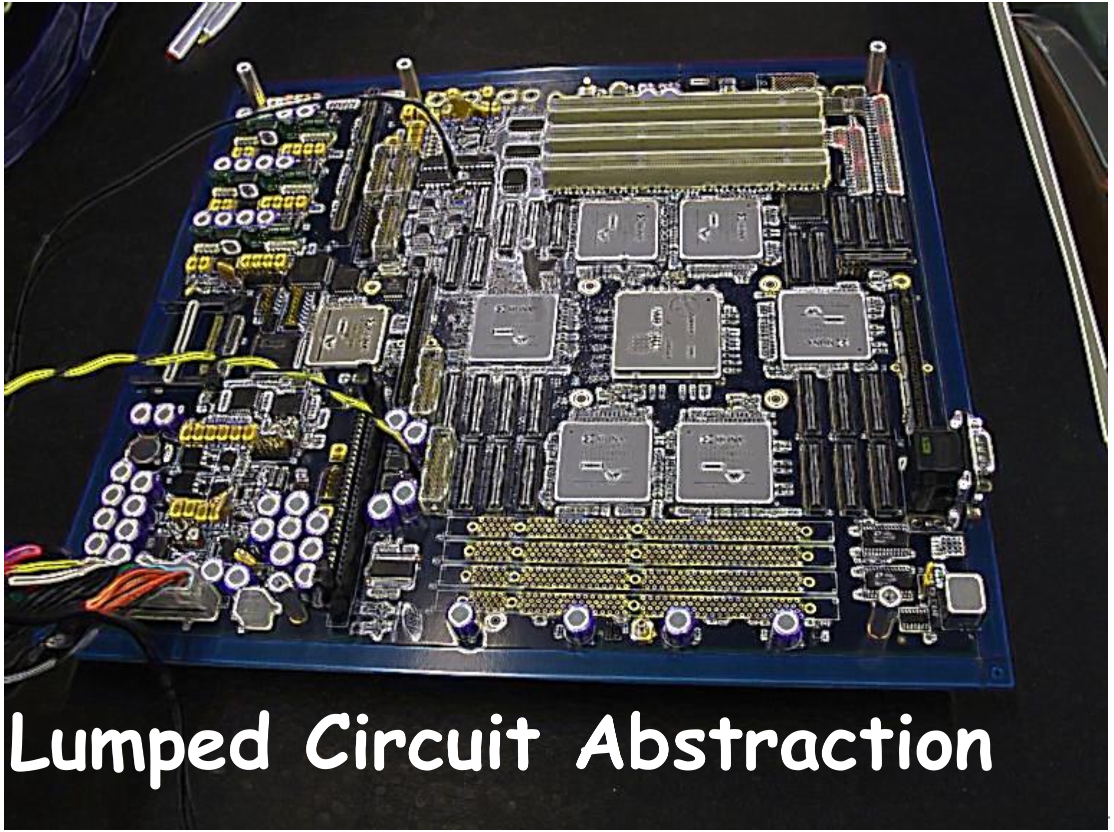
6.002x CIRCUITS AND ELECTRONICS

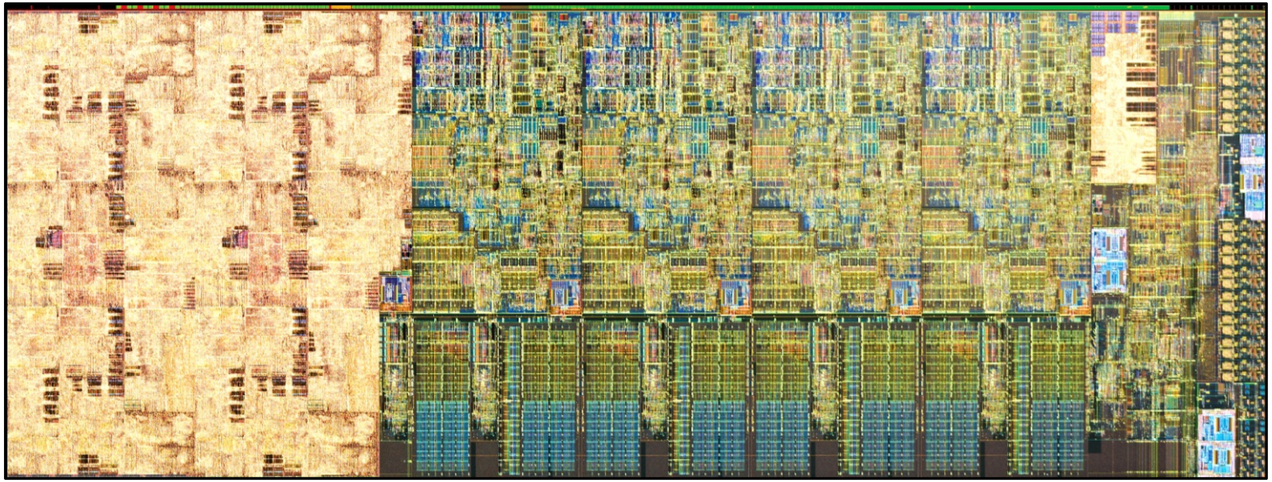


Introduction and Lumped Circuit Abstraction

6.002x is Exciting!

What's behind this?

…and this



Chip photo of Intel's 22nm multicore processor codenamed Ivy Bridge

Photograph courtesy of Intel Corp.

ADMINISTRIVIA

- Prerequisites
  - AP level course on electricity and magnetism; e.g., MIT's 8.02 (check it out on MIT OpenCourseware)
  - It is also useful to have a basic knowledge of solving simple differential equations
- Textbook Agarwal and Lang (A&L)
  Underlined readings (in course-at-a-glance handout) are very important as they stress intuition
- Weekly homeworks and labs must be completed by the deadline indicated on the assignment
- Assessments
  Homeworks 15%
  Labs 15%
  1 Midterm 30%
  Final exam 40%

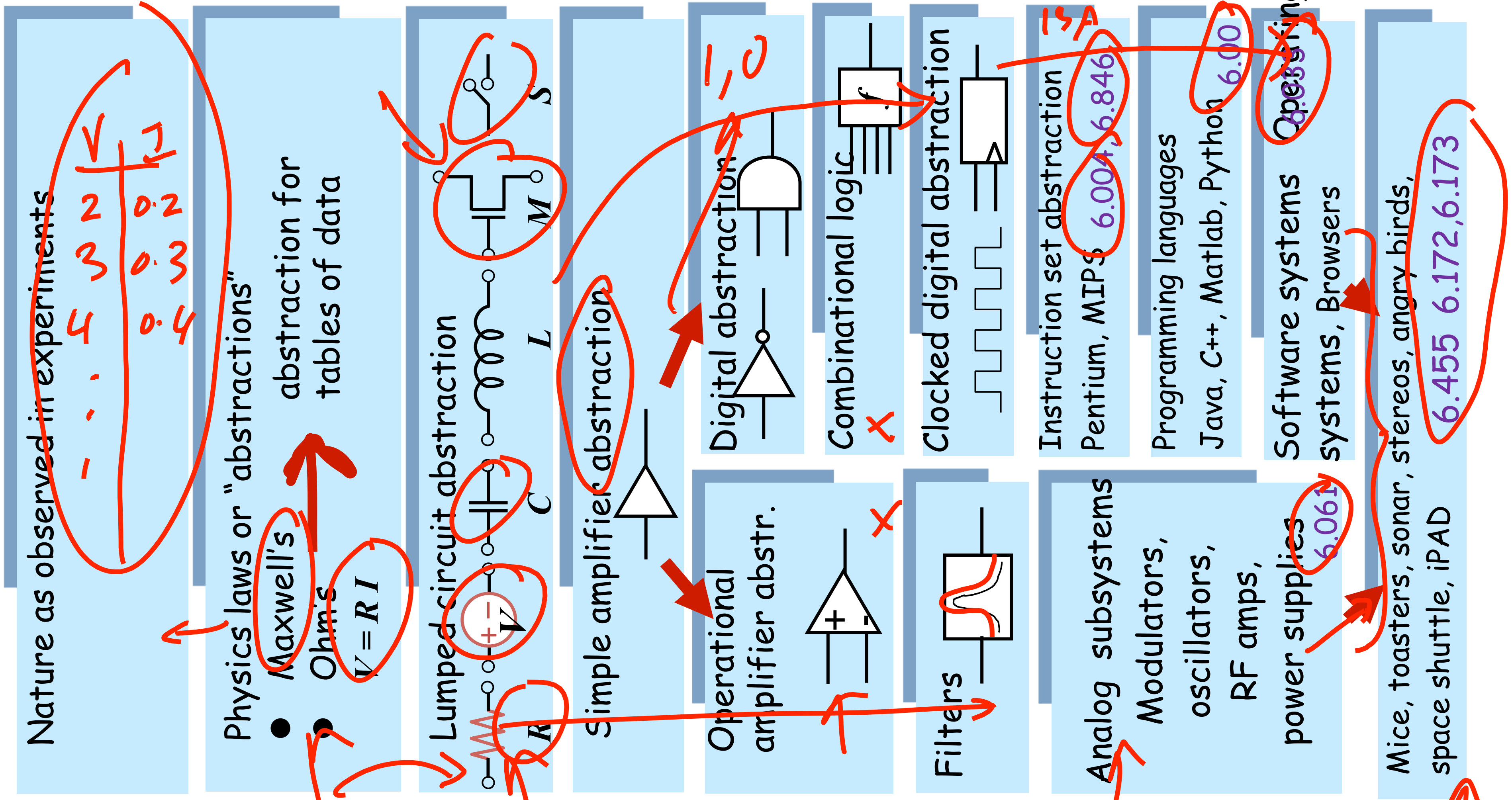
What is engineering?

Purposeful use of science

What is 6.002x about?

Gainful employment of Maxwell's equations

From electrons to digital gates and op-amps

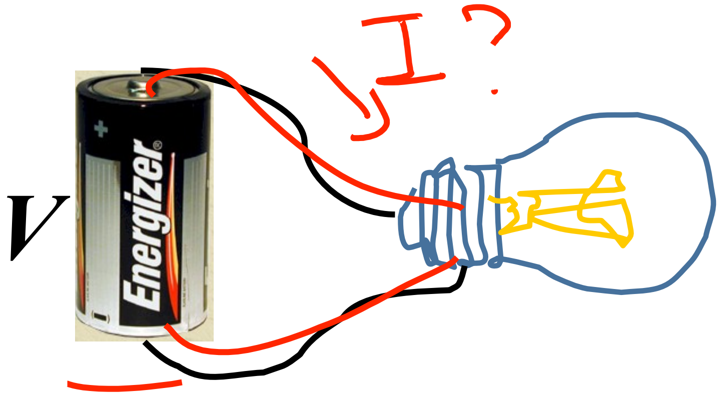


Nature as observed in experiments
V I
2 0.2
3 0.3
4 0.4
Physics laws or "abstractions"
• Maxwell's
• Ohm's $V = R I$
abstraction for tables of data
Lumped circuit abstraction
S
M
L
C
V
R
Simple amplifier abstraction
Digital abstraction
1, 0
Combinational logic
f
Clocked digital abstraction
ISA
Instruction set abstraction
Pentium, MIPS
6.004, 6.846
Programming languages
Java, C++, Matlab, Python
6.00
Software systems
Operating systems, Browsers
6.033
Mice, toasters, sonar, stereos, angry birds, space shuttle, iPAD
6.455 6.172, 6.173
Operational amplifier abstr.
Filters
Analog subsystems
Modulators, oscillators, RF amps, power supplies
6.061

6.002x

Lumped Element Abstraction

Consider



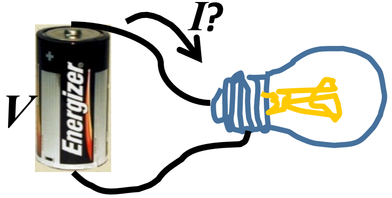
The Big Jump from physics to EECS

Suppose we wish to answer this question:

What is the current through the bulb?

Reading: Skim through Chapter 1 of A&L

We could do it the Hard Way…



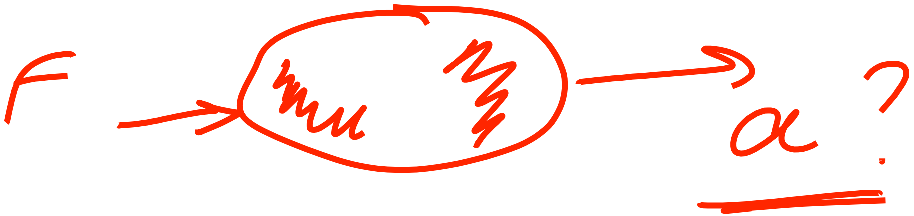
Apply Maxwell's

	Differential form	Integral form
Faraday's	$\nabla \times E = -\frac{\partial B}{\partial t}$	$\oint E \cdot dl = -\frac{\partial \phi_B}{\partial t}$
Continuity	$\nabla \cdot J = -\frac{\partial \rho}{\partial t}$	$\oint J \cdot dS = -\frac{\partial q}{\partial t}$
Others	$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$	$\oint E \cdot dS = \frac{q}{\varepsilon_0}$
	$\vdots$	$\vdots$

Instead, there is an Easy Way…

First, let us build some insight:

Analogy



I ask you: What is the acceleration?

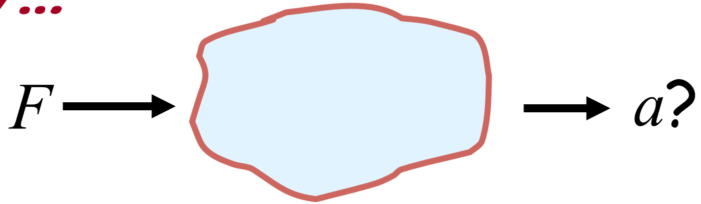
You quickly ask me: What is the mass? m

I tell you: m

You respond: $a = \frac{f}{m}$

Done !!!

Instead, there is an Easy Way...



In doing so, you ignored

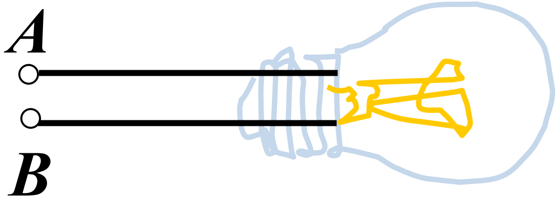
- the object's shape
- its temperature
- its color
- point of force application
- ...

m

→ Point-mass discretization

The Easy Way...

Consider the filament of the light bulb.



I ?

We do not care about

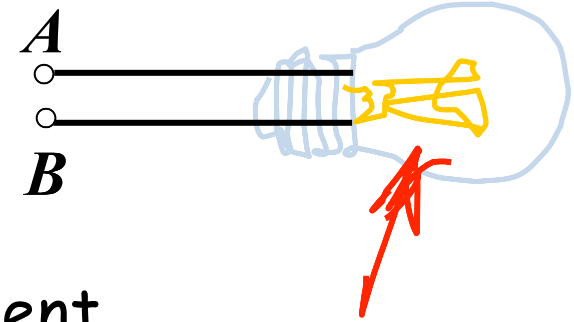
- how current flows inside the filament
- its temperature, shape, orientation, etc.

We can replace the bulb with a

discrete resistor

for the purpose of calculating the current.

The Easy Way…



Replace the bulb with a
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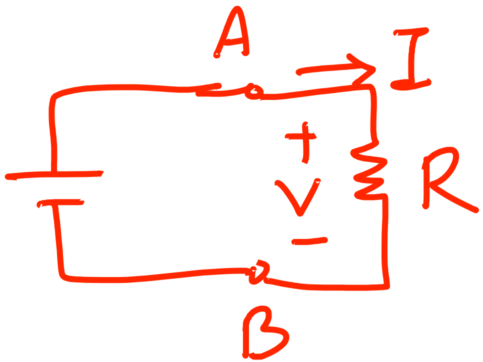
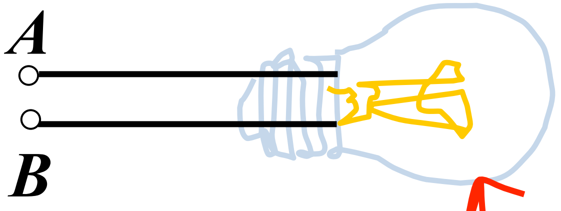
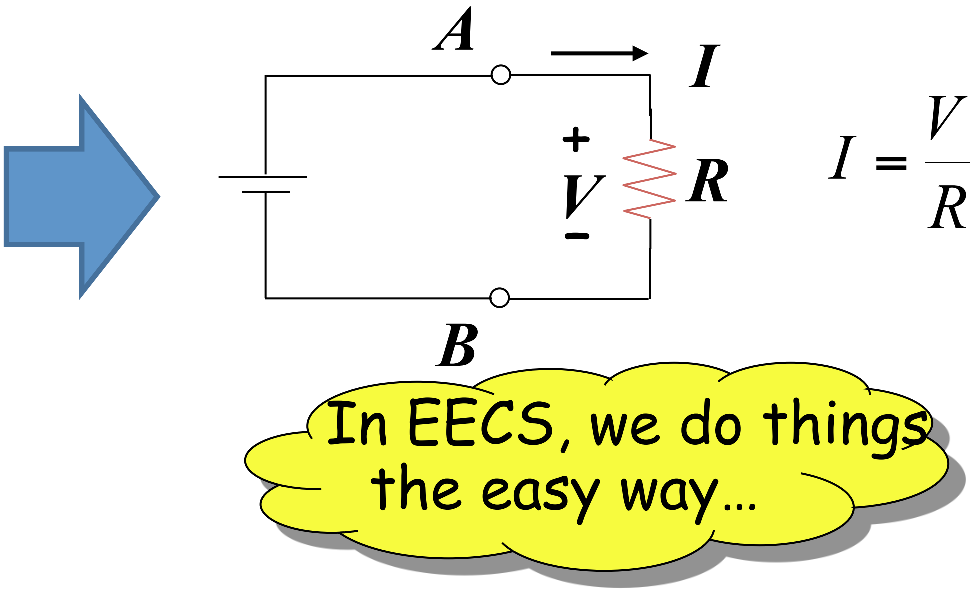


$$I = \frac{V}{R}$$

The Easy Way...



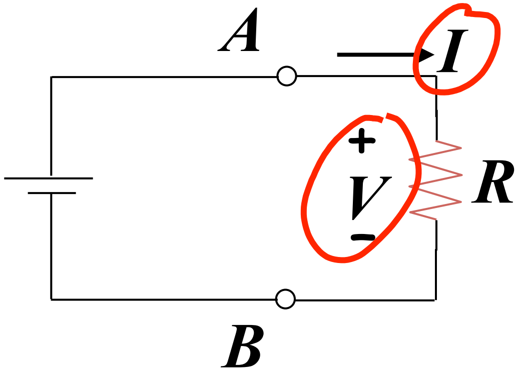


R represents the only property of interest!

Like with point-mass:

replace objects with their mass m to find $a = \frac{F}{m}$

V-I Relationship



and $I = \dfrac{V}{R}$

R represents the only property of interest!

R relates element V and I

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

$$I = \frac{V}{R}$$ called element v-i relationship

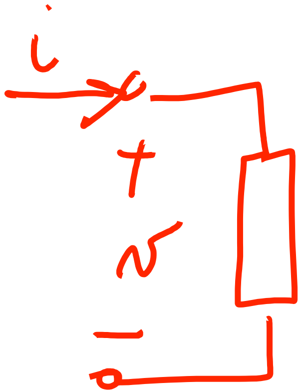
int f(- -)

f()

int

R is a lumped element abstraction for the bulb.

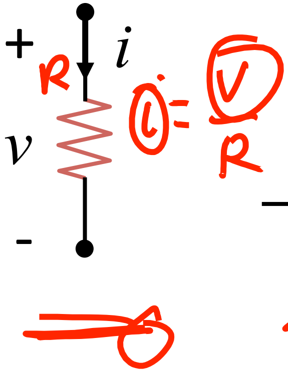
Lumped Elements

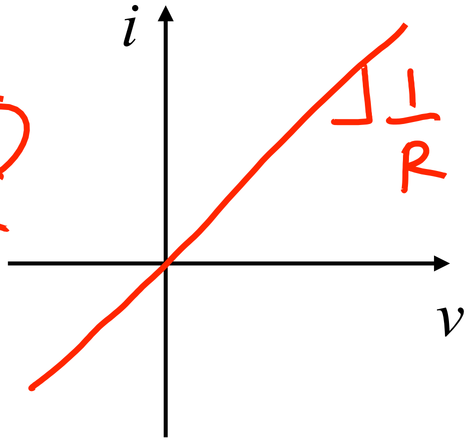


Lumped circuit element described by its vi relation

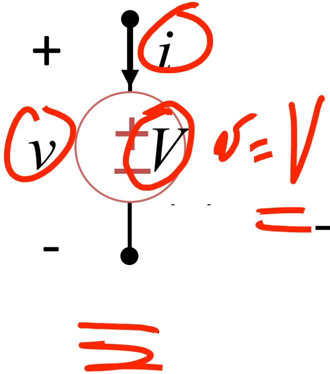
$\boxed{\text{Power consumed by element} = vi}$

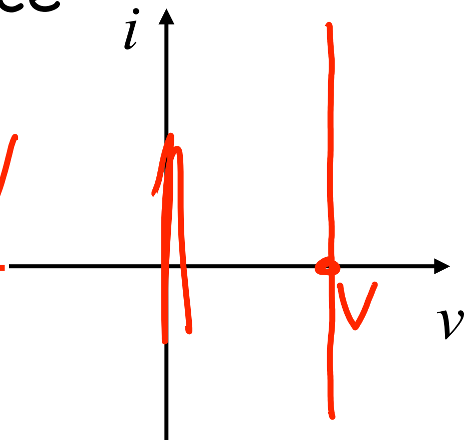
Resistor





Voltage source





Demo → Lumped element examples whose behavior is completely captured by their V–I relationship.

only for the sorts of questions we as EEs would like to ask!

Demo →

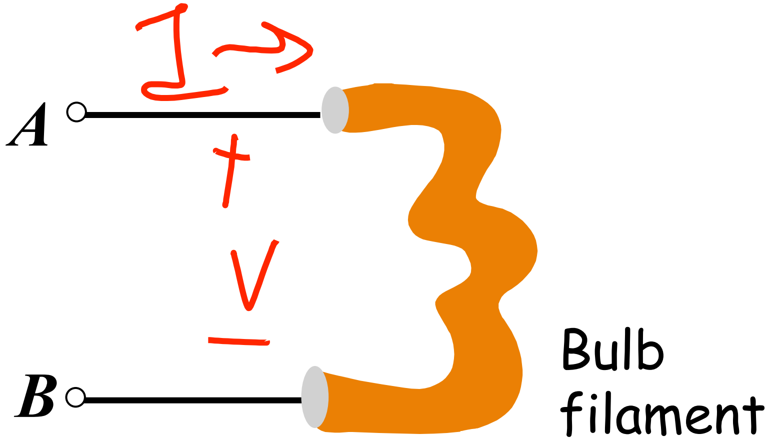
Exploding resistor demo

→ can't predict that!

Pickle demo

→ can't predict light, smell

Not so fast, though ...

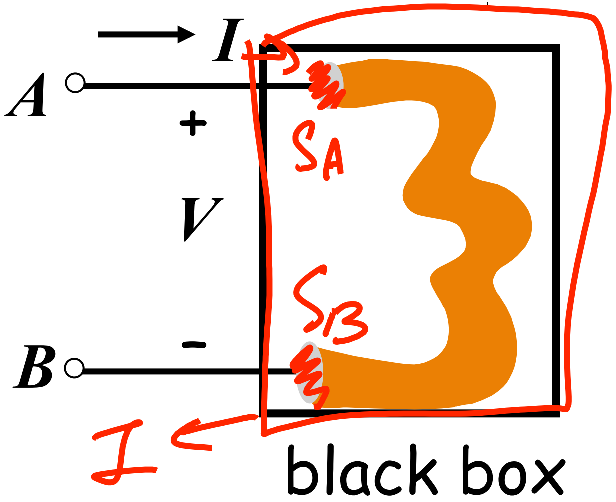


Although we will take the easy way using lumped abstractions for the rest of this course, we must make sure (at least for the first time) that our abstraction is reasonable.

In this case, ensuring that $\boxed{V}$ $\boxed{I}$ are defined for the element

$\boxed{I}$ must be defined.

I into S_A = I out of S_B



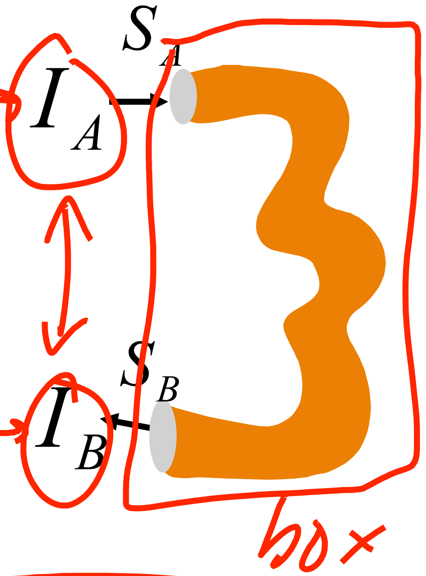
$\boxed{I}$ must be defined. True when

I into S_A = I out of S_B

True only when $\dfrac{\partial q}{\partial t} = 0$ in the filament!

$\int_{S_A} J \cdot ds \rightarrow I_A$

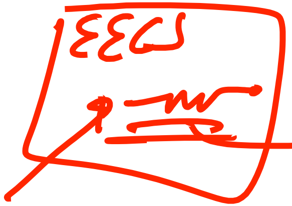
$\int_{S_B} J \cdot ds \rightarrow I_B$



from Maxwell

$\underbrace{\int_{S_A} J \cdot ds}_{I_A} - \underbrace{\int_{S_B} J \cdot ds}_{I_B} = \dfrac{\partial q}{\partial t}$

$I_A = I_B$ only if $\dfrac{\partial q}{\partial t} = 0 \rightarrow 0$

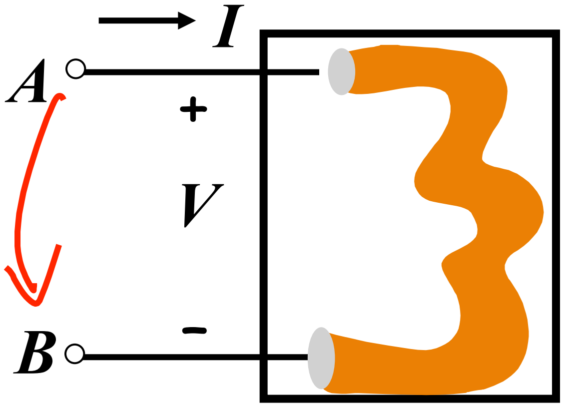


$\dfrac{\partial q}{\partial t} = 0$

So, are we stuck?

We're engineers! So, let's make it true!

$\boxed{V}$ Must also be defined.



V_{AB} defined $\frac{\partial \phi_B}{\partial t}$

V_{AB} defined when $\frac{\partial \phi_B}{\partial t} = 0$

So $V_{AB} = \int_{AB} E \cdot dl$ outside elements

So $V_{AB} = \int E \cdot dl$ outside elements

① $\frac{\partial q}{\partial t} = 0$

see
A & L Appendix A.3

So let's assume this too!

② $\frac{\partial \phi_B}{\partial t} = 0$

③

Also, signal speeds of interest should be way lower than speed of light

Welcome to the EECS Playground

The world

The EECS playground

Our self imposed constraints in this playground

$$\frac{\partial \phi_B}{\partial t} = 0$$ Outside

$$\frac{\partial q}{\partial t} = 0$$ Inside elements

Bulb, wire, battery

Where good things happen

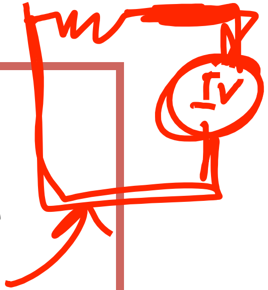
Lumped Matter Discipline (LMD)

Or self imposed constraints:

- $\dfrac{\partial \phi_B}{\partial t} = 0$ outside
- $\dfrac{\partial q}{\partial t} = 0$ inside elements
  bulb, wire, battery

More in Chapter 1 of A & L

Connecting using ideal wires lumped elements that obey LMD to form an assembly results in the lumped circuit abstraction

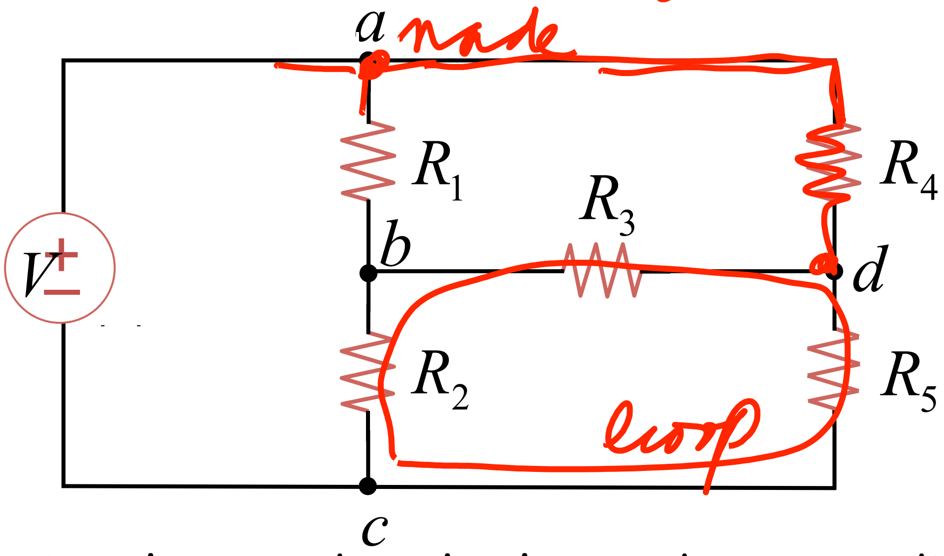


So, what does LMD buy us?

Replace the differential equations with simple algebra using lumped circuit abstraction (LCA).

$2a + 3b = 0 \cdots$

For example:



What can we say about voltages in a loop under the lumped matter discipline?

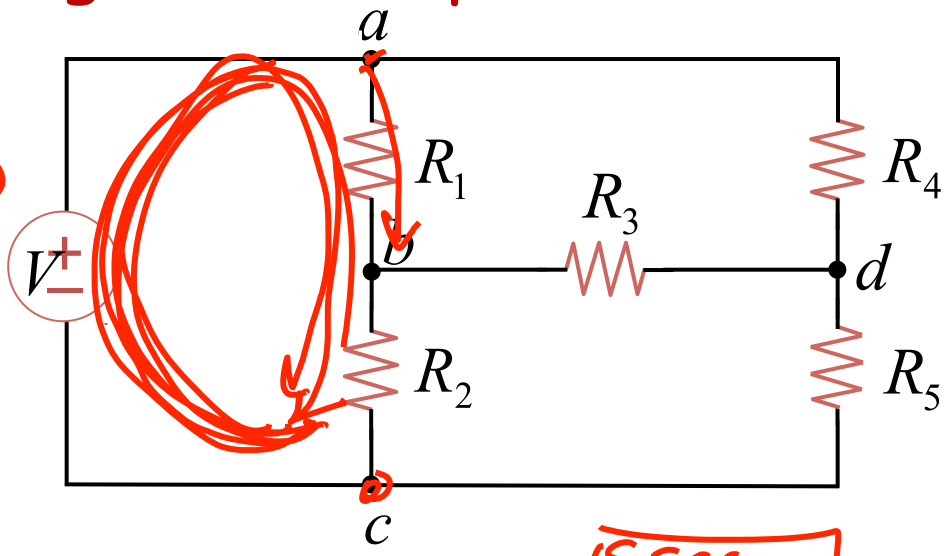
Reading: Chapter 2.1 – 2.2.2 of A&L

What can we say about voltages in a loop under LMD?

$$\oint E \cdot dl = -\frac{\partial \Phi_B}{\partial t} \xrightarrow{\text{LMD}} 0$$

$$\Rightarrow \int_{ca} E \cdot dl + \int_{ab} E \cdot dl + \int_{bc} E \cdot dl = 0$$

$$\rightarrow V_{ca} + V_{ab} + V_{bc} = 0$$



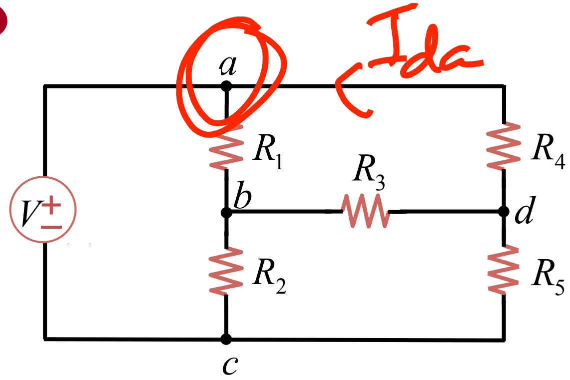
EECS

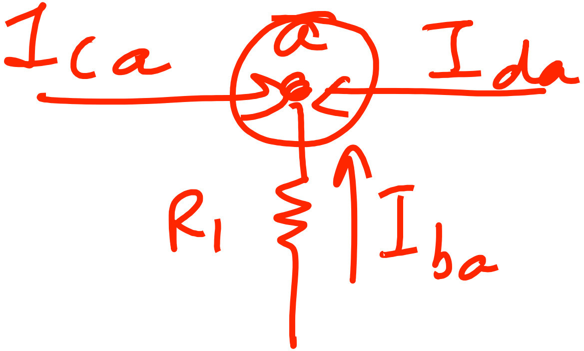
Kirchhoff's Voltage Law (KVL):

The sum of the voltages in a loop is 0.

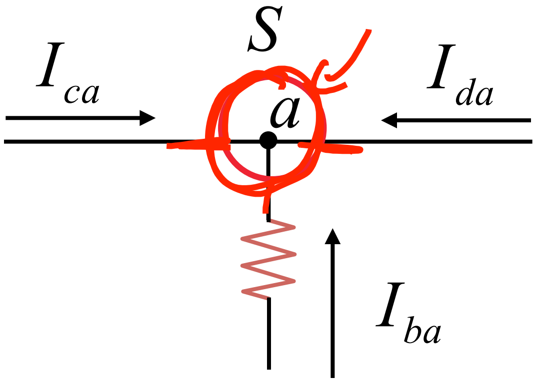
Remember, this is not true everywhere, only in our EECS playground

What can we say about currents?





What can we say about currents?



$$\oint_S J \cdot ds = \cancel{-\frac{\partial q}{\partial t}} \rightarrow 0 \quad \text{CMD!}$$

$$\Rightarrow I_{ca} + I_{da} + I_{ba} = 0$$

Kirchhoff's Current Law (KCL):

The sum of the currents into a node is 0.

simply conservation of charge

KVL and KCL Summary

KVL:

$$\sum_{j}^{\text{loop}} v_j = 0$$

KCL:

$$\sum_{i}^{\text{node}} i_i = 0$$

Summary

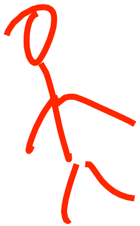
Lumped Matter Discipline LMD:

Constraints we impose on ourselves to simplify our analysis

$$\frac{\partial \phi_B}{\partial t} = 0$$ Outside elements

$$\frac{\partial q}{\partial t} = 0$$ Inside elements

wires resistors sources

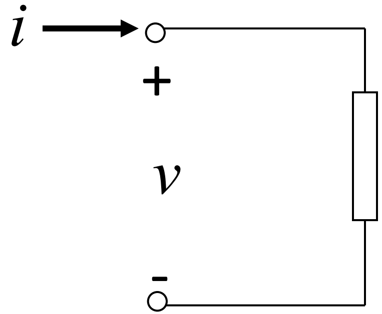


Also, signals speeds of interest should be way lower than speed of light

Allows us to create the lumped circuit abstraction

Remember, our EECS playground

Summary



Lumped circuit element

$i = f(v)$

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

$i = 6.7v^2 + \frac{v}{2} + 1$

power consumed by element = vi

Summary

Maxwell's equations simplify to algebraic KVL and KCL under LMD.

KVL:

$$\sum_j v_j = 0$$

loop

This is amazing!

KCL:

$$\sum_j i_j = 0$$

node