What is a CIRCUIT ?

↑in the abstract, idealised sense

it is:

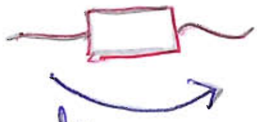
COMPONENTS and their CONNECTIONS

- often "two-terminal" components
  tvåpol

a component

- We can define a current and voltage

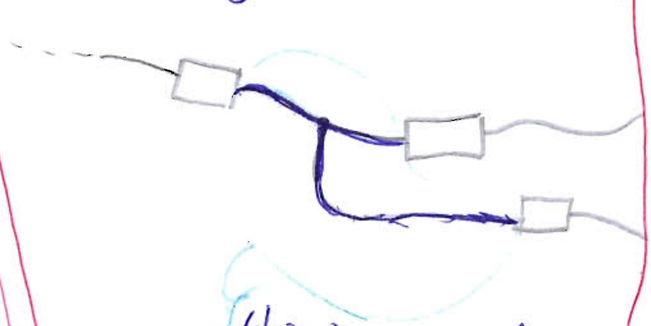
current (same at both sides)



difference in potential between sides

- several types: resistor, voltage source, etc.

- shown by "nodes" (ideal connections)

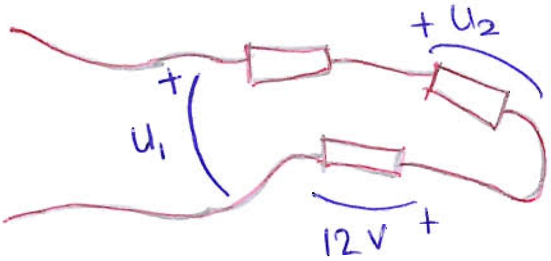


this is one node, joining three terminals

The node defines all the terminals it connects to as having the same potential, and as being able to exchange current.

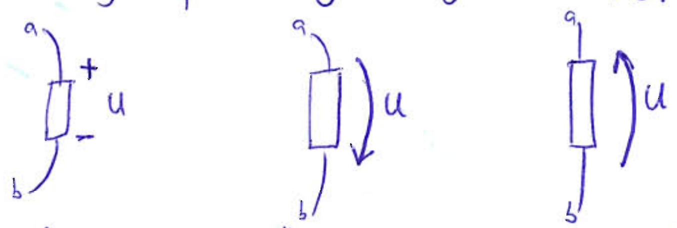
- The components determine one aspect of their current and voltage. (No component fully determines both of these.)
- The connections provide further demands by Kirchhoff's laws.
- Together, these two sets of "constraints" determine the solution for all voltages and currents in a circuit.

We often need to mark **voltages** across components, or more generally, <u>between nodes</u>:



⇐ Here are some voltages, marked with symbolic or number+unit quantities.
The '+' side shows that this side is greater in potential than the other side, <u>by the marked amount</u>.
(That might be a negative amount.)

Other ways of showing voltage include:



all mean the same thing.

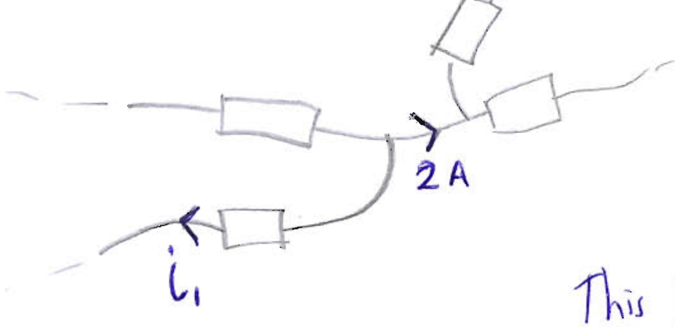
common modern textbooks

common European way showing field direction or "current in resistor"

common English-language way showing change in potential <u>from</u> tail <u>to</u> head of arrow.

I prefer the '+' or '+ –' method ... no doubt about meaning.

Likewise, we mark **currents** through components' terminals or other parts of nodes.



This is easy, using a little arrow.

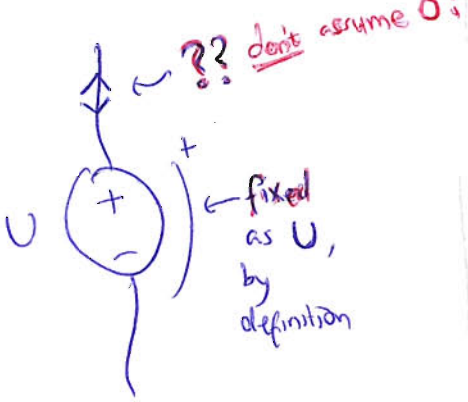
Define three core-components.

VOLTAGE SOURCE

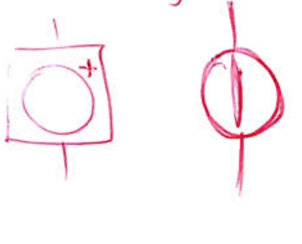
↖ "component value"

Difference of potential of '+' terminal compared to '−' terminal is fixed by the source's value (6V in this example).

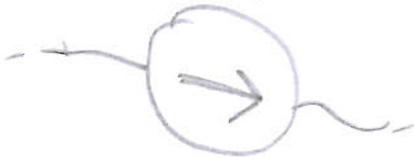
The current is not at all determined by the source definition ... it is dependent on the rest of the circuit.



other symbols include:

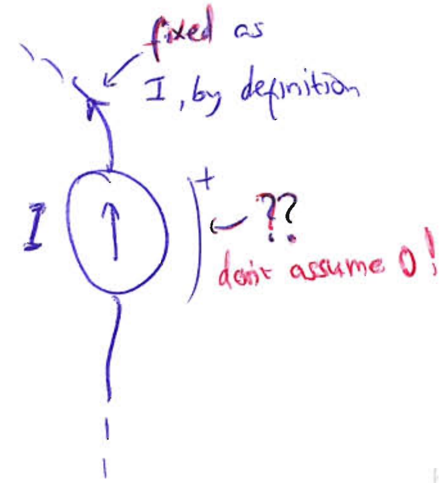


CURRENT SOURCE

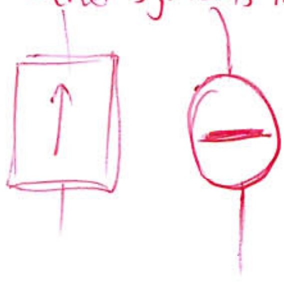


The current through the component is fixed by its value; (2A in this example).

The voltage depends on the rest of the circuit. The source will adjust to the voltage that is needed to cause the required current to flow.



Other symbols include:



RESISTOR

Voltage is not fixed by the components definition.

Current is not fixed either!

But their RATIO (kvot) is fixed: Ohm's law:

$$R = \frac{U}{i}$$

The actual values depend on the rest of the circuit.

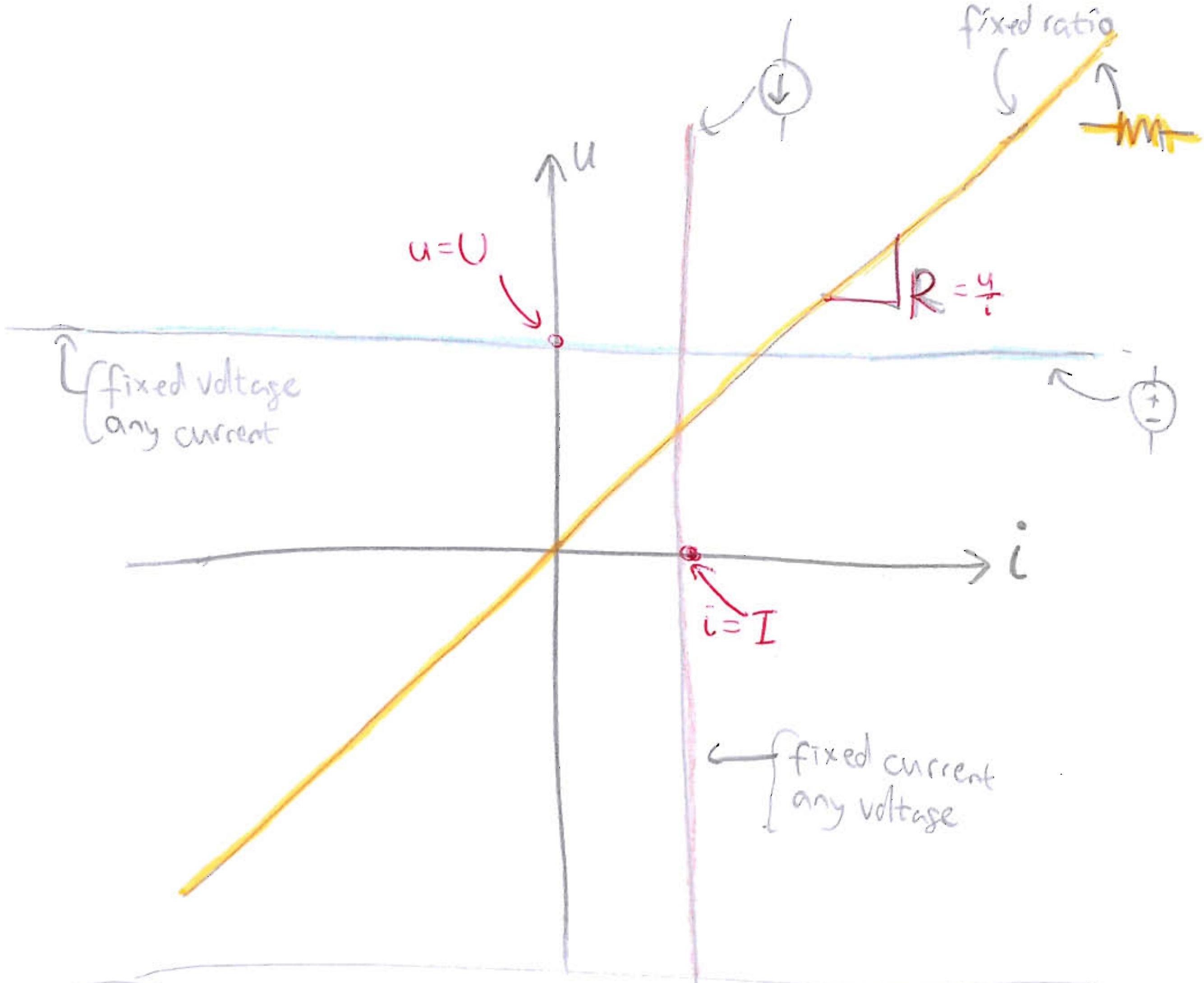
Note in most of this course material, the notation is that:

 is resistor

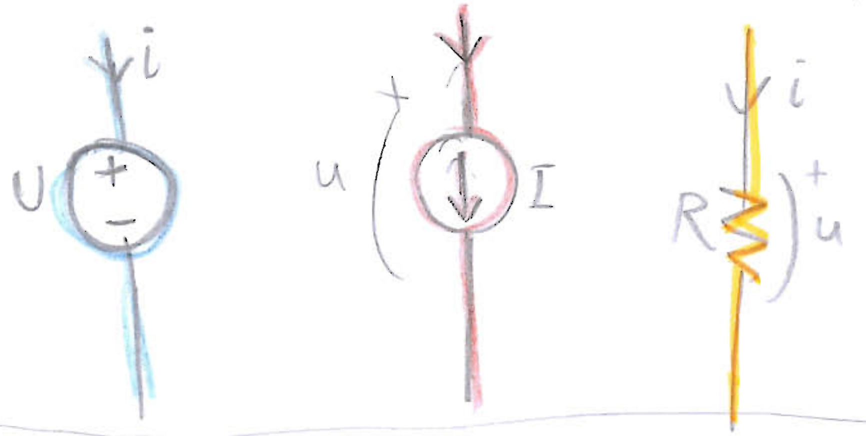
and  is GENERIC COMPONENT with two terminals

- could be voltage source, resistor, etc.
- So don't be surprised to see power being supplied by these symbols in later examples!

A graphical view of two-terminal components' u, i

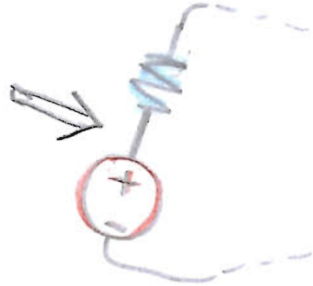


In the above, the definitions of u, i, U, I, R are:



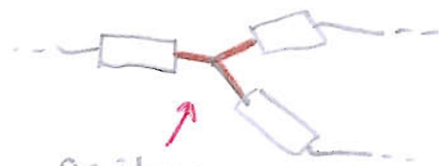
... Some people like thinking of things as graphs. No problem if you don't — ignore it!

The CONNECTIONS: nodes



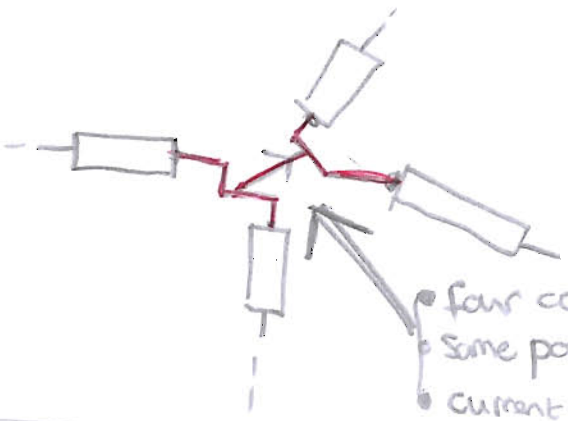
- lines joining terminals show connections.
- all terminals linked in a group are one node.
- in circuit diagrams (ideal) the shape of the lines doesn't matter

a node joining three terminals



an identical node (with different shape)

- a node defines all the connected terminals as having the same potential
- a node shows that currents can flow between all the connected terminals



- four connected terminals
- same potential at all of them
- current can exchange between them

In a simple lab circuit we think of "node ≡ wire". (≡: equivalent to; node: nod; wire: sladd)

It is not necessarily a good assumption.

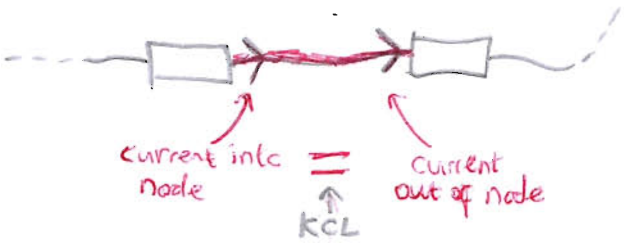
That is often ok when wires have resistance much less than the resistance of other components: eg. ≪1Ω wire, and >1 kΩ resistors.

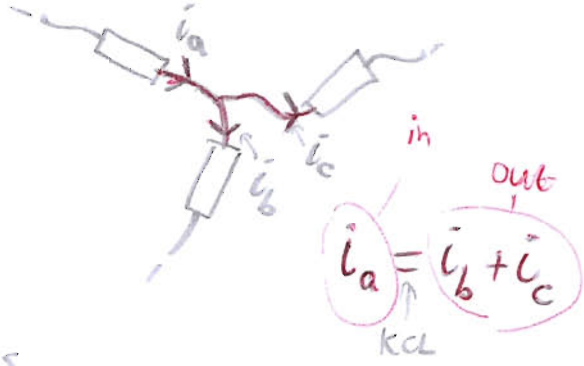
In many other cases, wires are modelled as resistors (or inductors!) and nodes model their connection to other components.

Kirchhoff's CURRENT LAW (KCL).

"Current doesn't go missing in a circuit"

- classic example is to study <u>one node</u> for current-balance.

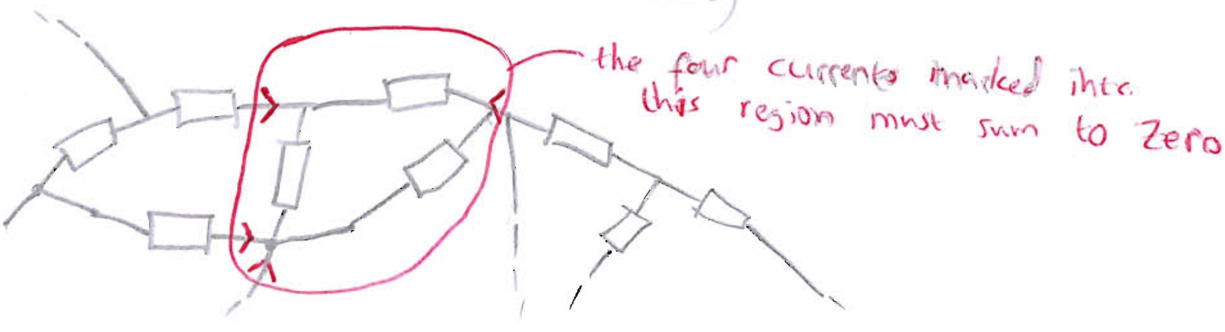




  - the examples above state KCL as "What goes in equals what comes out"

  - Sometimes it may be more systematic and reliable to avoid classifying connections by incoming versus outgoing arrows: "the currents defined into the node from each terminal must sum to zero"
    - in the above example, this means $i_a - i_b - i_c = 0$, (which can be seen by rearranging the earlier equation)
    - alternatively, change "into" to "out of": $-i_a + i_b + i_c = 0$

- KCL applies more generally, to currents into any region of a circuit (not just one node)



Kirchhoff's VOLTAGE LAW (KVL)

"the sum of voltages (potential changes) in a closed loop is zero"

(or)

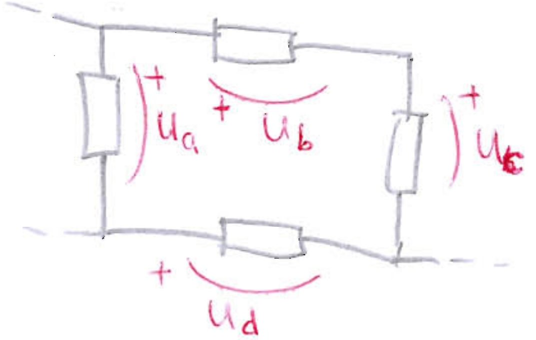
"circuit potential is conservative"

(or)

"a charge moving in a complete loop in a circuit loses as much energy as it gains"

↑ proportional to voltage for a given charge

- to apply this we could equate gains to losses



- if we choose to go clockwise from bottom left, we gain u_a then lose u_b then lose u_c then gain u_d

$$u_a + u_d = u_b + u_c$$

gained potential — KVL — lost potential

.... or we can just sum the total gains (with losses seen as negative gains) and equate to zero:

$$u_a - u_b - u_c + u_d = 0$$

↑ KVL

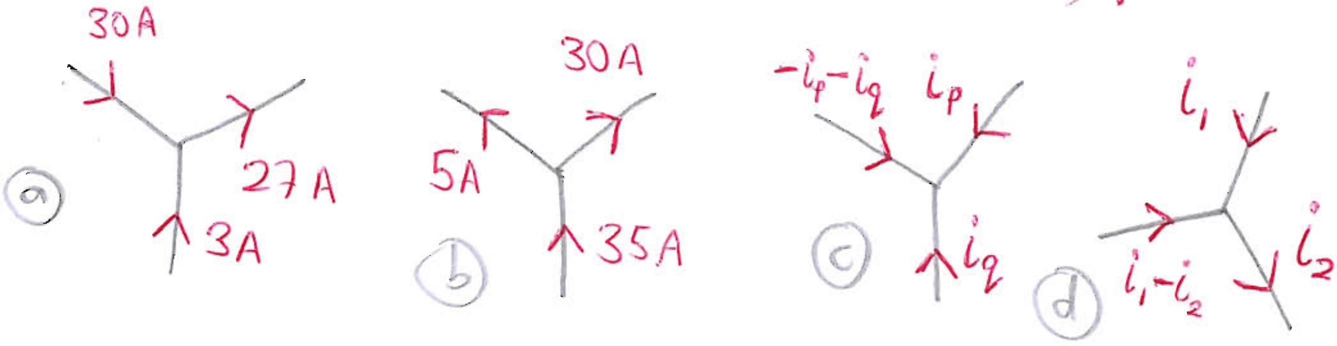
- it's the same result, rearranged
- another rearrangement is obtained by going anticlockwise (motors)

⟹ Lots of ways to write KCL & KVL

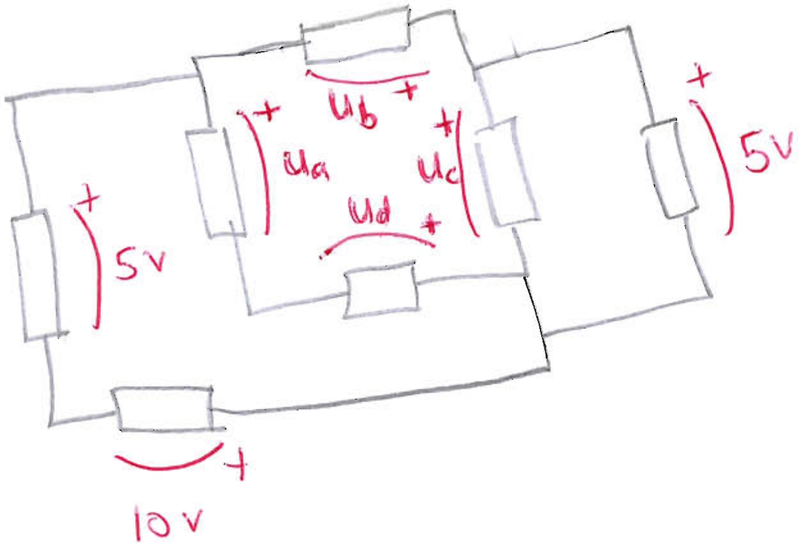
need to be very CAREFUL and SYSTEMATIC to avoid errors.

Quiz

Which of the following is/are WRONG (by KCL)?



Which of the following is/are WRONG (by KVL)?



(a) $u_a + u_b - u_c + u_d = 0$

(b) $u_b = 0$

(c) $u_c = 5\,V$

(d) $u_d - u_a = 5\,V$

(solutions on next page)

Solutions

KCL

(a) WRONG: 33 A goes in but 27 A comes out

(b) right: 35 A in, 35 A out

(c) right: total current going in is $\underbrace{-i_p - i_q + i_p + i_q}_{=0 \text{ (balances)}}$

(d) WRONG: total going in is $\underbrace{i_1 + (i_1 - i_2) + (-i_2)}_{= 2(i_1 + i_2)}$ not necessarily zero.

KVL

(a) WRONG: needed "$-u_d$" instead of "$+u_d$"

(b) WRONG: KVL in the loop of u_b and all the components with numeric values, gives:

$$5V + u_b - 5V - 10V = 0 \Rightarrow u_b = 10V$$

(c) WRONG: KVL in the loop of the two rightmost resistors gives

$$u_c - 5V = 0 \Rightarrow u_c = 5V$$

(d) right: KVL in the leftmost loop gives:

$$5V - u_a + u_d - 10V = 0$$

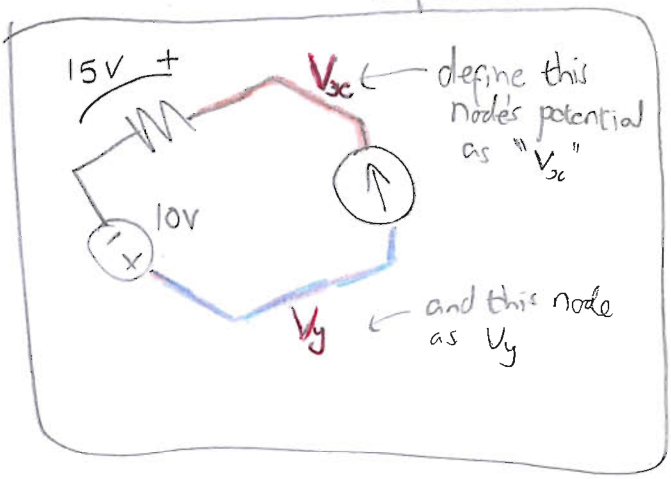
$$\Rightarrow u_d - u_a = 5V$$

Potential

same thing ...

We've mentioned voltages (e.g. across components) and "changes of potential" (e.g. in KVL)

Potentials can be defined:



by looking at the marked voltages we can see that

$$V_y - 10V + 15V = V_x$$

> there's a nice Swedish term for this process of following changes of potential: "Potentialvandring"

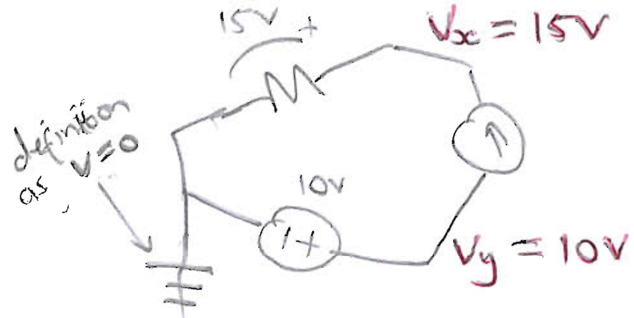
hence $V_x - V_y = 5V$

But the circuit's voltages only let us find $V_x - V_y$ (a voltage) ... what **is** V_x? (or V_y)

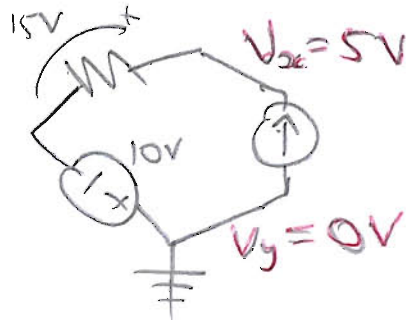
We have to define a value of one of the potentials in a circuit if we want potentials to have defined values.

One option would be to say e.g. "let $V_x = 20$ V". (Then in our case, $V_y = 15$ V).

Another is to mark a node as zero potential (reference, earth, ground) (jord)

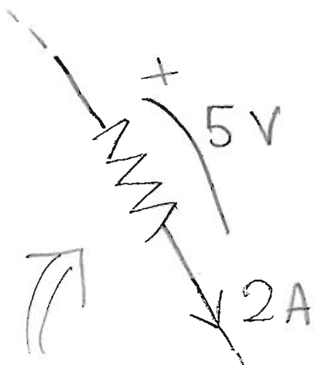


or



or ----

Power calculations



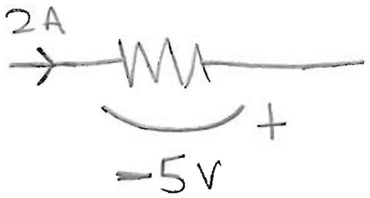
10 W is consumed by this component.

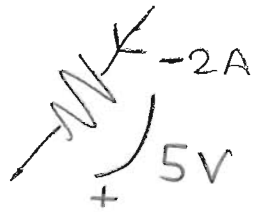
Here, "2 coulombs of charge every second lose 5 joules each."

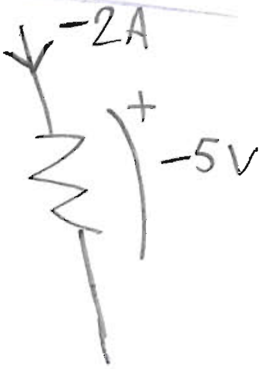
The power that this component takes from the circuit is therefore 10 W.

$[V] = \frac{[J]}{[C]}$ $[W] = \frac{[J]}{[s]}$ $[A] = \frac{[C]}{[s]}$

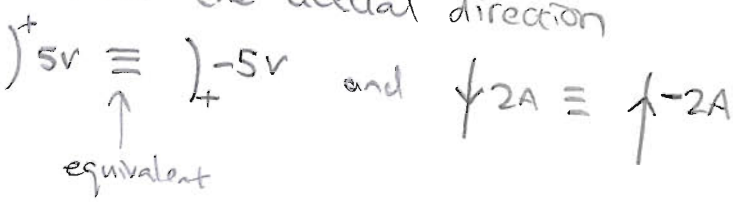
The same is true in these cases:

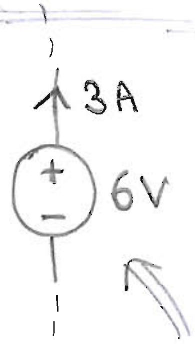






Negative voltage or current means that the actual direction is opposite to the marking:



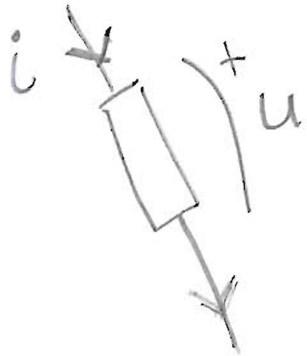


18 W is generated by this component

In this case, the charge is <u>given</u> energy when it passes through the component.

The component supplies 18 W to the circuit. (försörjer)

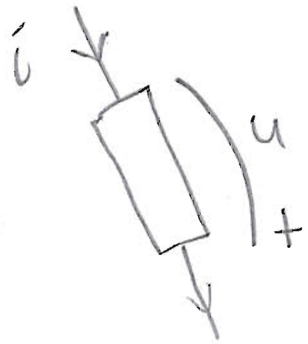
More generally, with symbolic quantities:



current i goes <u>down</u> in potential by u

the power { supplied to component / consumed by component / delivered to component / taken from rest of circuit / etc. } $= ui$

<u>or</u>



current i goes <u>up</u> in potential by u

the power { supplied from / generated by / produced by } the component $= ui$

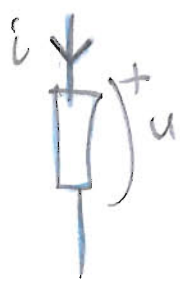
<u>So</u>, depending on the <u>relative direction</u> of the marked u and i, the product $P = ui$ can give either the power <u>consumed by</u> or the power <u>produced by</u> the component.

If we want the opposite, we negate it:

$P_{produced} = ui$

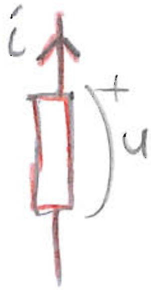
$P_{consumed} = -ui$

There are names for the two possible "relative directions" for marking u and i:



<u>passive</u> <u>convention</u> choice

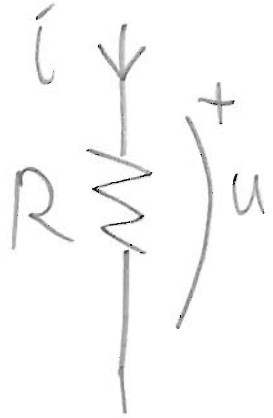
ui is power <u>consumed</u>



<u>active</u> convention

ui is power <u>produced</u>

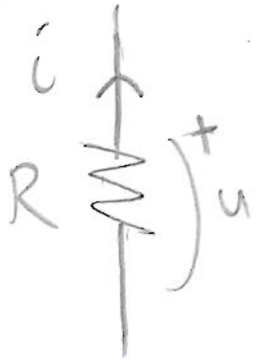
For Ohm's law too, the relative directions are important.



here the current is marked going <u>down</u> in potential by an amount u:

$$R = \frac{u}{i}$$ (Ohm's law, with u & i following the passive convention)

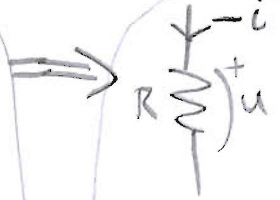
for a resistor, the current is pushed down the potential gradient



but here, the marked current is being pushed <u>up</u> in potential by an amount u;

$$R = -\frac{u}{i}$$ (Ohm's law, with u & i following the active convention)

One way to see this is to make the second case look like the first by swapping the direction <u>and</u> sign of voltage or current:



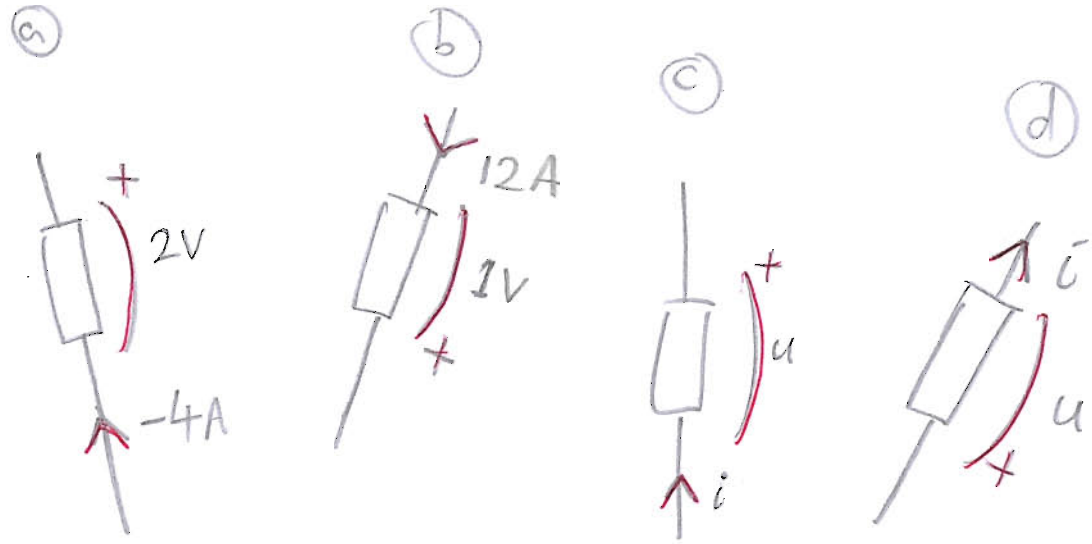
$$R = -\frac{u}{i}$$

$$R = \frac{u}{(-i)} = -\frac{u}{i}$$

active convention

passive convention

Quiz



Let $\begin{cases} u = 5V \\ i = -3A \end{cases}$

① Which component produces the most power?

② How much does each consume?

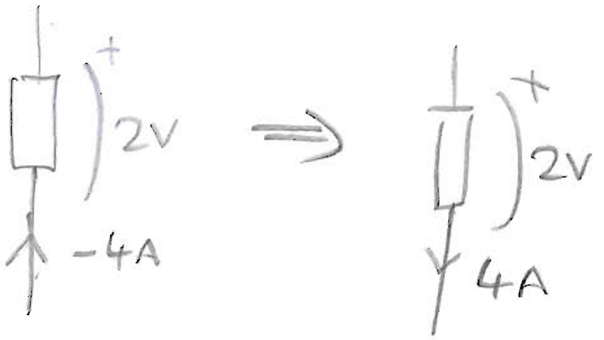
SOLUTION

① The component 'd' produces most power – see below

② Lets find how much each <u>consumes</u>

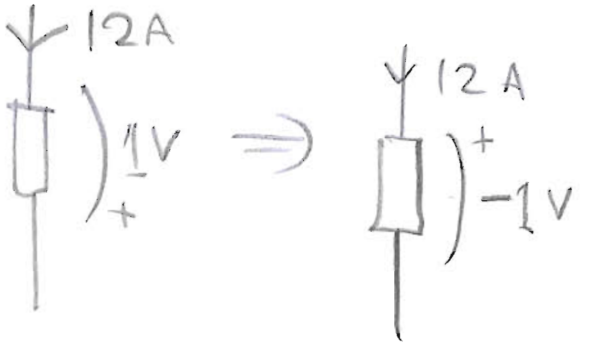
We can rewrite in passive convention by swapping direction <u>and</u> sign if it's in active convention.

ⓐ



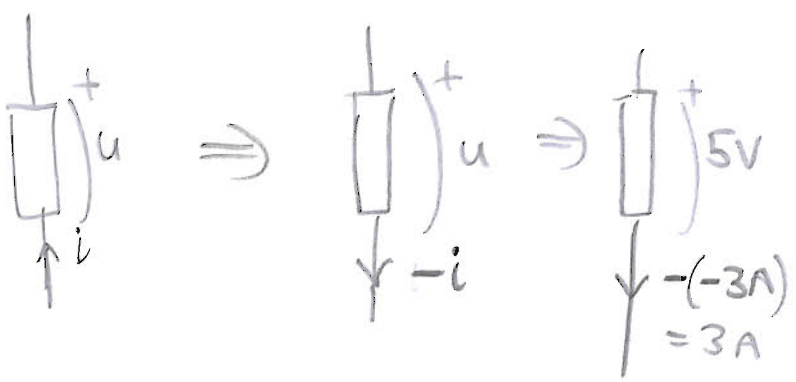
$\Rightarrow 2V \cdot 4A = 8W$ consumed

ⓑ



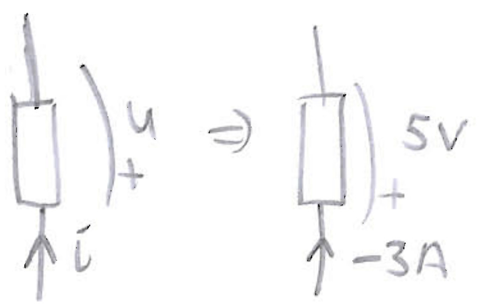
$\Rightarrow (-1V) \cdot 12A = -12W$ consumed

ⓒ



$\Rightarrow 5V \cdot 3A = 15W$ consumed

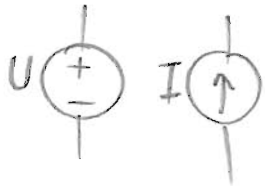
ⓓ



already passive convention

$\Rightarrow 5V \cdot (-3A) = -15W$ consumed

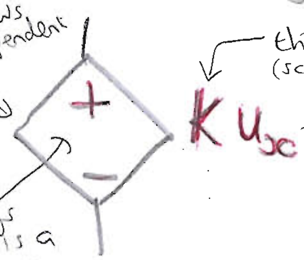
Dependent sources

We have seen INDEPENDENT sources: 

Their component-values (eg. U and I) don't depend on anything else in the circuit.

DEPENDENT SOURCES are different in that their output is proportional to a voltage or current defined somewhere in the circuit!
Their component-value is the proportionality constant.
We use a diamond shape to show a dependent source.

Example: Voltage controlled voltage source (VCVS)

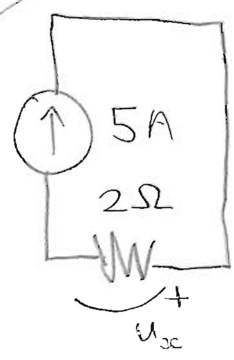


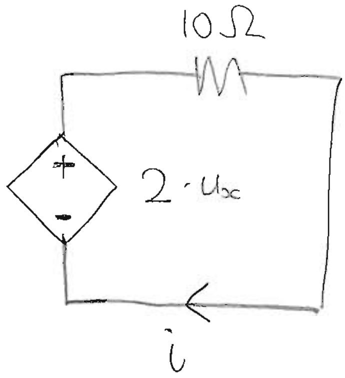
shape shows it is dependent

markings show it is a voltage source

this proportionality constant (scale factor) is the component's value

this voltage u_x should be marked somewhere in the circuit; it is the "controlling variable" of the source





find i

In this case the VCVS behaves as a voltage source of $2 \cdot u_x$.

We see the marked definition of u_x, which by KVL + Ohm tells us

$$u_x = 5A \cdot 2\Omega = 10V$$

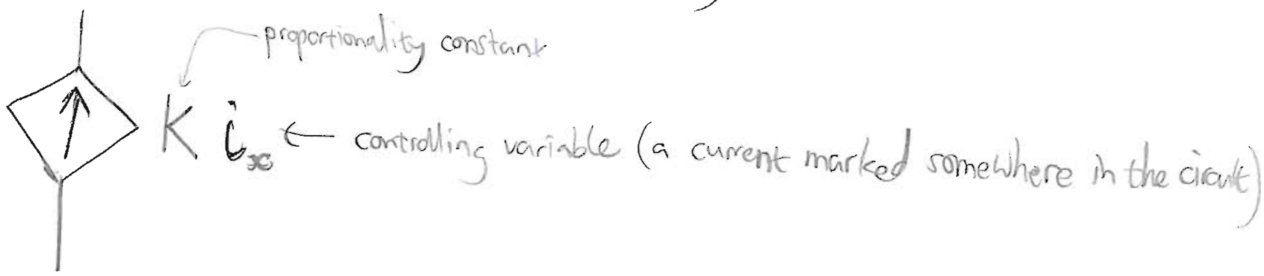
Therefore,

$$i = \frac{2 \cdot 10V}{10\Omega} = 2A$$

There are 4 dependent sources.

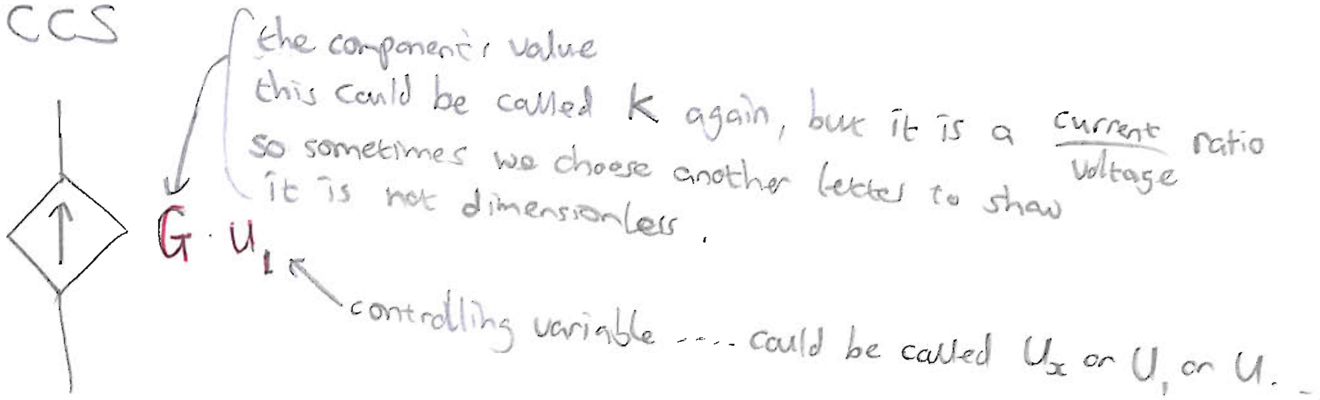
We've seen the VCVS.

The current controlled current source (CCCS) is:

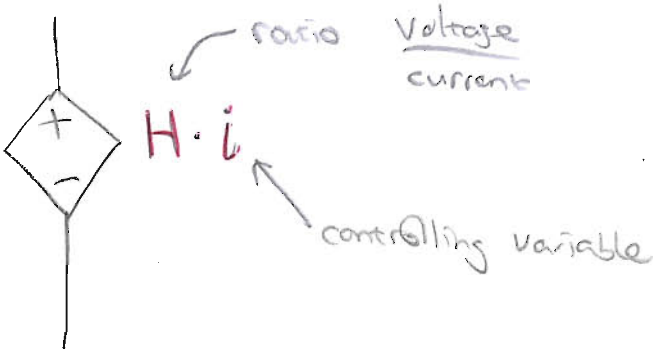


The others can be guessed:

VCCS



CCVS

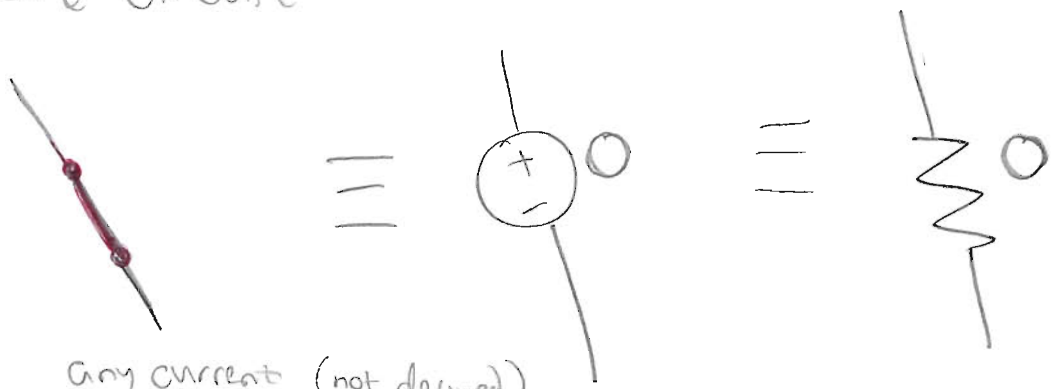


Strange things (dependent sources)?

They're used a lot to make models of transistors and electronic circuits — useful in later courses.

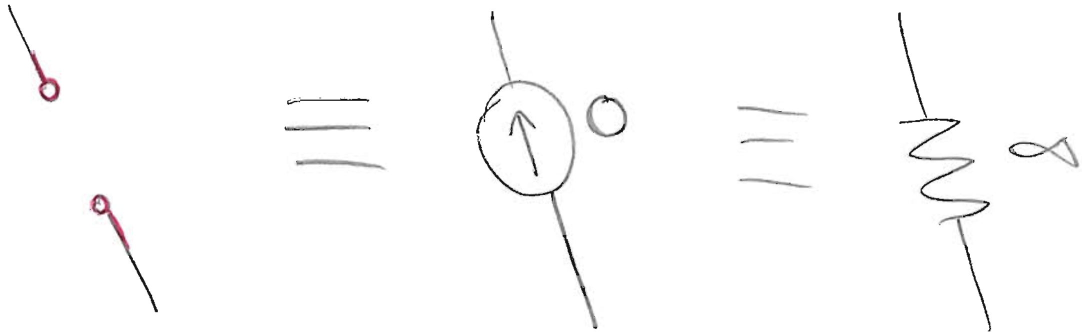
Other components/concepts

short circuit



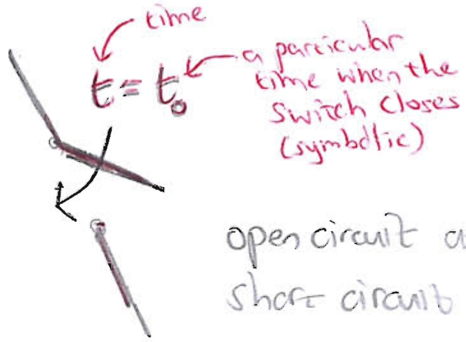
any current (not defined)
no voltage

open circuit



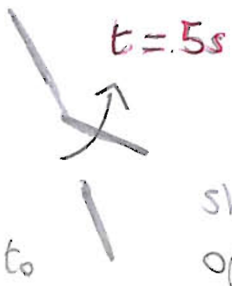
any voltage (not defined)
no current

Switch with time



open circuit at $t < t_0$
short circuit at $t \geq t_0$

closing switch

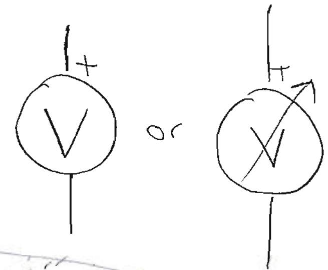


short circuit at $t < 5s$
open circuit at $t \geq 5s$

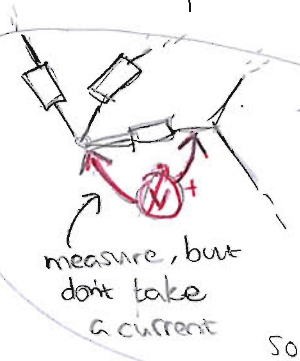
opening switch

Meters for measuring circuit quantities.

VOLTMETER

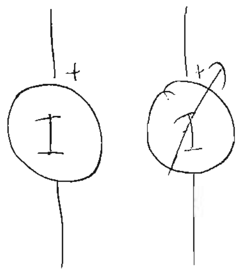


- show the voltage of its '+' terminal relative to the other
- should look like open circuit in how the circuit 'sees' it

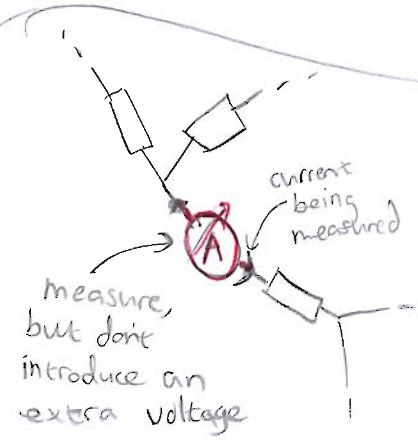


To measure a voltage, the meter is connected between two potentials, ie two nodes. If the meter does not behave like open circuit some current may flow between the nodes --- so we have changed the circuit --- not good.

AMMETER



- show the current passing through from '+' terminal to the other.
- should look like short circuit



To measure a current, the circuit is broken and the ammeter is inserted to join the break — the current flows through it.

If it does not behave as a short circuit, some voltage can exist across the meter. Then were measuring on a different circuit from the one we were trying to measure! The result could be unacceptably wrong.

Real meters are not ideal, but should be chosen "good enough"

voltmeter $R_{meter} \neq \infty$ (← ideal) & ammeter $R_{meter} \neq 0$ (← ideal)

but $R_{meter} \gg R_{circuit}$ but $R_{meter} \ll R_{circuit}$

Other meters --- just for background knowledge

Ohm meter — measure resistance by making a current or a voltage, measuring the other quantity, then dividing $\frac{V}{I} = R$

Common in labs

multimeter — combines a { voltmeter, ammeter, ohmmeter }

widely used

power meter — measure voltage and current : multiply them

energy meter — integrate power over time

like the electricity meter in a home : kWh (kilowatt timmar)

Charge meter or electrometer — useful in some laboratories : mainly "electrostatics"