Capacitors
What are they?
How do they work?

Let’s begin with the definition of a capacitor

What is a capacitor?

Why were capacitors called “condensers” in the old days

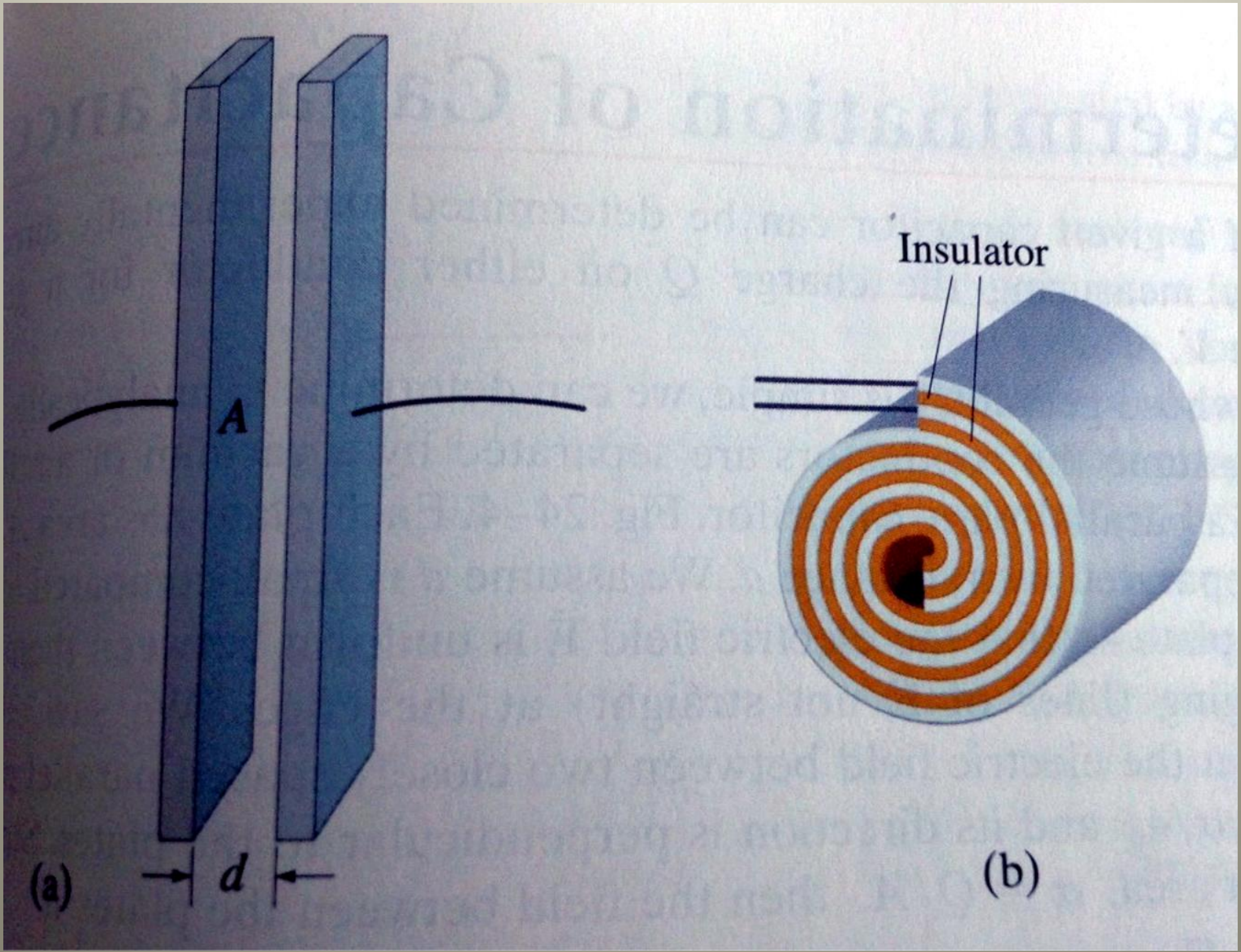
A capacitor is any device which can store energy in an electric field

Model of a Capacitor

Capacitors are often represented (modeled) as two parallel conducting "plates" separated by an insulator or dielectric.

The dielectric can be a vacuum, air, or other non-conductor (mica, glass, oil, etc.)

Capacitors have a plate area A and a plate separation d
Capacitors are often "rolled up" into a cylinder



Capacitance

The capacitance (C) of a capacitor is directly proportional to the area (A) of the plates

inversely proportional to the separation (d) between its plates

C proportional to (A / d)

Units of Capacitance

The "capacitance" of any capacitor is a RATIO of the amount of charge (Q) on one of its plates divided by the voltage (V) across its plates

C = Q / V (charge per volt)

where C is in units "farads"
Q in in units "coulombs"
V is in units "volts"

1 farad = 1 coulomb per 1 volt

Capacitance

I've heard some hams describe capacitance as

"the amount of charge a capacitor can hold"

Is that a good definition?

What exactly is meant by "hold" ?

Capacitance: a simple view

You can think of capacitance as the amount of charge (**Q**) required on each plate in order to raise the potential difference (**V**) across the plates to **1 volt**

C = Q per one volt

Question

Capacitor **A** has a charge of
3 microcoulombs and a voltage of 3 volts

Capacitor **B** has a charge of
6 microcoulombs and a voltage of 6 volts

Which capacitor has the greater value of capacitance?

SAME

Since $C = Q / V$

C = 3 microcoulombs / 3 volts

= 1 microfarad

C = 6 microcoulombs / 6 volts

= 1 microfarad

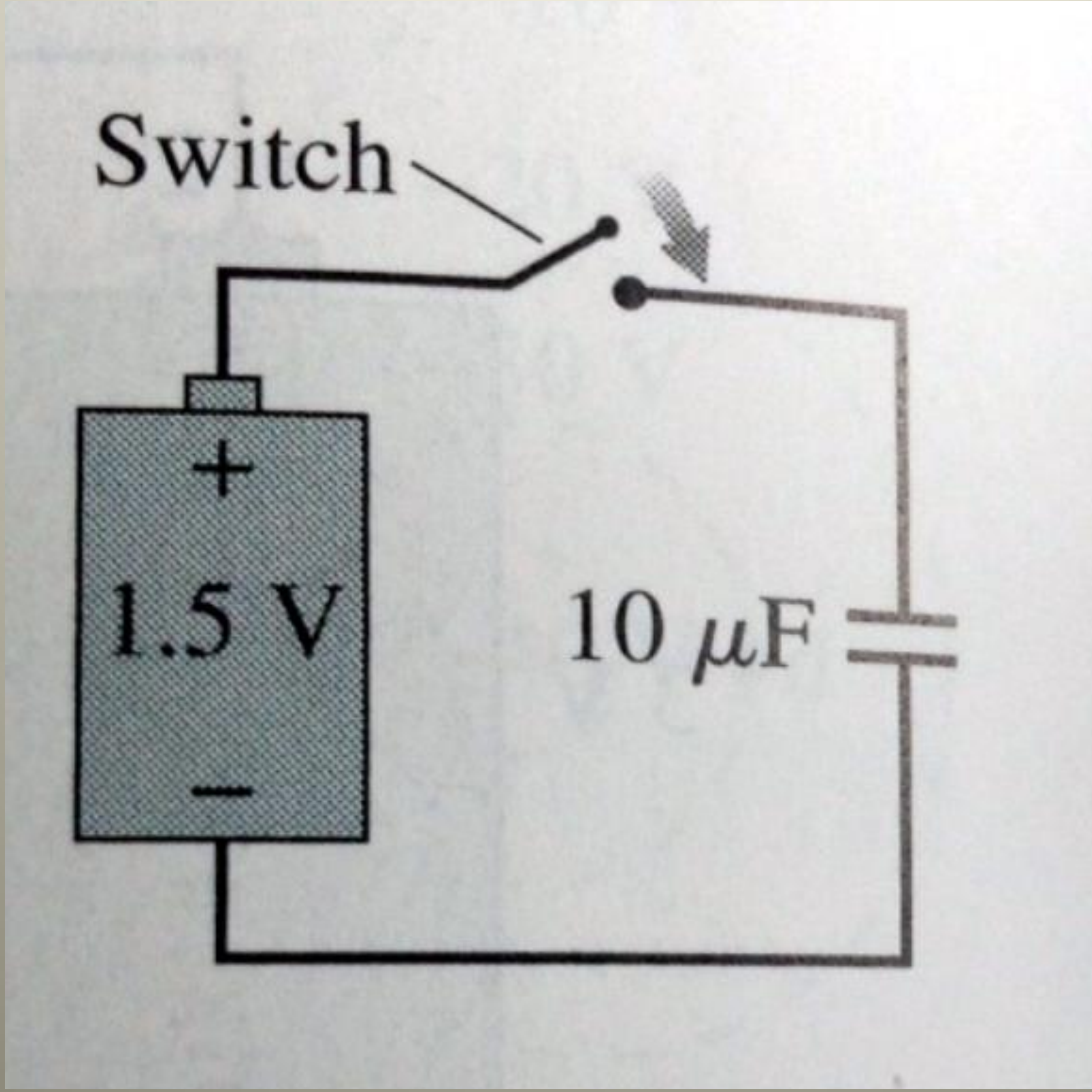
Since $C = Q / V$

the CHARGE on either plate of a capacitor (Q) is proportional to the product of the capacitance and the voltage:

$$Q = C\ V$$

Q in coulombs, C in farads, V in volts

How much charge Q is transferred from one plate of the capacitor to the other plate?



answer

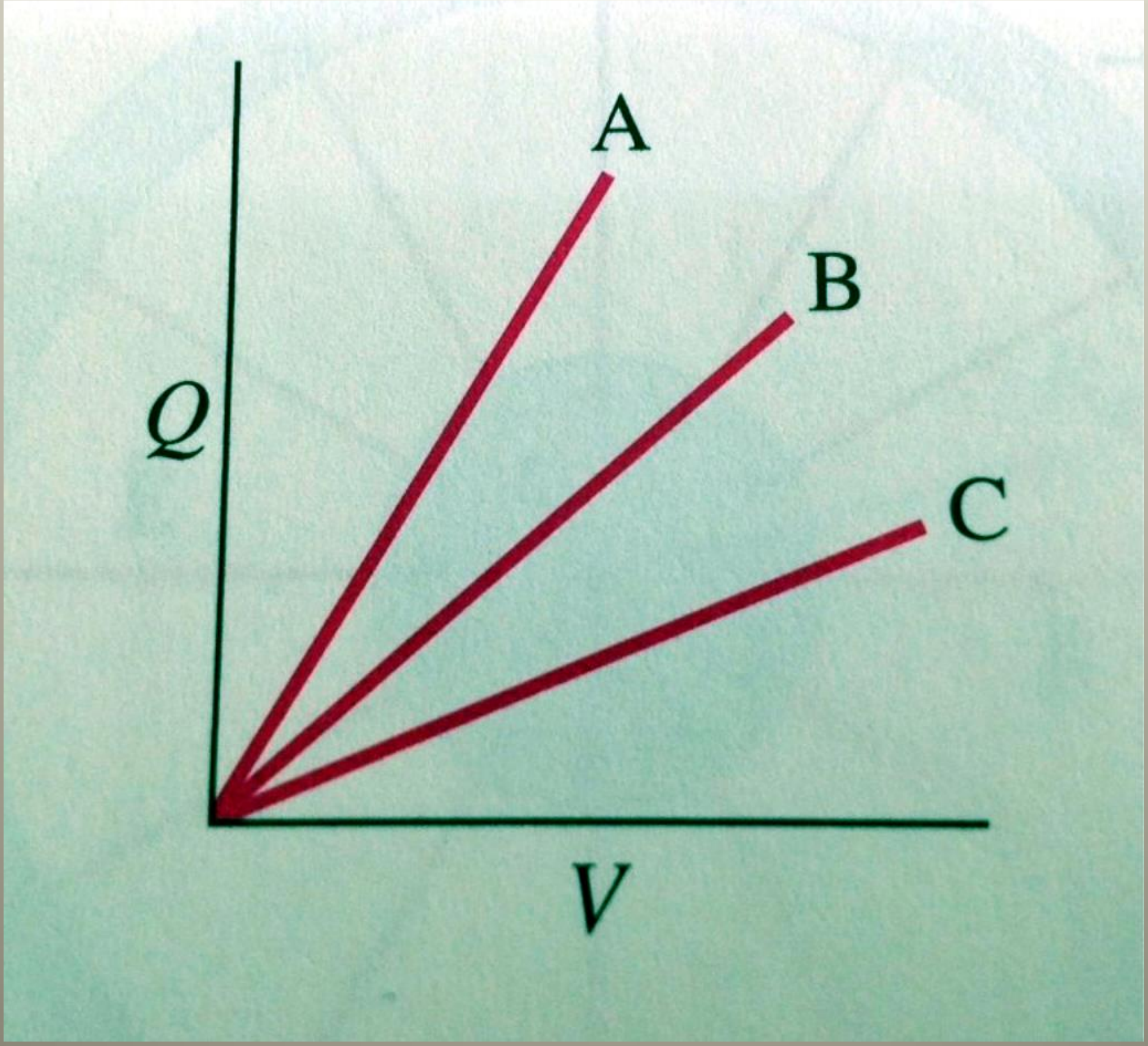
$$C = Q / V$$ definition of capacitance

$$Q = C \quad V$$

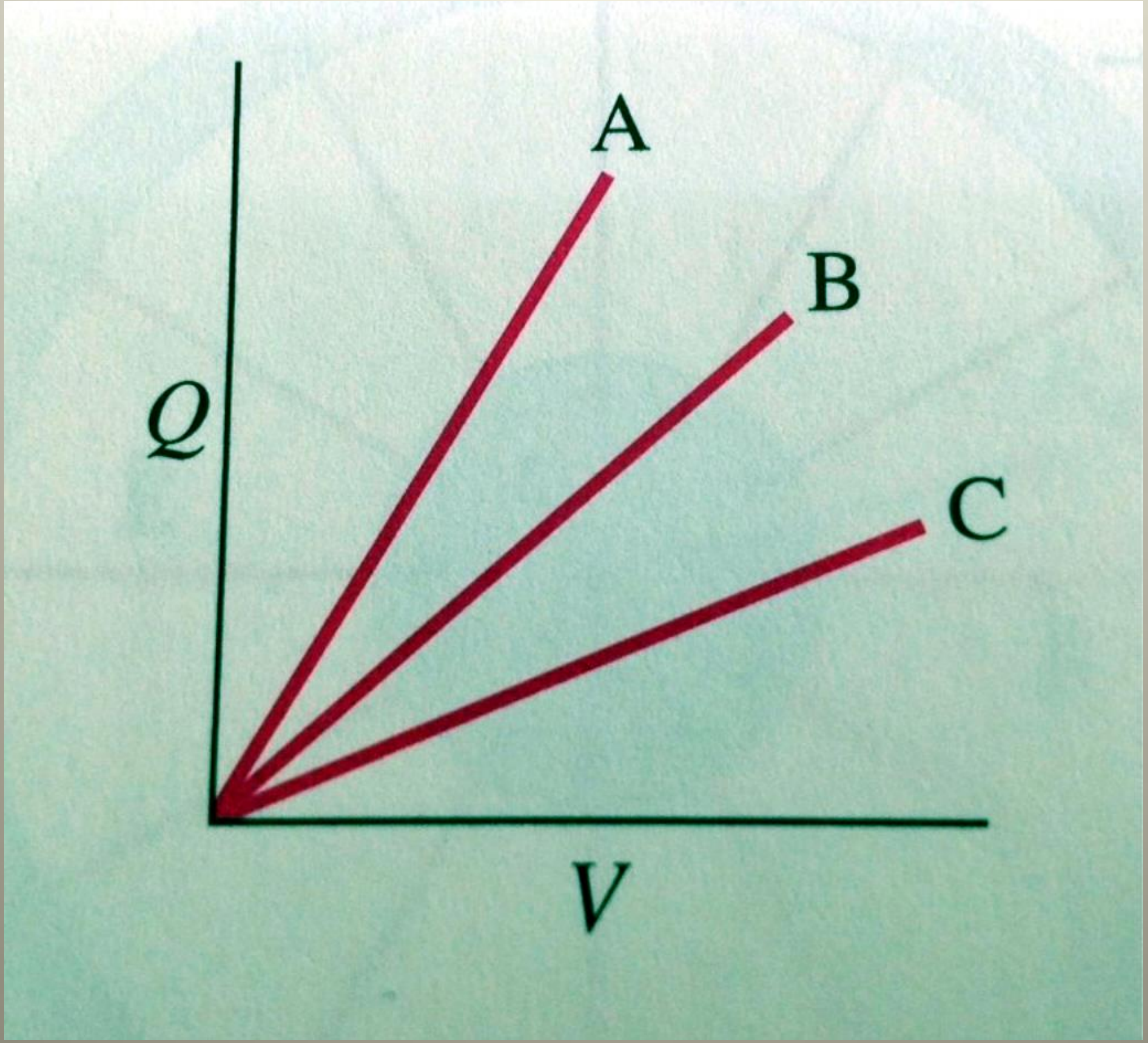
$$Q = 10 \text{ microfarad} \times 1.5 \text{ volts}$$

$$Q = 15 \text{ microcoulombs}$$

Which capacitor (A,B,C) has the greatest capacitance?



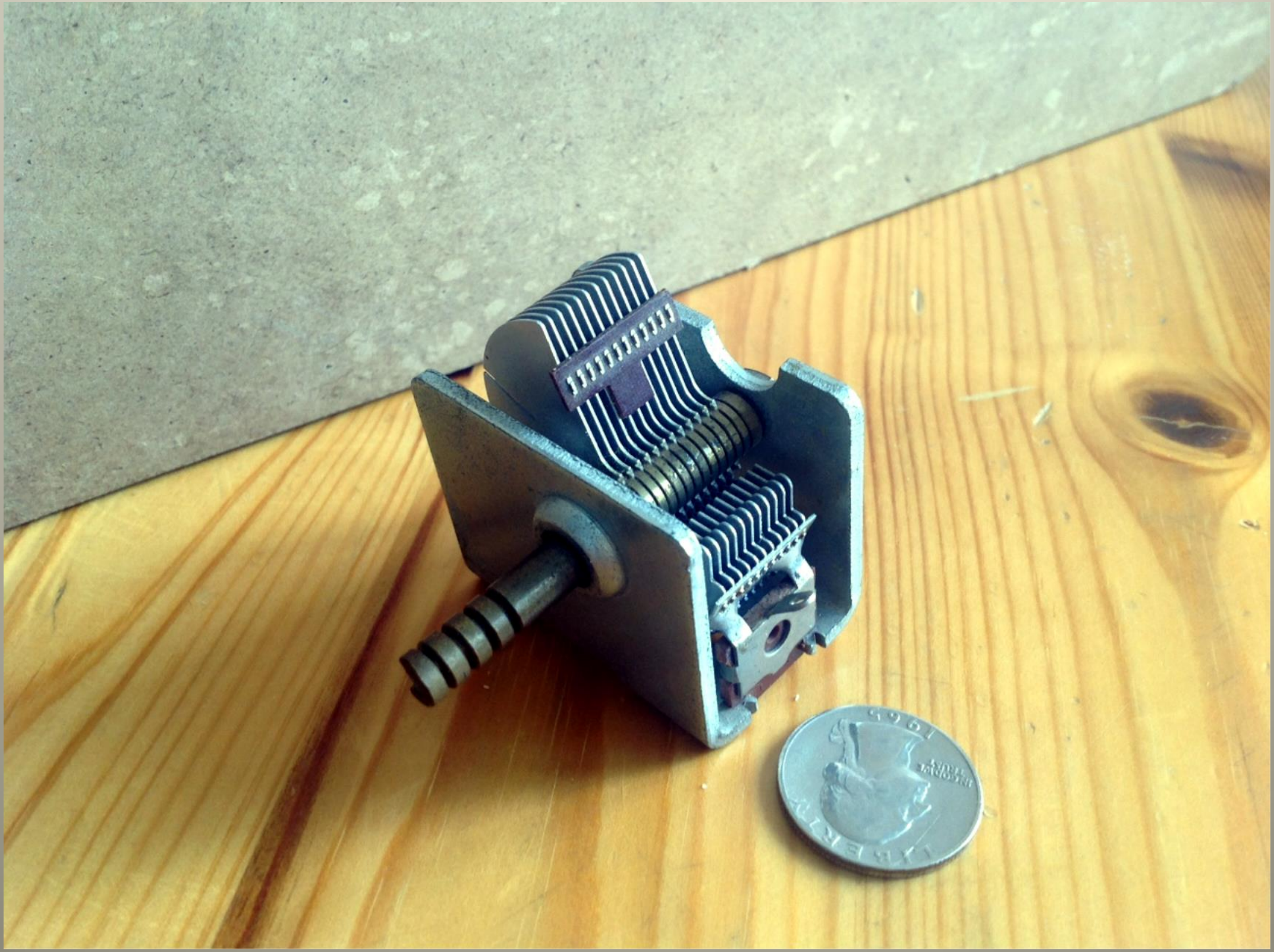
What does the SLOPE of each line represent?



Large Electrolytic Capacitor used in DC power supplies

Small Ceramic Capacitor

Variable Capacitor: 300 pf
(taken from old AM radio)



Energy stored in a Capacitor

Electric Power = current x voltage

(**P**oison **IV**y)

Power = Energy / time

So Energy = Power x Time

Energy = current x voltage x time

current = charge per second (Q/t)

So Energy = charge/sec x voltage x sec

Energy = Q/t x V x t (t cancels)

Energy = charge x voltage

$$E = Q V$$

Derivation of formula for energy stored in a charged capacitor

When you charge a capacitor, the voltage across the capacitor starts at 0 volts initially, and ends at V volts at the end.

V(original) = 0 V(final) = V

What is the **average voltage** during the charging process?

V (average) = (1/2) V

Energy Stored in a Capacitor

The energy stored in a capacitor depends on the capacitance (C) of the capacitor and the **average** charging voltage (1/2) V

$$\text{Energy} = Q\ (1/2\ V)$$

and since $Q = CV$

$$\mathbf{E = (1/2)\ C\ V^2}$$

$$E = (1/2)\, C\, V^2 = (1/2)\,(1/C)\, Q^2$$

The energy stored in a capacitor is directly proportional to the capacitance **C** and

to the **square** of the voltage **V**

to the **square** of the charge **Q**

Question

Capacitors **A** and **B** have the same value of capacitance.

Capacitor **A** is charged to 1 volt
Capacitor **B** is charged to 2 volts

How much more energy is stored in capacitor **B** ?

Energy stored in Capacitor

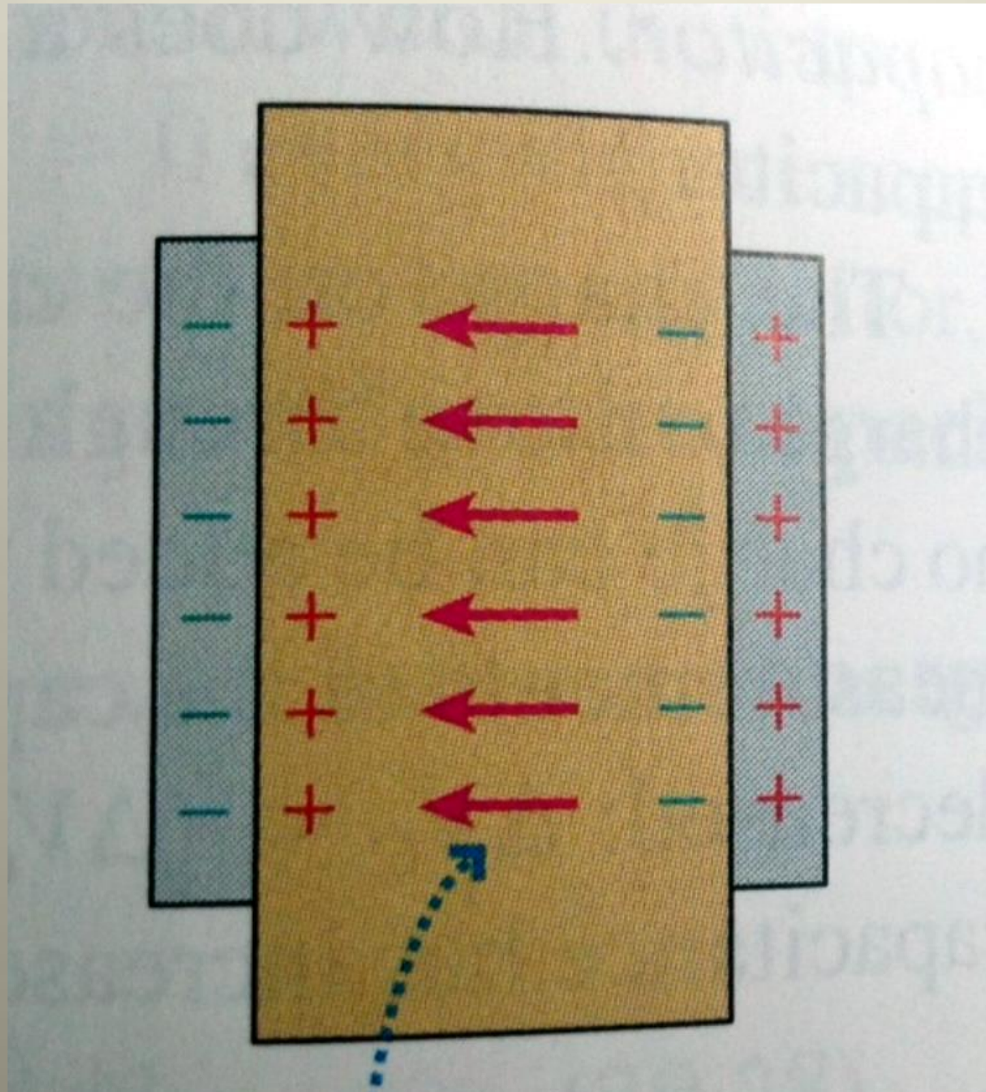
E (cap A) = (1/2) C 1^2 = (1/2) C

E (cap B) = (1/2) C 2^2 = 2 C

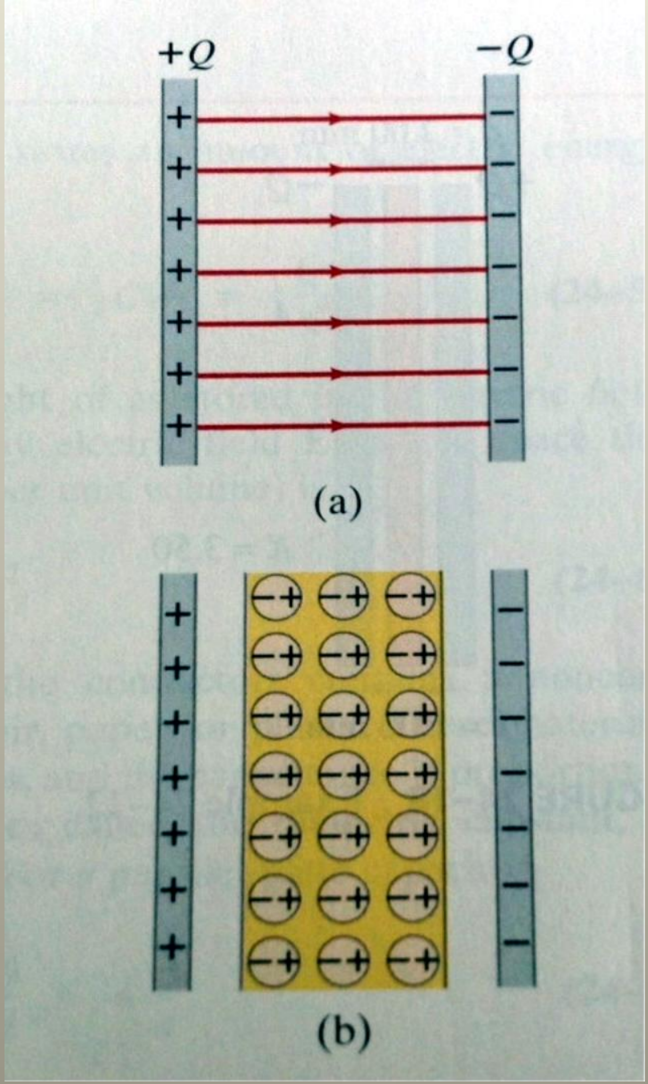
So capacitor B stores **4x** more energy than capacitor A

Twice the voltage ➔ 4 x the energy

What is the purpose of the “dielectric” material between the two plates of the capacitor?



The dielectric DECREASES the electric field between the plates and increases the capacitance, allowing more charge and more energy to be stored at any given charging voltage



Capacitors have an insulator or dielectric between their plates which serves to alter the electric field between the plates and increase the capacitance, thus increasing the stored energy in the electric field

The dielectric “constant” is k
where k = 1 for a vacuum

C proportional to k A / d

Dielectrics commonly used in capacitors

TABLE 24–1
Dielectric Constants (at 20°C)

Material	Dielectric constant K	Dielectric strength (V/m)
Vacuum	1.0000	
Air (1 atm)	1.0006	3×10^6
Paraffin	2.2	10×10^6
Polystyrene	2.6	24×10^6
Vinyl (plastic)	2–4	50×10^6
Paper	3.7	15×10^6
Quartz	4.3	8×10^6
Oil	4	12×10^6
Glass, Pyrex	5	14×10^6
Porcelain	6–8	5×10^6
Mica	7	150×10^6
Water (liquid)	80	
Strontium titanate	300	8×10^6

Capacitors

So large value capacitance capacitors have the following

1) Large plate areas (A)
2) Small separation between plates (d)
3) Large value dielectric constants (k)

Values of Capacitors

Capacitors can have values in the

picofarad range (micro-micro farad) 10^{-12} f

nanofarad range: 10^{-9} farad

microfarad range: 10^{-6} farad

millifarad range: 10^{-3} farad

farad range

Voltage Rating of Capacitor

Capacitors also have a "working voltage" meaning the maximum safe voltage you can apply across the plates.

If exceeded, the capacitor can short out by sparking across the dielectric.

Let’s now look at what happens when an uncharged capacitor is attached to a battery of voltage V

Atoms: a simple model

Atoms consist of charged and uncharged particles.

The positive charges are the protons, locked in the nucleus (they don't move).

The negative charges are the electrons, surrounding the nucleus in various orbits and are easily moved if the atom is a "conductor".

Neutrons, in the nucleus, have no NET charge, and do not move.

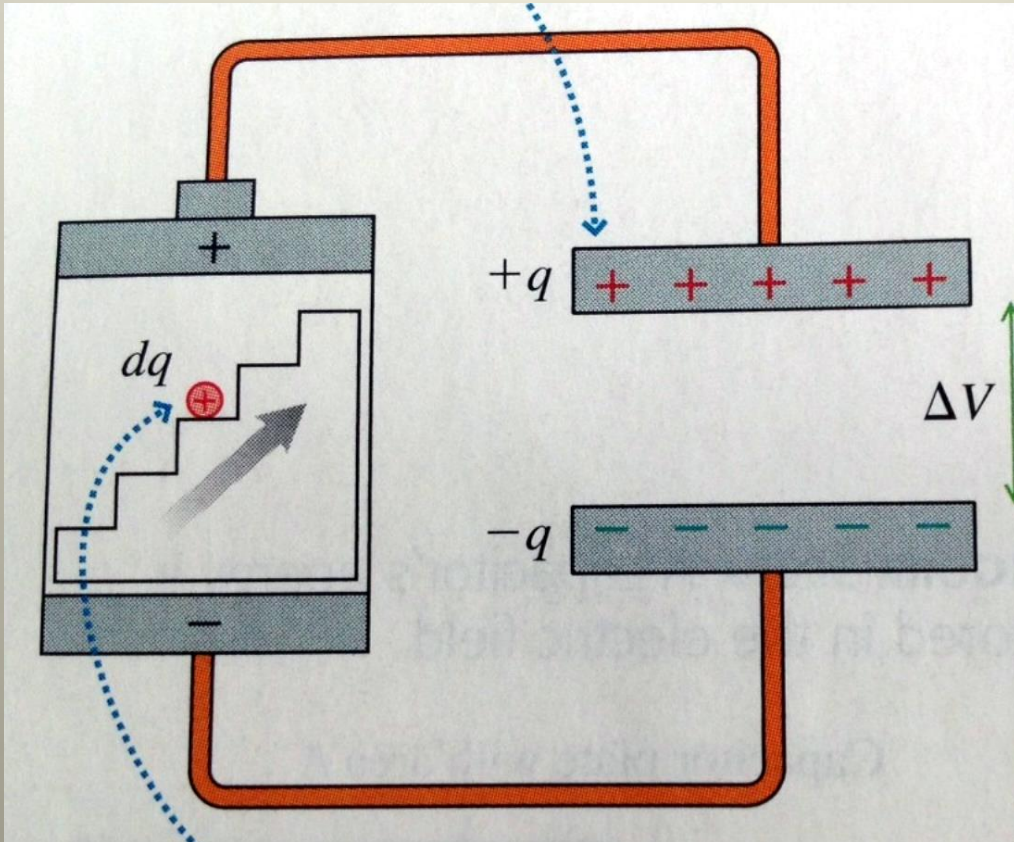
What actually moves?

Most Engineering and Physics textbooks show the moving charges as the **POSITIVE** charges (blame that on Ben Franklin) rather than the motion of the negative electrons.

Positive charges moving one way is mostly equivalent to negative charges moving the other way.

The battery acts like a "charge elevator" moving charges from one plate to the other plate.

Batteries must do WORK to charge the capacitor.



The charge escalator does work $dq\,\Delta V$ to move charge dq from the negative plate to the positive plate.

Misconception

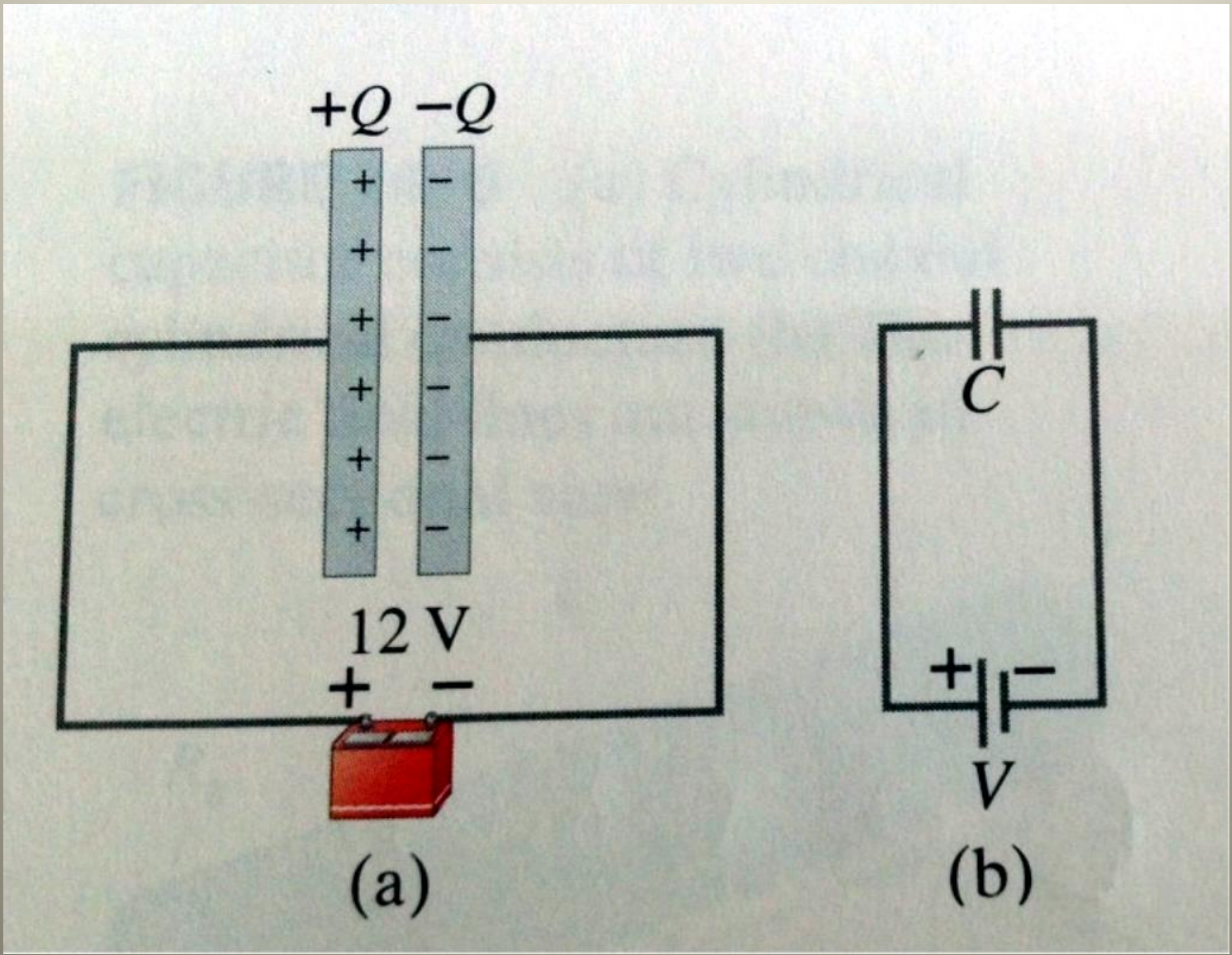
Note: batteries do NOT supply the electrons that charge the capacitor.....

batteries just MOVE the electrons that are already in the wires and capacitor plates from one plate of the capacitor to the other plate of the capacitor.

Batteries supply ENERGY, not electrons!

What happens when a capacitor is connected to a battery?

Why does charge flow on to the plates of the capacitor?



QUESTIONS

In an "**uncharged capacitor**" there are atoms on each of its two plates.

What is the overall "net" charge on any given atom?

What is the overall "net" charge on either plate?

What is the overall "net" charge on the entire capacitor?

Connect a capacitor to a battery and allow it sufficient time to "charge"

What is the "net charge" on a charged capacitor?

Net Charge

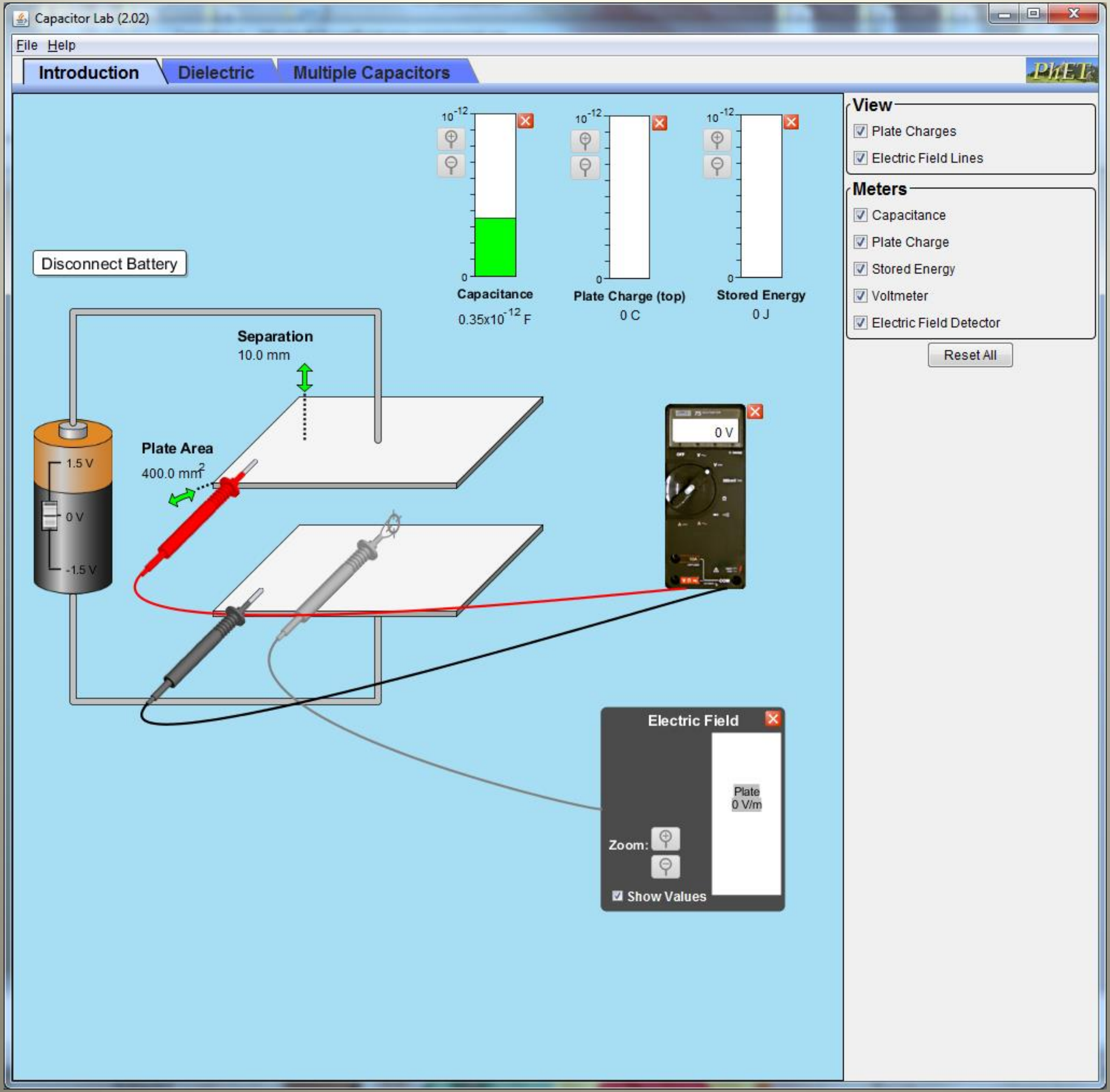
A capacitor "charges" when electrons move from the negative side of the battery to one plate of the capacitor, and other electrons move from the other plate of the capacitor into the positive side of the battery.

note: electrons do not themselves pass through a capacitor.

Let's take a closer look at this with a model of a battery and a capacitor.

We begin with a 1.5 volt battery, a 0.35 pf capacitor, voltmeter, electric field meter, and a switch.

We can measure the charge on any plate, the electric field strength between the plates, the voltage across the plates and the energy stored in the capacitor.



Capacitor Lab (2.02)
File Help
Introduction
Dielectric
Multiple Capacitors
PhET
View
Plate Charges
Electric Field Lines
Meters
Capacitance
Plate Charge
Stored Energy
Voltmeter
Electric Field Detector
Reset All
Disconnect Battery
Capacitance
0.35x10-12 F
Plate Charge (top)
0 C
Stored Energy
0 J
Separation
10.0 mm
Plate Area
400.0 mm2
1.5 V
0 V
-1.5 V
0 V
Electric Field
Plate
0 V/m
Zoom:
Show Values

Initial Values

The area of the plates is 400 square mm

The separation between plates is 10 mm

Note that the voltmeter reads 0

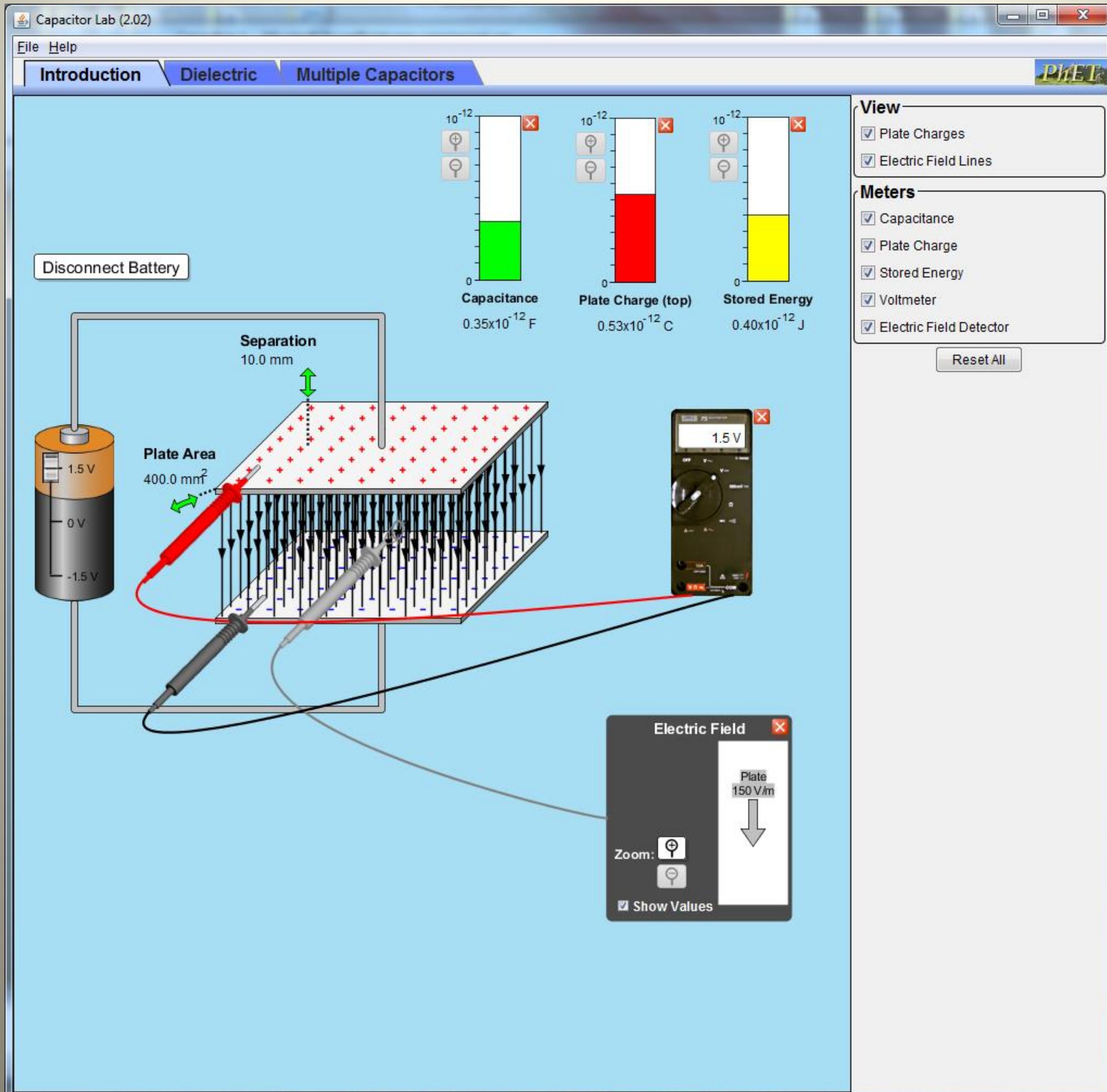
The electric field meter reads 0

The capacitance of the capacitor is set for a value of 0.35 pf independent of its connection in the circuit

The charge on each plate is zero

The energy stored in the capacitor is zero

Let's now charge the capacitor such that the top plate is connected to the (+) side of the battery and the bottom plate is connected to the (-) side of the battery.



Capacitor Lab (2.02)
File Help
Introduction
Dielectric
Multiple Capacitors
Disconnect Battery
Capacitance
0.35x10-12 F
Plate Charge (top)
0.53x10-12 C
Stored Energy
0.40x10-12 J
Separation
10.0 mm
Plate Area
400.0 mm2
1.5 V
0 V
-1.5 V
Electric Field
Plate
150 V/m
Zoom:
Show Values
View
Plate Charges
Electric Field Lines
Meters
Capacitance
Plate Charge
Stored Energy
Voltmeter
Electric Field Detector
Reset All

Values after charging

The capacitor still has a value of 0.35 pf (not changed)

Notice the capacitor plates now have a voltage of **1.5 volts** across the plates (same as battery).

Notice the top plate is charged (+) and the bottom plate is charged (-) but the overall charge on the capacitor is still zero

Notice the electric field (E) between the plates of the capacitor looks uniform (even) and has a value of

E = 150 volts/meter: 1.5 volts per 0.01 meter (10 mm)

$$E = V / d$$ where d = 0.01 meter

Electric Fields

Electric fields describe a property of space where electric charges reside

Electric fields always point in the direction that a POSITIVE charge would move

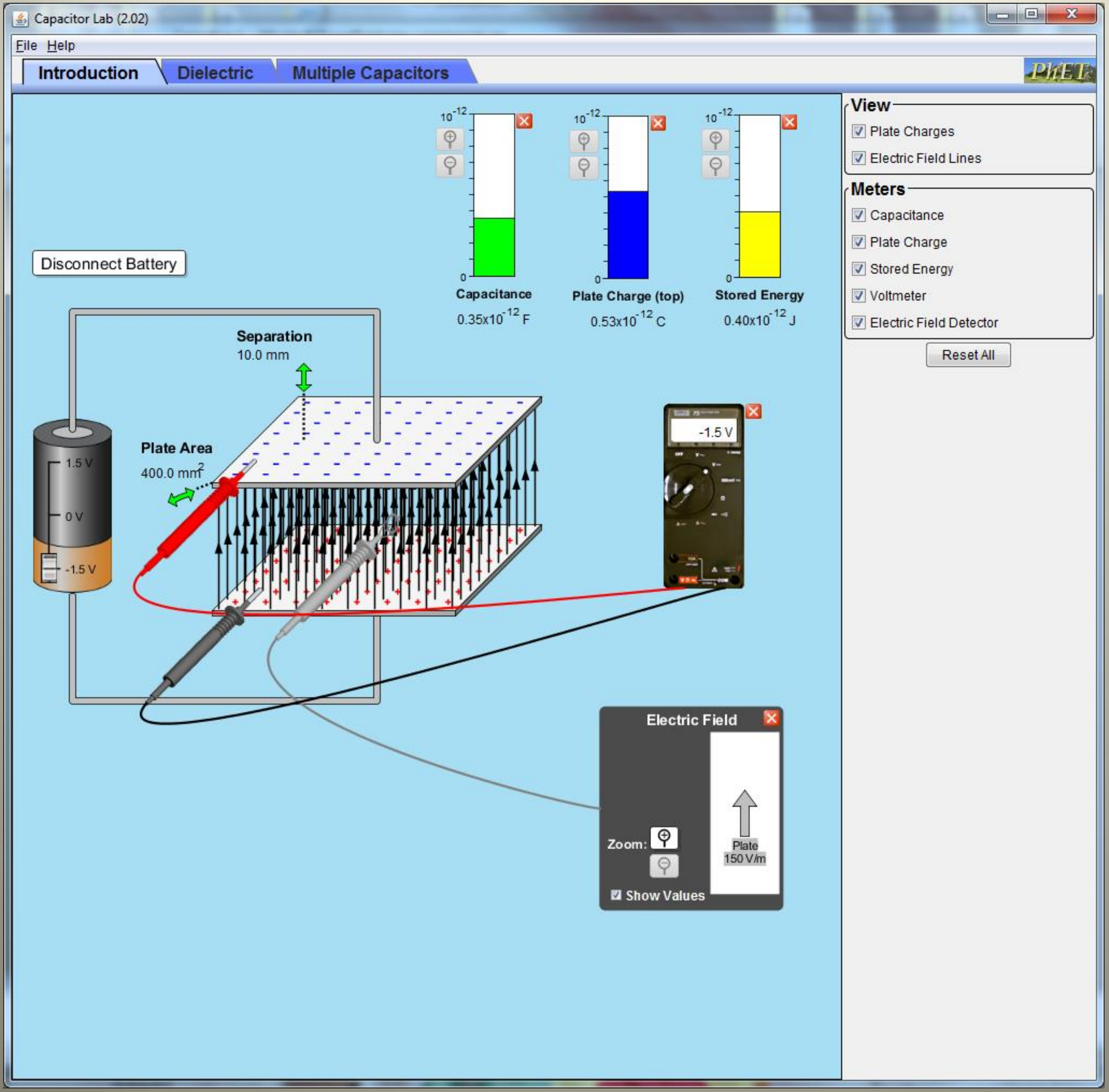
Electric fields can change the speed and the direction of moving charges

The electric field between the plates of the charged capacitor is uniform or constant

Electric fields can STORE ENERGY

What would change if we connect the battery “backwards” so that the top plate is connected to the (-) side of the battery, and the bottom plate is connected to the (+) side of the battery?

Make a prediction before we look.


Capacitor Lab (2.02)
File Help
Introduction
Dielectric
Multiple Capacitors
Disconnect Battery
Capacitance
0.35x10-12 F
Plate Charge (top)
0.53x10-12 C
Stored Energy
0.40x10-12 J
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10.0 mm
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1.5 V
0 V
-1.5 V
-1.5 V
Electric Field
Zoom:
Show Values
Plate
150 V/m
View
Plate Charges
Electric Field Lines
Meters
Capacitance
Plate Charge
Stored Energy
Voltmeter
Electric Field Detector
Reset All

The voltmeter now reads -1.5 volts and the top plate is negative.

The electric field has reversed direction but still has the value of 150 volt/meter.

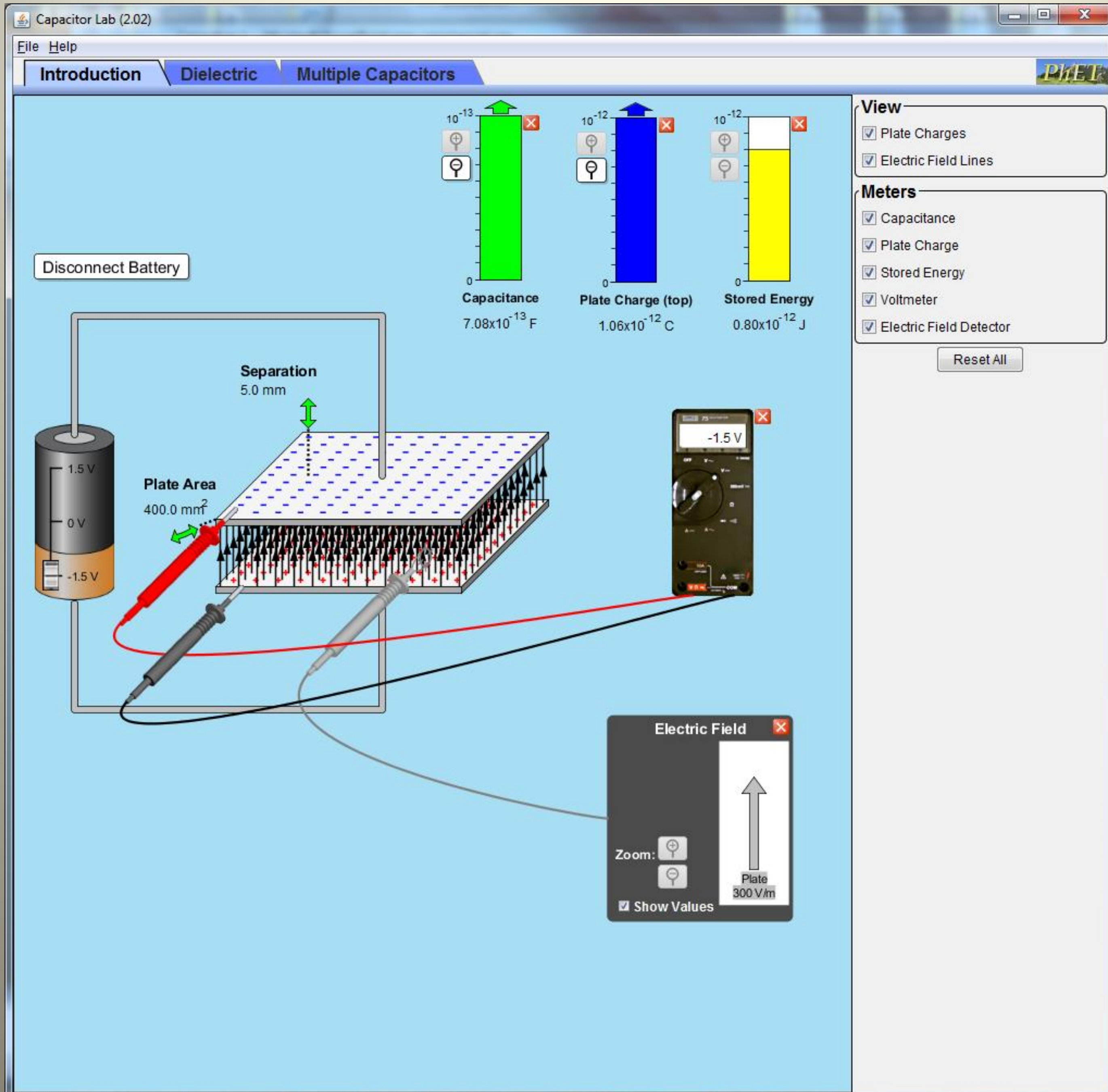
The amount of charge on each plate (Q) is the same and the energy (E) stored in the capacitor is the same.

Predictions

If we keep the battery connected to the capacitor, and keep the plate area the same, but **decrease** the separation (d) between the plates by 50% from 10 mm to 5 mm what WILL change?

Make a prediction: charge? voltage?

electric field? stored energy?



Capacitor Lab (2.02)
File Help
Introduction
Dielectric
Multiple Capacitors
PhET
Disconnect Battery
Capacitance
7.08x10^-13 F
Plate Charge (top)
1.06x10^-12 C
Stored Energy
0.80x10^-12 J
Separation
5.0 mm
Plate Area
400.0 mm^2
1.5 V
0 V
-1.5 V
-1.5 V
Electric Field
Zoom:
Show Values
Plate
300 V/m
View
Plate Charges
Electric Field Lines
Meters
Capacitance
Plate Charge
Stored Energy
Voltmeter
Electric Field Detector
Reset All

Decreasing the separation between the plates while the battery is still connected

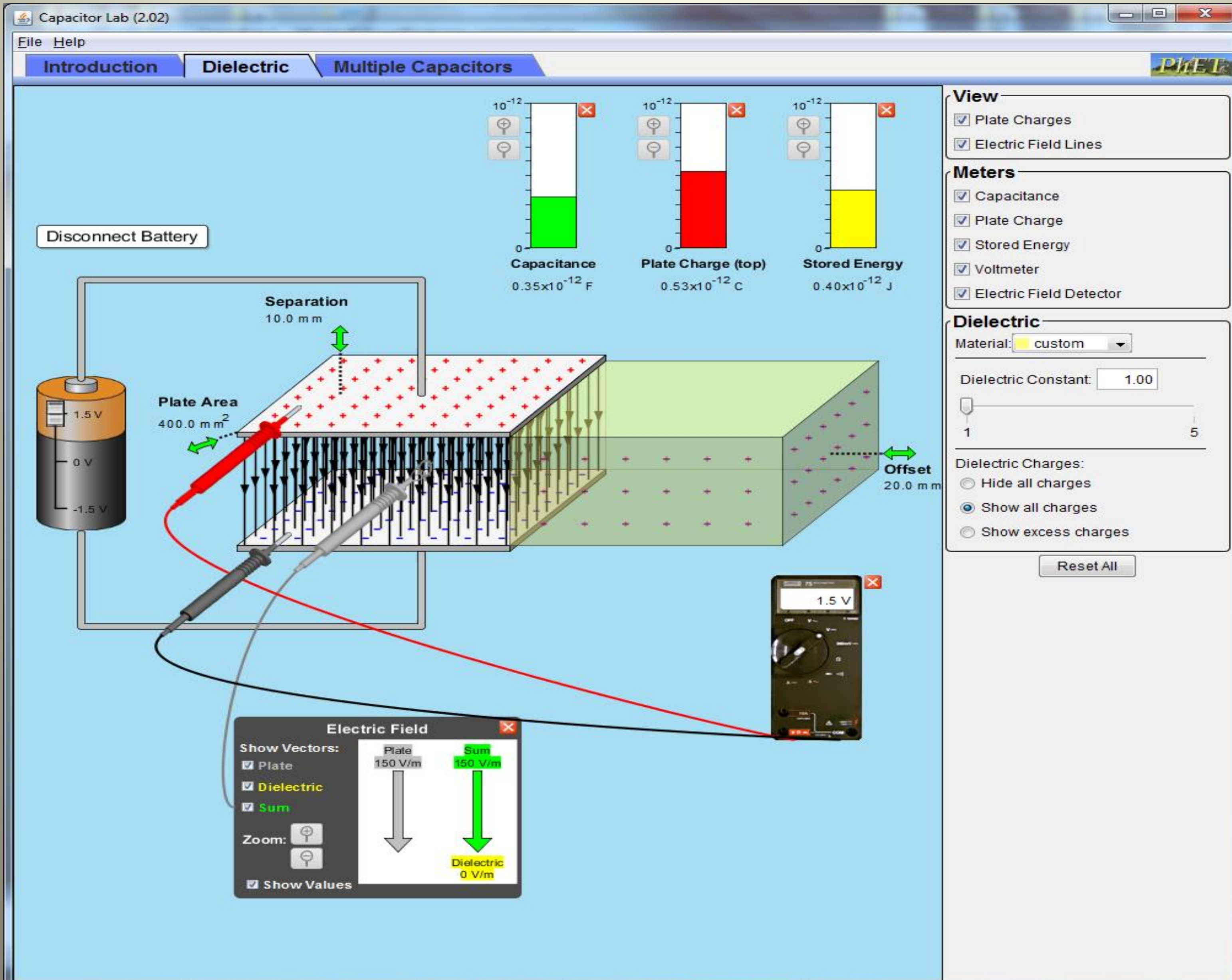
1) More charge flows onto the plates
2) The electric field increases
3) The capacitance increases
4) The energy stored increases

but the voltage across the plates is still the same 1.5 volts.

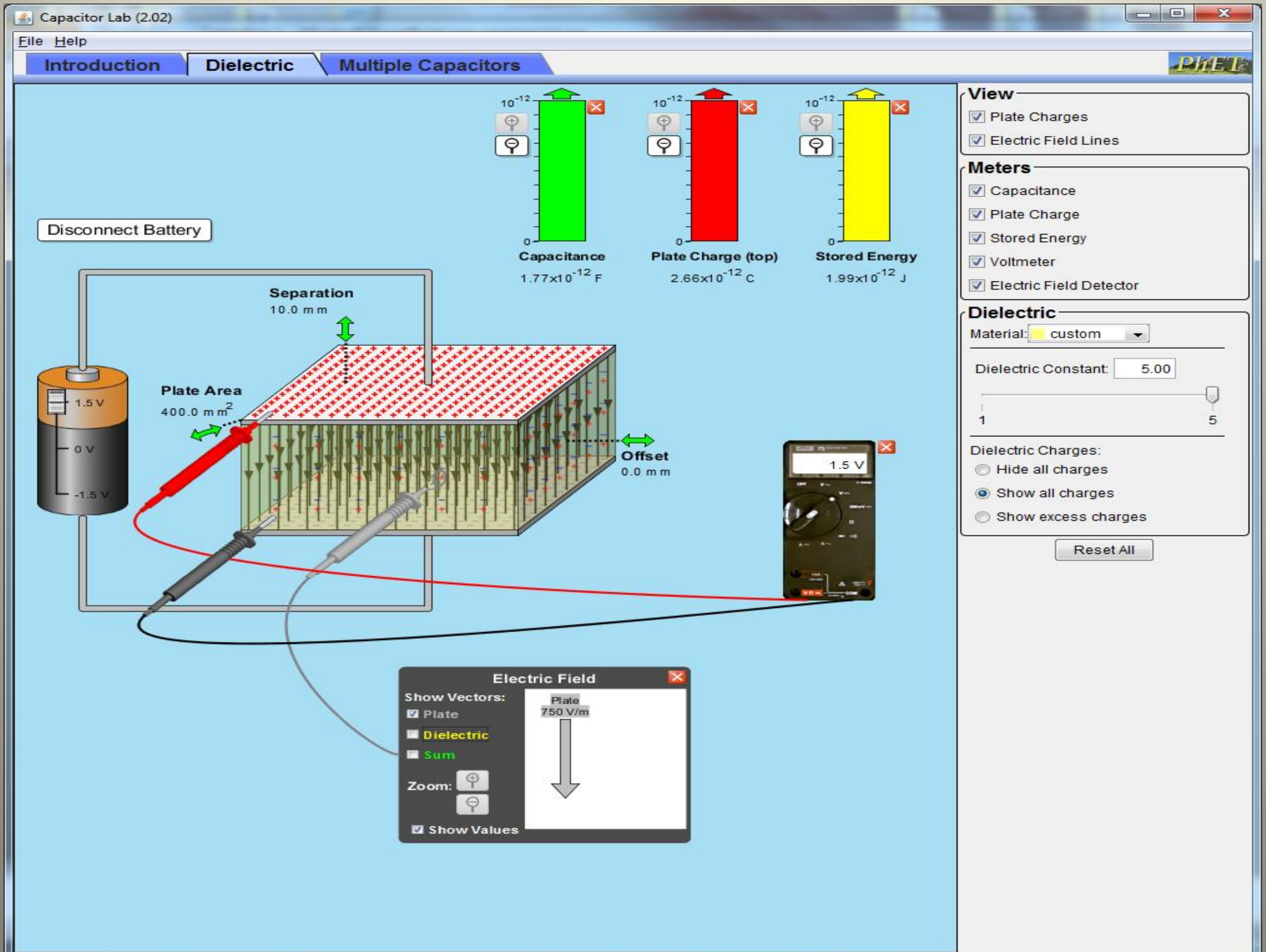
What if we now charge the capacitor but put in a dielectric other than air?

What will change?

Dielectric of AIR k=1



Dielectric of k=5



Effects of a Dielectric k=5

The capacitance increases by 5

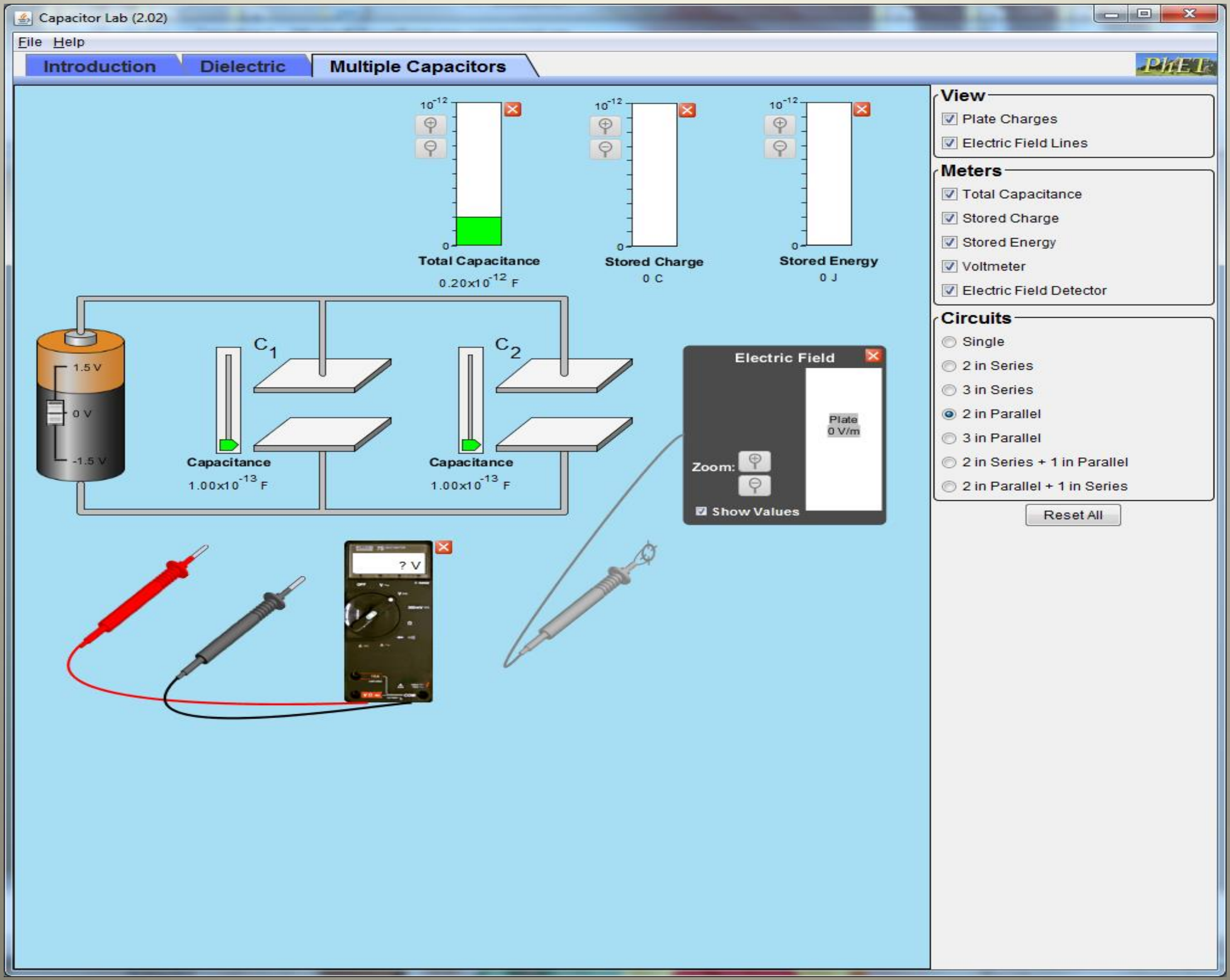
The electric field increases by 5

The charge on each plate increases by 5

The energy stored increases by 5

But the voltage across the capacitor is still the same 1.5 volts

Capacitors in parallel: 0.1pf each



Capacitors connected in PARALLEL

What happens when two capacitors of the same value are connected in PARALLEL to the same 1.5 volt battery?

What factors will change?

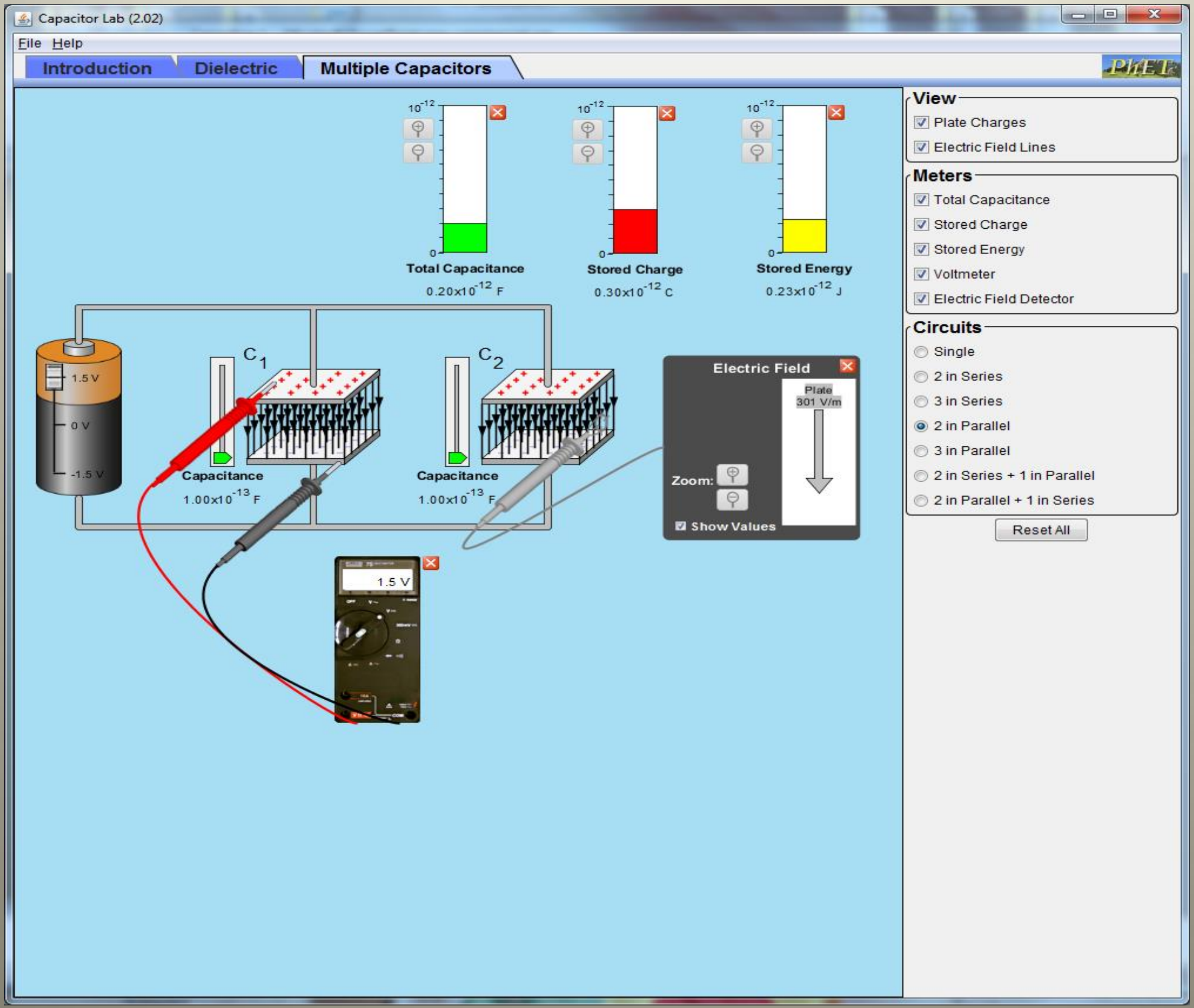
- voltage across each capacitor
- electric field between the plates
- charge stored on each capacitor
- energy stored in each capacitor
- total energy stored in BOTH capacitors

Hint

Can you think of 2 identical capacitors connected in parallel as ONE capacitor with 2 times the plate area A?

Remember: C is proportional to A

Two 0.1 pf capacitors in parallel



Charge stored on two capacitors connected in parallel

Imagine two capacitors, each $C = 0.1$ pf, connected in parallel to a 1.5 volt battery

The charge on **each** plate is __________

$Q = CV = 0.1 \text{ pf} \times 1.5 \text{ volt}$

$Q = 0.15$ picocoulombs

But two capacitors in parallel will store 0.30 picocoulombs (twice as much charge) and store twice as much energy

Conclusions about parallel capacitors

The voltage, electric field, charge and stored energy on EACH capacitor is the **same value** as when only one is in the circuit

But the total charge stored doubles, so the capacitance of the circuit doubles, and the stored energy also doubles.

The voltage on each capacitor is still 1.5v

Three Identical Capacitors in PARALLEL

What quantities are the SAME on all three capacitors?

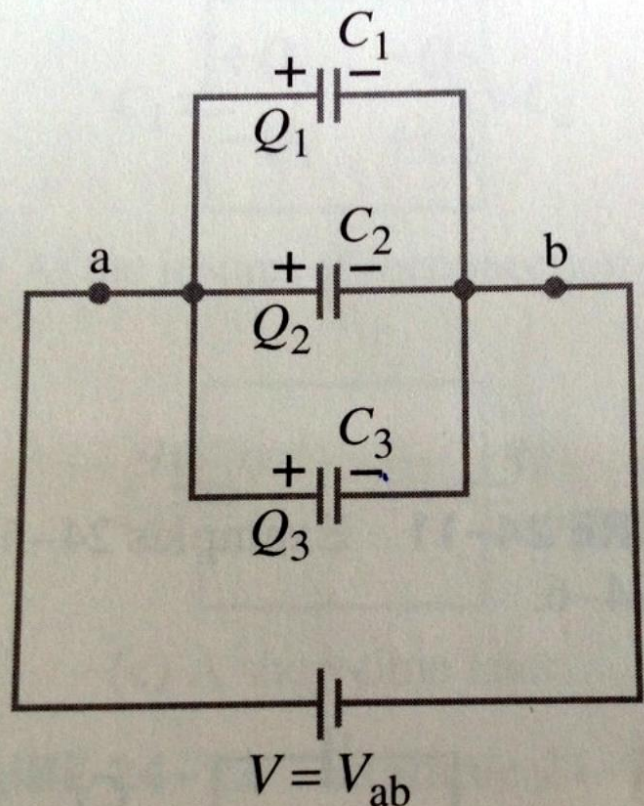


FIGURE 24–9 Capacitors in parallel:

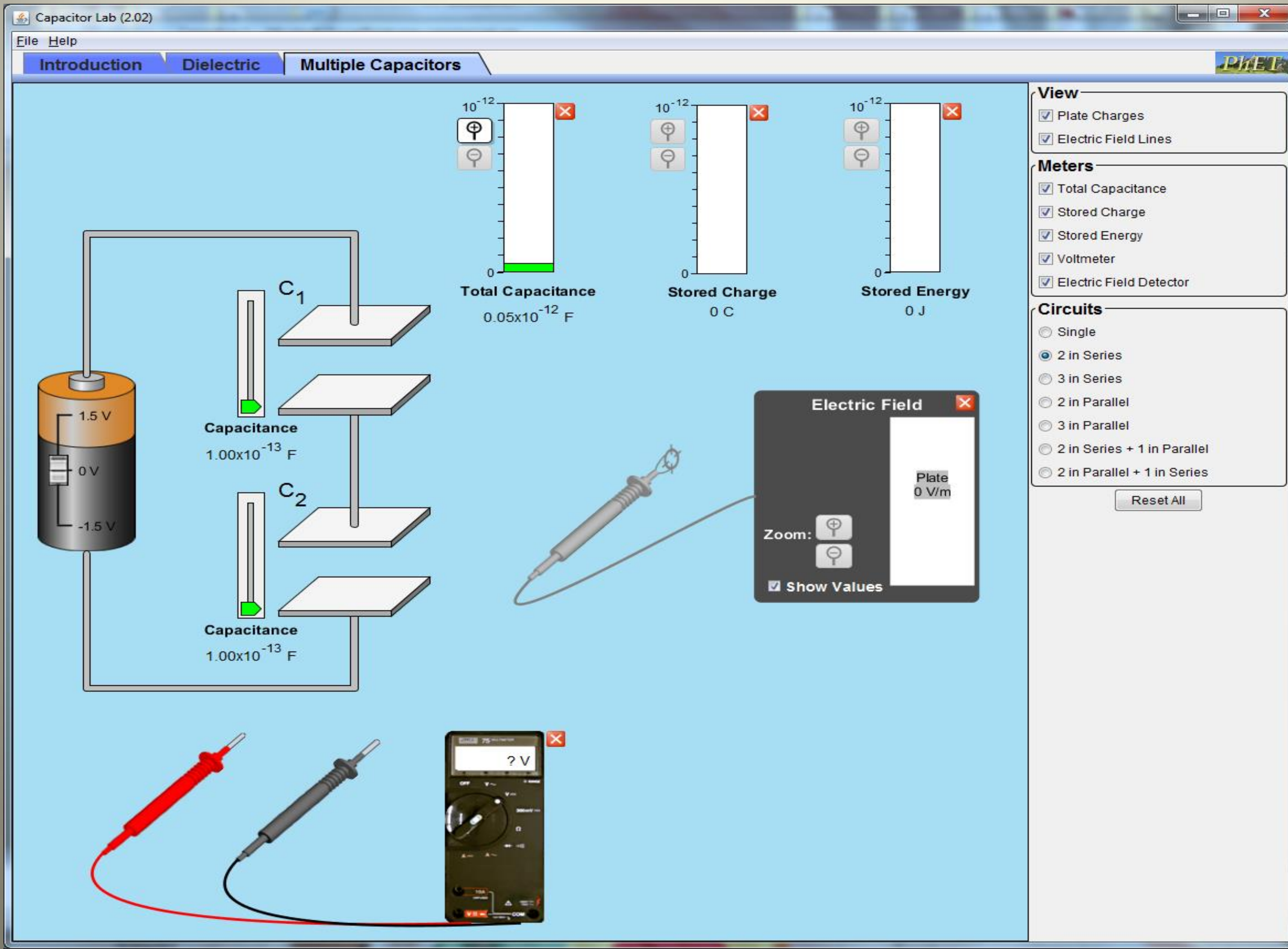
$$C_{eq} = C_1 + C_2 + C_3.$$

Formula for Capacitors in Parallel

Capacitors in PARALLEL add their values in the same way that resistors in SERIES add their values:

$$C\,(\text{total}) = C1 + C2 + C3 \quad (\text{parallel})$$

What happens when TWO 0.1 pf capacitors are connected in series to the same 1.5 volt battery?



hint

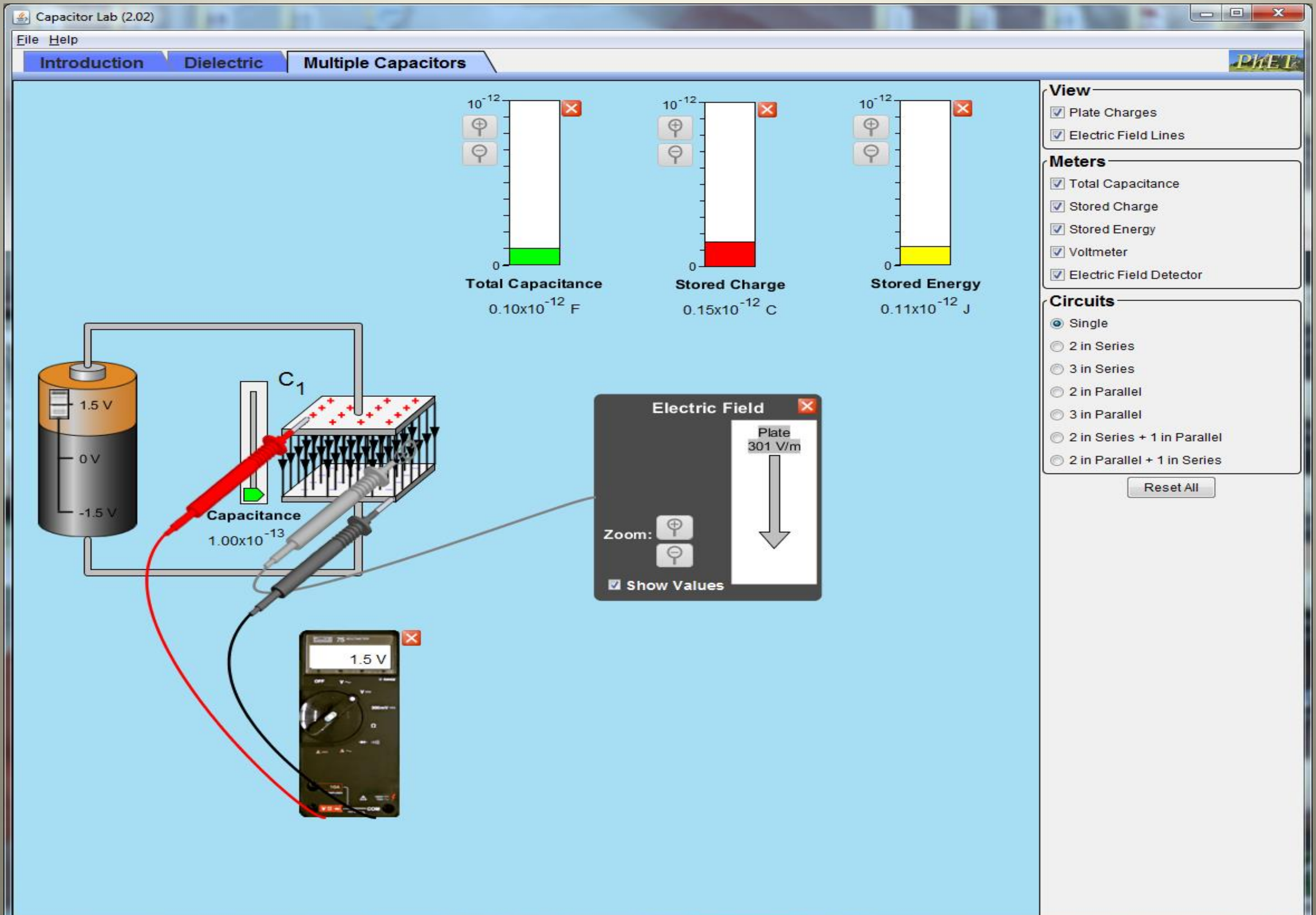
Can you think of two identical capacitors in SERIES as one capacitor with the same plate area A but DOUBLE the plate separation d ?

Remember: C is proportional to 1/d

Where d is the plate separation

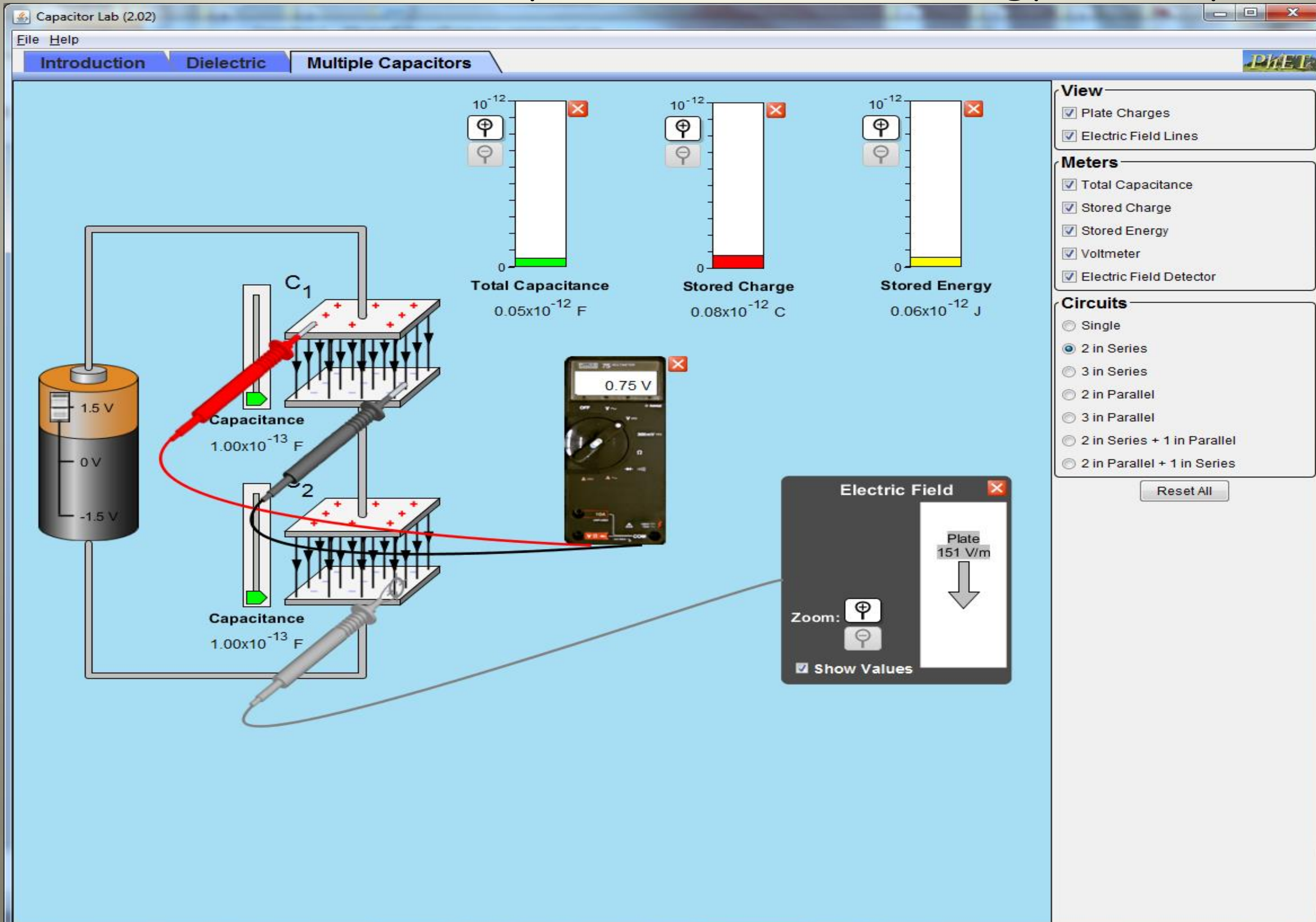
Here is a 0.1 pf capacitor connected to a 1.5 volt battery:

V = 1.5 volt   Q = 0.15 pC   E = 300 V/m   Energy = 0.1 pJ



Two 0.1pf capacitors in series to a 1.5 volt battery

V = 0.75 volt Q = 0.08 pC E = 150 V/m Energy = 0.06 pJ



Two 0.1 pf capacitors in SERIES

Notice that the voltage across EACH capacitor is only

V = 0.75 volts (half of 1.5)

Thus, the charge on each capacitor is only one half the charge stored on the single capacitor

Q = C V = 0.1pf x 0.75v =

Q = 0.075 picocoulombs

Half the charge, at half the voltage, is only **1/4th the energy** stored compared to a single capacitor 0.1 pf at 1.5 volts.

Added together both capacitors store only 1/2 the energy of the single capacitor.

Three identical capacitors connected in SERIES
What quantities are the SAME on all three capacitors?

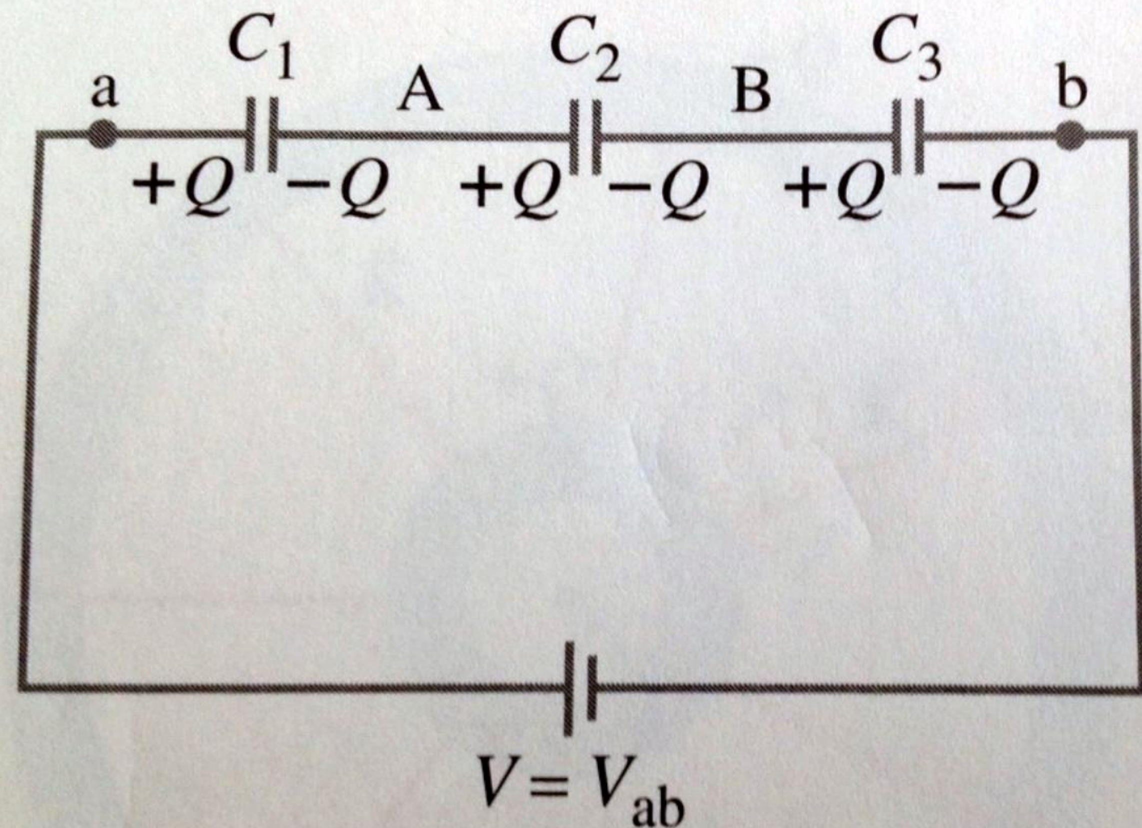


FIGURE 24–10 Capacitors in series:

Charging a Capacitor with a battery

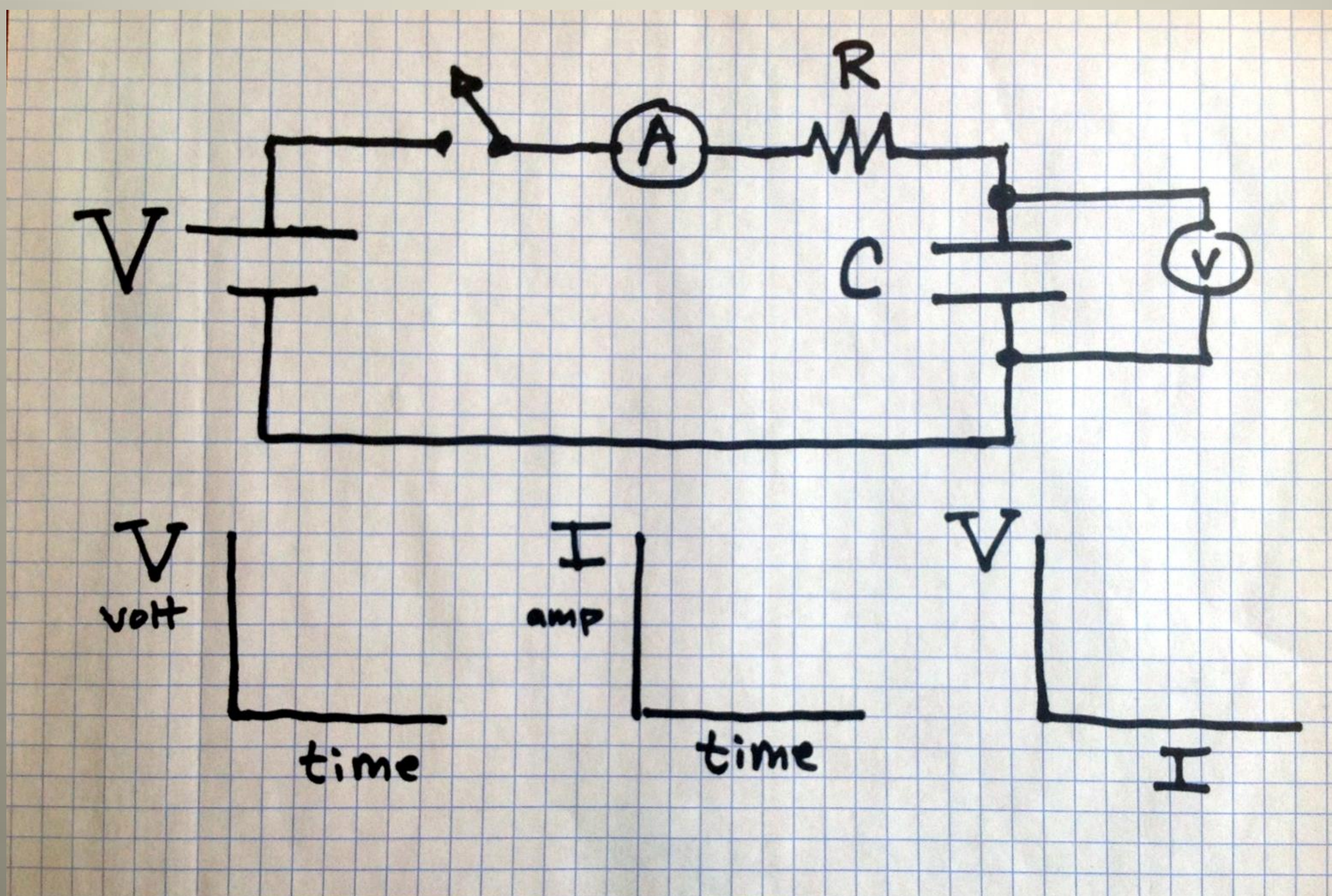
When an uncharged capacitor is connected to a battery and a resistor in a series circuit, charge flows until the capacitor and the battery achieve the same voltage.

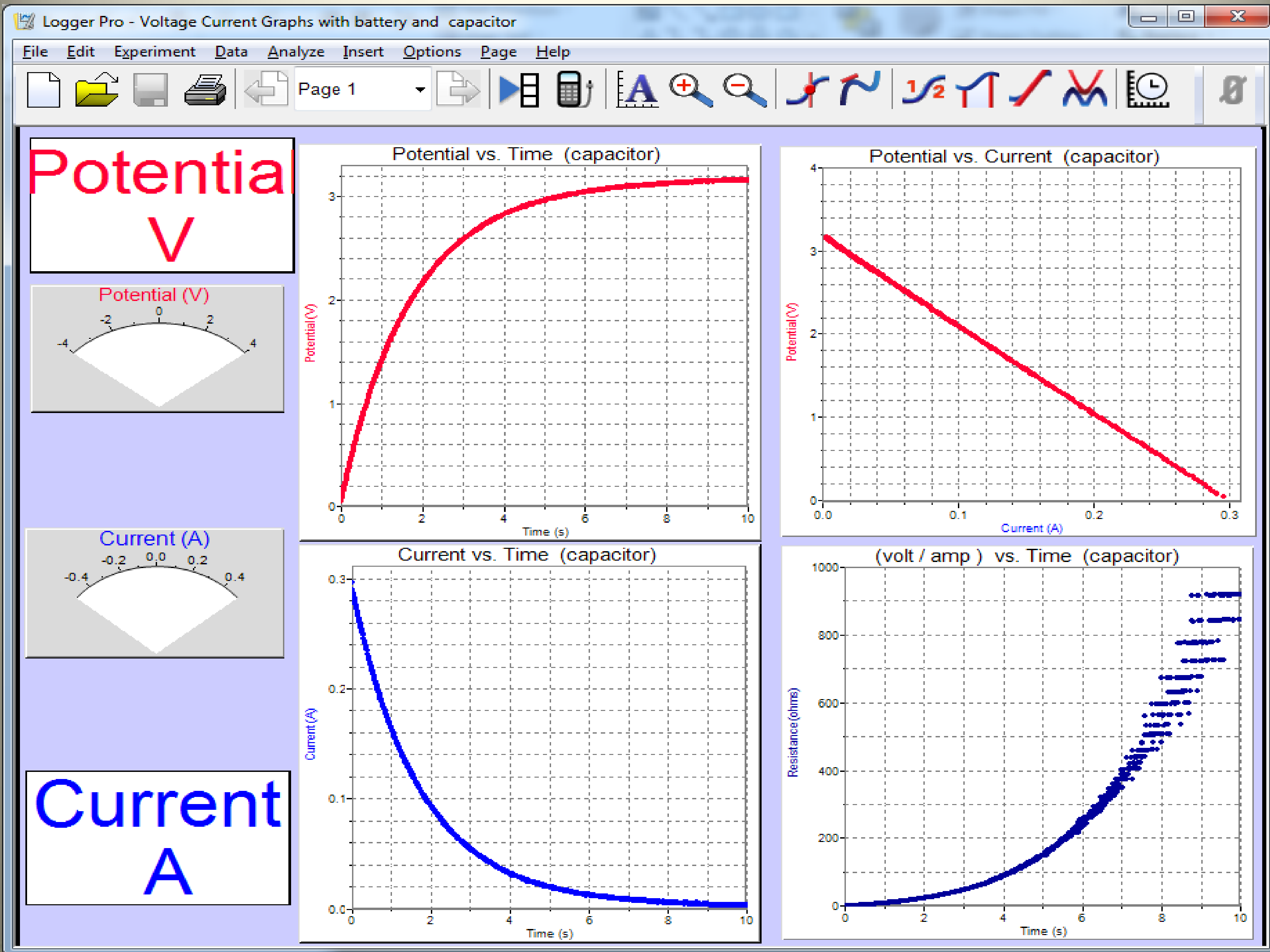
But how fast does this happen?

Predict the shapes of the following graphs:

Capacitors

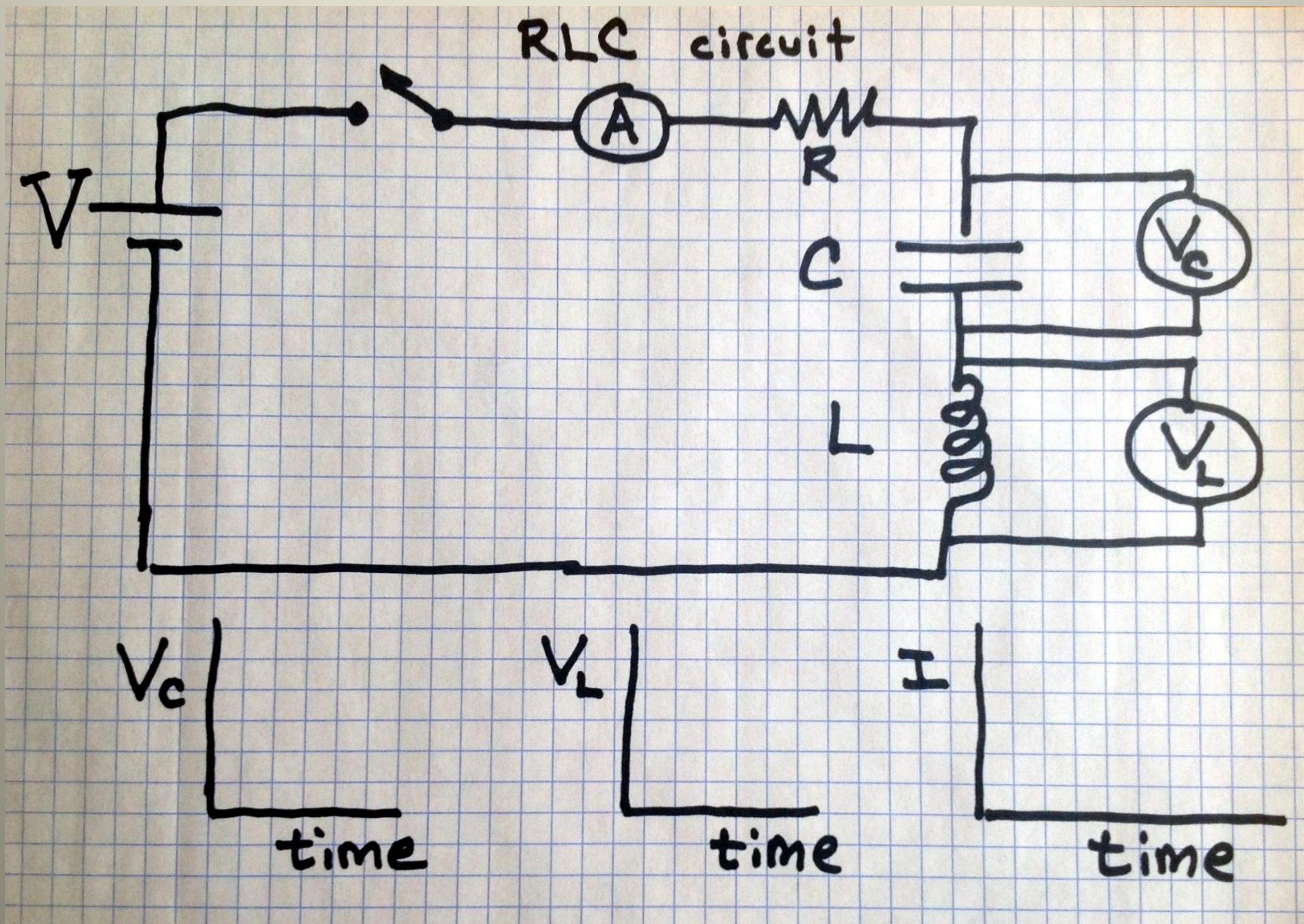
Connect a 3 volt battery to a capacitor and resistor connected in **series**, via an open switch. The capacitor is initially uncharged.
The voltage is measured across the capacitor.
The current is measured anywhere in the circuit.
Now close the switch, completing the circuit.



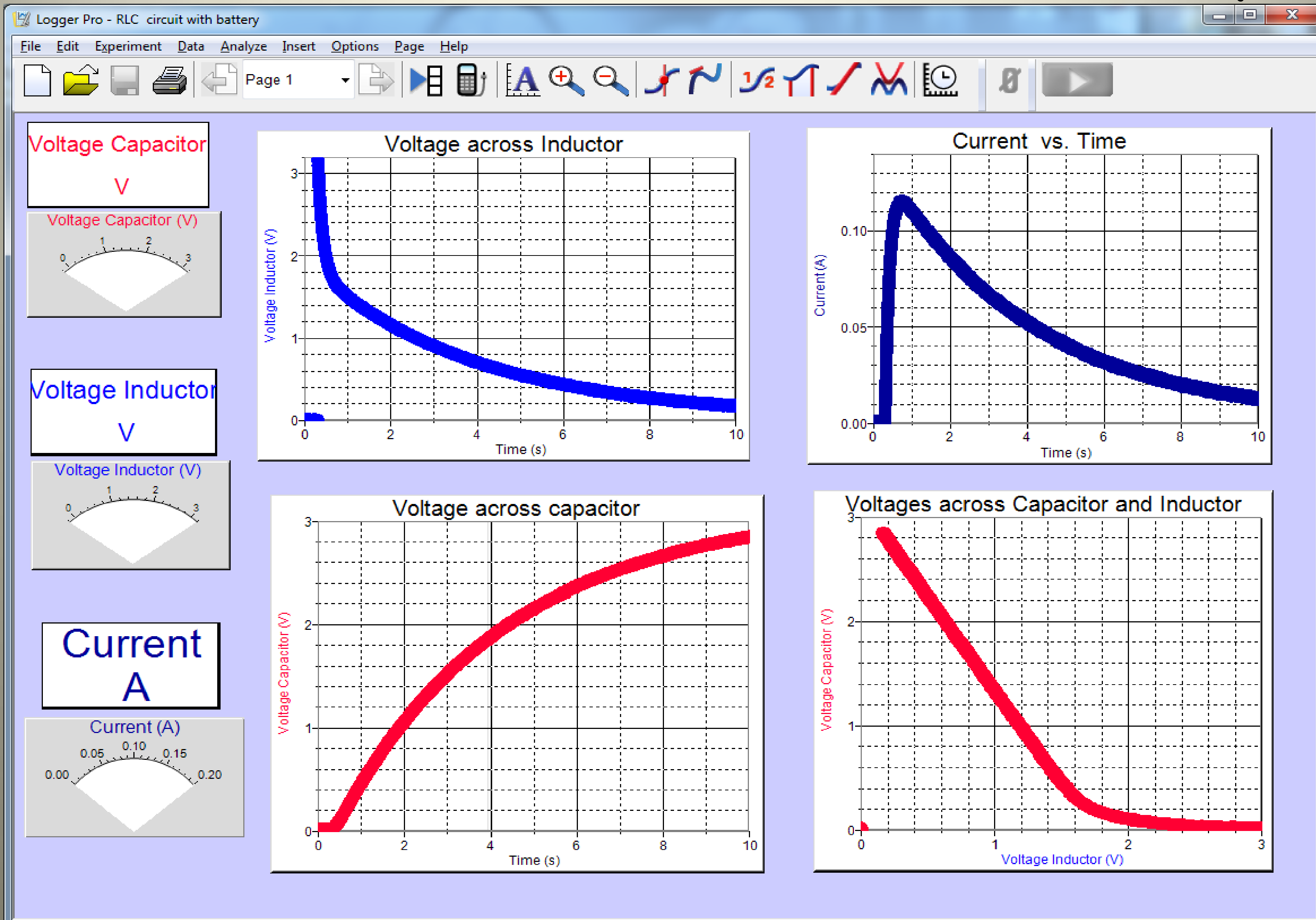

Logger Pro - Voltage Current Graphs with battery and capacitor
File Edit Experiment Data Analyze Insert Options Page Help
Page 1
Potential
V
Potential (V)
-4 -2 0 2 4
Current (A)
-0.4 -0.2 0.0 0.2 0.4
Current
A
Potential vs. Time (capacitor)
Potential (V)
Time (s)
Potential vs. Current (capacitor)
Potential (V)
Current (A)
Current vs. Time (capacitor)
Current (A)
Time (s)
(volt / amp) vs. Time (capacitor)
Resistance (ohms)
Time (s)

Series RLC Circuit

Connect a resistor, capacitor and coil in SERIES with a switch and DC battery. When the switch is closed, predict the following graphs:



Series RLC Circuit with battery



Capacitors and Inductors in AC Circuits

When a capacitor and an inductor (coil) are connected in an AC circuit, each represents a certain kind of resistance or opposition to the current, called "reactance" (in ohms)

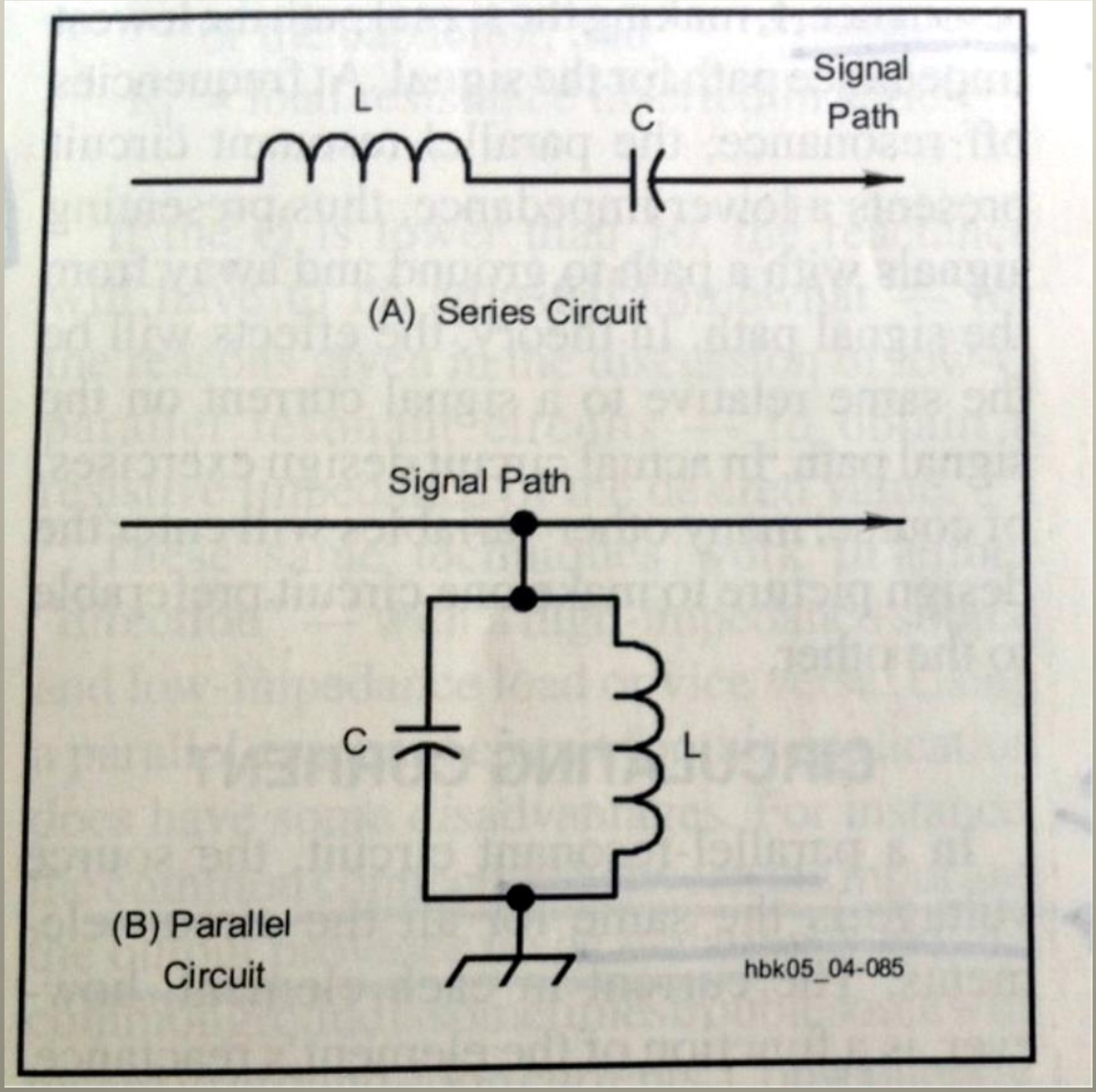
inductor => inductive reactance $X_L = 2 \text{ pi } f L$
capacitor => capacitive reactance $X_C = 1 / (2 \text{ pi } f C)$

The combination of resistance and reactance offers an "impedance" (AC resistance) in the circuit

At the "resonant" frequency of the coil and capacitor their reactances are equal in value and opposite in sign.

$X_L = X_C$ and impedance $Z = R$

What frequencies will pass through in (A)?
What frequencies will be bypassed in (B)?
Are these two methods of accomplishing the same goal?



Capacitors can be used in loudspeaker crossover filters

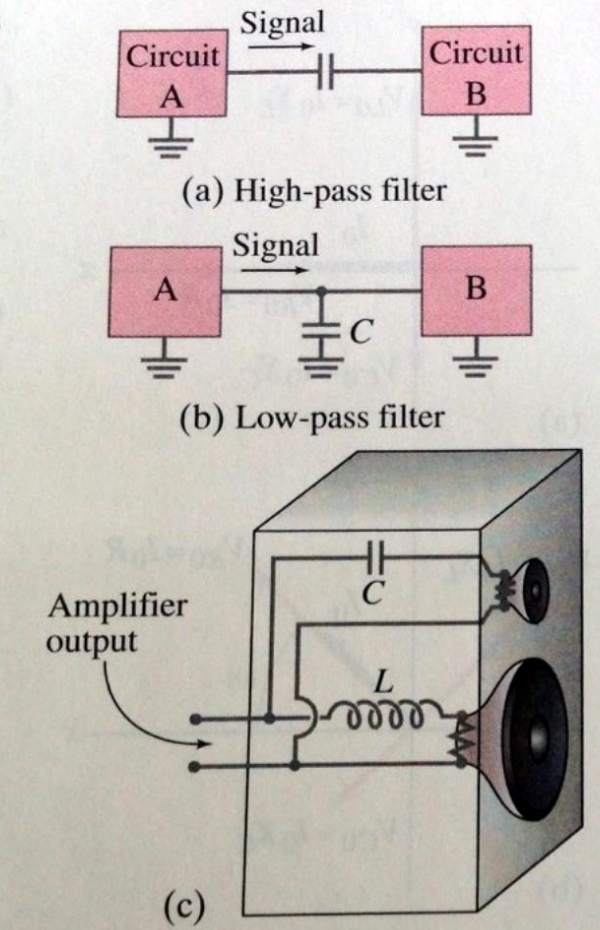
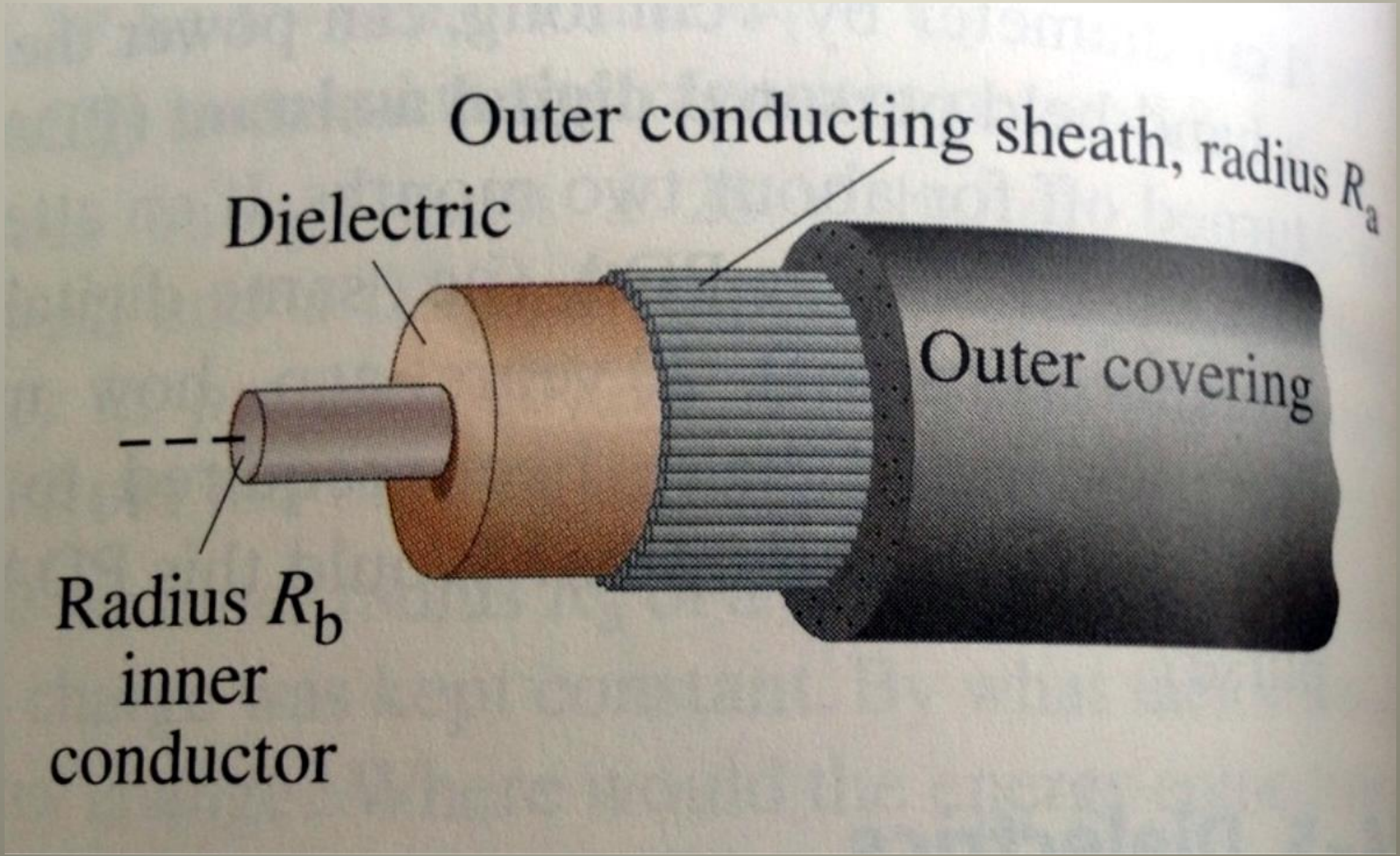
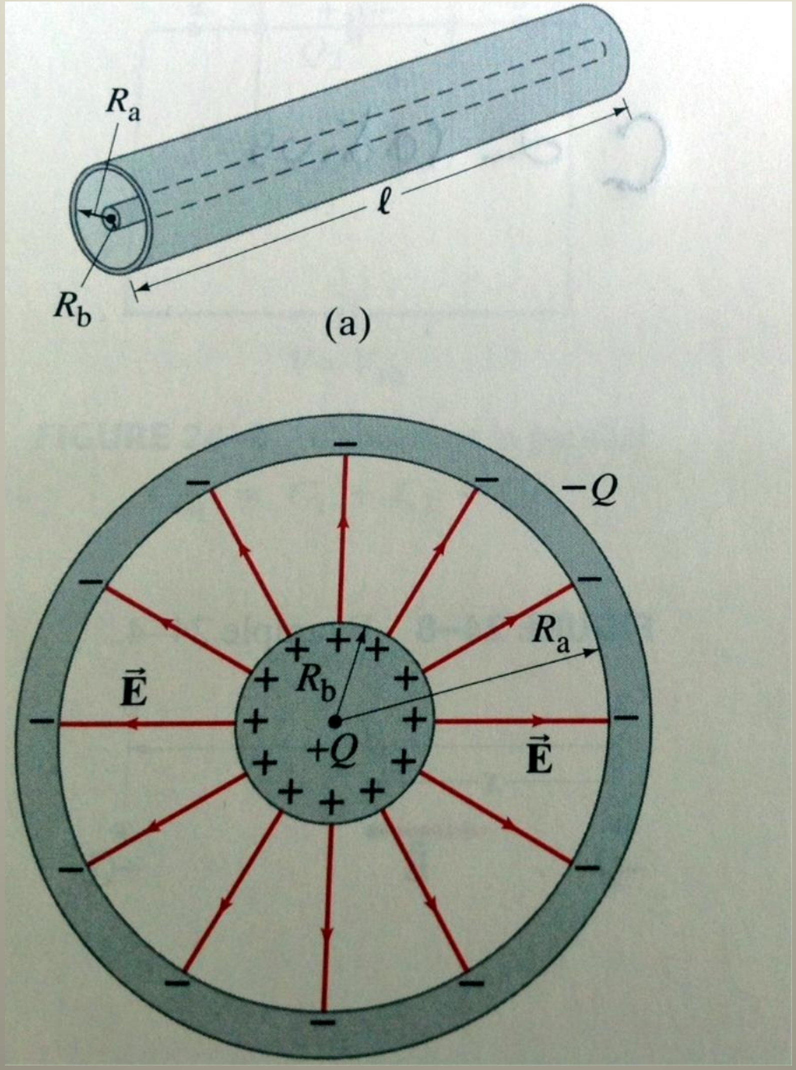


FIGURE 30–18 (a) and (b) Two common uses for a capacitor as a filter. (c) Simple loudspeaker cross-over.

Coaxial Cable acts like a capacitor
depending on the radius of inner and outer conductors
and dielectric of the insulator



Capacitance (per unit length) depends on the ratio of the inner and outer diameter conductors and on the dielectric between them



Antenna Trap: LC parallel circuit

10 meter antenna trap
note adjustable coil tap

Antennas and Capacitors

Consider stringing a "half-wave" center-fed dipole for 75 meters in your yard (120 ft) fed with 50 ohm coax

You can only get the dipole up 30 ft above ground (1/8 wavelength)

At this low height the antenna's resonant frequency will be too _____ and the antenna's impedance will be ______ than the impedance of the 50 ohm coax.

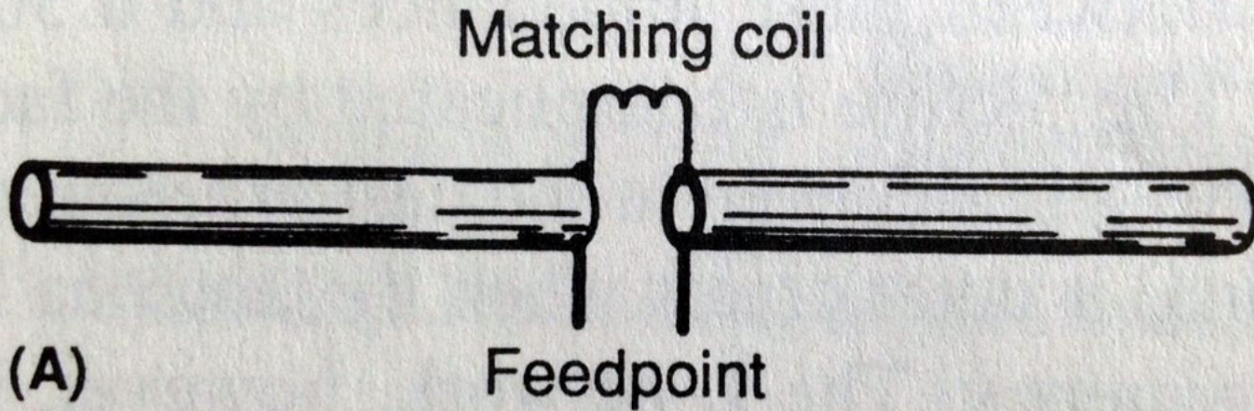
What could you do to “match”
a 130 ft long
80 meter dipole 30 ft above ground
to
50 ohm coaxial cable
at the point where the cable connects to the center of the dipole?

Impedance Matching

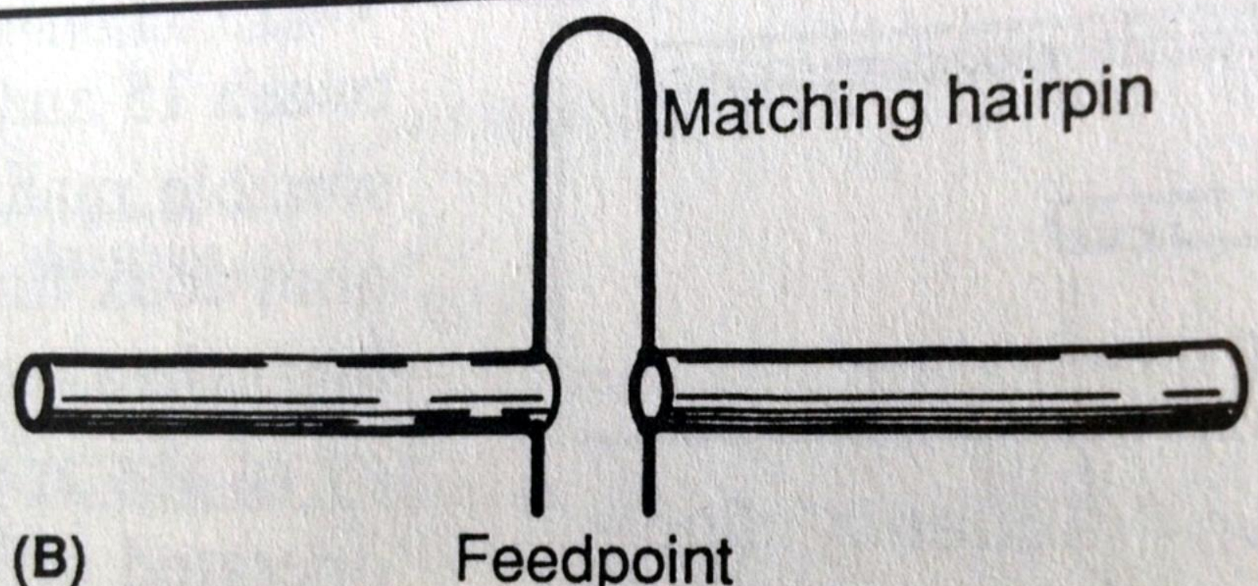
Hint

You want to match an antenna with perhaps 20 ohms impedance with a coax feed line of 50 ohms impedance.

Often multi-element Yagi antenna has a feedpoint impedance of 10-30 ohms and is “matched” to the coax by a hairpin inductor



(A)



(B)

Extra Credit

What did the CAPACITOR say to the ELECTRON ?

answer

you are REVOLTING