3I_2 &= 42 \\
-3I_1 + 7I_2 &= 10
\end{align*}
\]

which gives $I_1 = 6$ A and $I_2 = 4$ A.

Once we know the mesh currents, we can find anything in the circuit!

- e.g., current flowing down the 3Ω resistor in the middle is equal to $I_1 - I_2$;
- current flowing up the 42V source is $I_1$;
- current flowing down the 10V source is $I_2$;
- and voltages can be found via Ohm’s law.
Mesh analysis

In general, we formulate the solution in terms of unknown mesh currents:

\[ [ R ] [ I ] = [ V ] \] — mesh equation

where

- \([ R ]\) is the resistance matrix
- \([ I ]\) is the unknown mesh current vector
- \([ V ]\) is the source vector

For a short cut in setting up the above matrix equation, see *Sec. 3.2.1.2 of the textbook*. This may be picked up in the tutorial.
Mesh analysis — observing superposition

Consider the previous example. The mesh equation is given by:

\[9I_1 - 3I_2 = 42\]
\[-3I_1 + 7I_2 = 10\]

or

\[
\begin{pmatrix}
9 & -3 \\
-3 & 7
\end{pmatrix}
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix}
=
\begin{pmatrix}
42 \\
10
\end{pmatrix}
\]

Thus, the solution can be written as

\[
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix}
=
\begin{pmatrix}
9 & -3 \\
-3 & 7
\end{pmatrix}^{-1}
\begin{pmatrix}
42 \\
10
\end{pmatrix}
\]

Remember what 42 and 10 are? They are the sources! The above solution can also be written as

\[
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix}
=
\begin{pmatrix}
9 & -3 \\
-3 & 7
\end{pmatrix}^{-1}
\begin{pmatrix}
42 \\
0
\end{pmatrix}
+
\begin{pmatrix}
9 & -3 \\
-3 & 7
\end{pmatrix}^{-1}
\begin{pmatrix}
0 \\
10
\end{pmatrix}
\]

or

\[
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix}
=
\mathcal{R}^{-1}
\begin{pmatrix}
V_1 \\
0
\end{pmatrix}
+
\mathcal{R}^{-1}
\begin{pmatrix}
0 \\
V_2
\end{pmatrix}
\]

\[
= \mathcal{R}^{-1}
\begin{pmatrix}
1 & \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
V_1 \\
V_2
\end{pmatrix}
\]

\[
= AV_1 + BV_2
\]

Prof. C.K. Tse: Basic Circuit Analysis
Problem with current sources

The mesh method may run into trouble if the circuit has current source(s).

Suppose we define the unknowns in the same way, i.e., \( I_1, I_2 \) and \( I_3 \).

The trouble is that we don’t know what voltage is dropped across the 14A source! How can we set up the KVL equation for meshes 1 and 3?

One solution is to ignore meshes 1 and 3. Instead we look at the supermesh containing 1 and 3.

So, we set up KVL equations for mesh 2 and the supermesh:

Mesh 2: \( (I_2 - I_1) \times 1 + I_2 \times 2 + (I_2 - I_3) \times 3 = 0 \)

Supermesh: \( -7 + (I_1 - I_2) \times 1 + (I_3 - I_2) \times 3 + I_3 \times 1 = 0 \)

One more equation: \( I_1 - I_3 = 14 \)

Finally, solve the equations.
Complexity of mesh method

In all cases, we see that the mesh method ends up with $N$ equations and $N$ unknowns, where $N$ is the number of meshes (windows) of the circuit.

**One important point:**
The mesh method is over-complex when applied to circuits with current source(s). WHY?

We don’t need $N$ equations for circuits with current source(s) because the currents are partly known!

In the previous example, it seems unnecessary to solve for both $I_1$ and $I_3$ because their difference is known to be 14! This is a waste of efforts! Can we improve it?
Nodal analysis

**Step 1: Define unknowns**
Each node is assigned a number. Choose a reference node which has zero potential. Then, each node has a voltage w.r.t. the reference node. Here, we have $V_1$ and $V_2$ — unknowns to be found.

**Step 2: Set up KCL equation for each node**

Node 1: 
\[-3 + \frac{V_1}{2} + \frac{V_1 - V_2}{5} = 0\]

Node 2: 
\[\frac{V_2 - V_1}{5} + \frac{V_2}{1} - 2 = 0\]

**Step 3: Simplify and solve**

\[
\begin{bmatrix}
\frac{1}{2} + \frac{1}{5} & -\frac{1}{5} \\
-\frac{1}{5} & \frac{1}{5} + 1 \\
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
\end{bmatrix}
= 
\begin{bmatrix}
3 \\
2 \\
\end{bmatrix}
\]

which gives $V_1 = 5$ V and $V_2 = 2.5$ V.

Once we know the nodal voltages, we can find anything in the circuit!

- e.g., voltage across the 5Ω resistor in the middle is equal to $V_1 - V_2$;
- voltage across the 3A source is $V_1$;
- voltage across the 2A source is $V_2$;
- and currents can be found via Ohm’s law.
Nodal analysis

In general, we formulate the solution in terms of unknown nodal voltages:

\[
[ G ][ V ] = [ I ] \quad \text{— nodal equation}
\]

where
- \([ G ]\) is the conductance matrix
- \([ V ]\) is the unknown node voltage vector
- \([ I ]\) is the source vector

For a short cut in setting up the above matrix equation, see Sec. 3.3.1.2 of the textbook. This may be picked up in the tutorial.
Nodal analysis — observing superposition

Consider the previous example. The nodal equation is given by:

\[
\begin{bmatrix}
\frac{1}{2} + \frac{1}{5} & -\frac{1}{5} \\
-\frac{1}{5} & \frac{1}{5} + 1
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} =
\begin{bmatrix}
3 \\
2
\end{bmatrix}
\]

Thus, the solution can be written as

\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} = \left( \begin{bmatrix}
\frac{7}{10} & -\frac{1}{5} \\
-\frac{1}{5} & \frac{6}{5}
\end{bmatrix} \right)^{-1}
\begin{bmatrix}
3 \\
2
\end{bmatrix}
\]

Remember what 3 and 2 are? They are the sources! The above solution can also be written as

\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} = \left( \begin{bmatrix}
\frac{7}{10} & -\frac{1}{5} \\
-\frac{1}{5} & \frac{6}{5}
\end{bmatrix} \right)^{-1}
\begin{bmatrix}
3 \\
0
\end{bmatrix}
+ \left( \begin{bmatrix}
\frac{7}{10} & -\frac{1}{5} \\
-\frac{1}{5} & \frac{6}{5}
\end{bmatrix} \right)^{-1}
\begin{bmatrix}
0 \\
2
\end{bmatrix}
\]

or

\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix} = G^{-1}
\begin{bmatrix}
I_1 \\
0
\end{bmatrix} + G^{-1}
\begin{bmatrix}
0 \\
I_2
\end{bmatrix}
\]

Thus, the solution can be written as

\[
AI_1 + BI_2
\]

Superposition of two sources
Problem with voltage sources

The nodal method may run into trouble if the circuit has voltage source(s).

Suppose we define the unknowns in the same way, i.e., $V_1$, $V_2$ and $V_3$.

The trouble is that we don’t know what current is flowing through the 2V source! How can we set up the KCL equation for nodes 2 and 3?

One solution is to ignore nodes 1 and 3. Instead we look at the supernode merging 2 and 3.

So, we set up KCL equations for node 1 and the supernode:

$$8 + (V_1 - V_2) \times 3 + 3 + (V_1 - V_3) \times 4 = 0$$

$$(V_2 - V_1) \times 3 - 3 + V_2 \times 1 + (V_3 - V_1) \times 4 + V_3 \times 5 + 25 = 0$$

One more equation: $V_3 - V_2 = 2$

Finally, solve the equations.
In all cases, we see that the mesh method ends up with N equations and N unknowns, where N is the number of nodes of the circuit minus 1.

One important point:
The nodal method is over-complex when applied to circuits with voltage source(s). WHY?

We don’t need N equations for circuits with voltage source(s) because the node voltages are partly known!

In the previous example, it seems unnecessary to solve for both $V_2$ and $V_3$ because their difference is known to be 2! This is a waste of efforts! Can we improve it?
Final note on superposition

Superposition is a consequence of linearity.

We may conclude that for any linear circuit, any voltage or current can be written as linear combination of the sources.

Suppose we have a circuit which contains two voltage sources $V_1$, $V_2$ and $I_3$. And, suppose we wish to find $I_x$.

Without doing anything, we know for sure that the following is correct:

$$I_x = a V_1 + b V_2 + c I_3$$

where $a$, $b$ and $c$ are some constants.

**Is this property useful?**
**Can we use this property for analysis?**

**We may pick this up in the tutorial.**