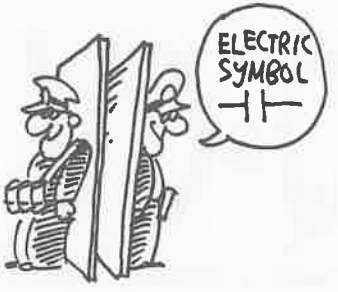
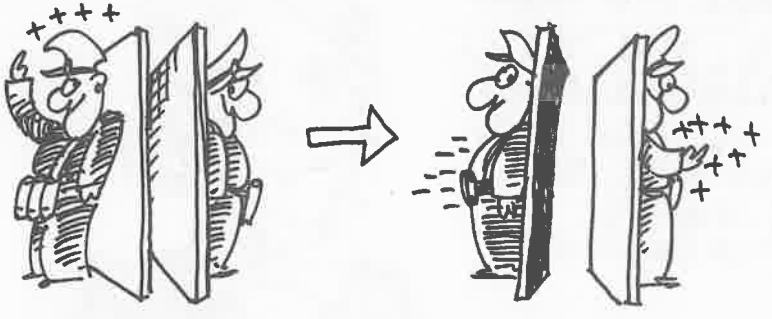
◊CHAPTER 14◊
CAPACITORS

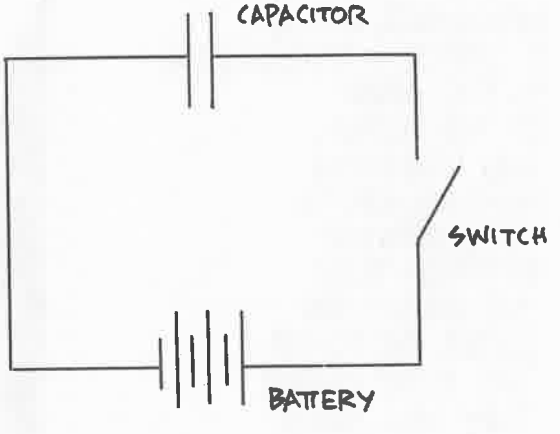
A CAPACITOR CONSISTS OF TWO CONDUCTORS SEPARATED BY AN INSULATOR, FOR EXAMPLE, TWO METAL PLATES WITH AIR BETWEEN THEM.



A CAPACITOR IS CHARGED BY REMOVING SOME CHARGE FROM ONE PLATE AND PLACING IT ON THE OTHER.



THE EASIEST WAY TO DO THIS IS TO CONNECT THE CAPACITOR BRIEFLY TO A BATTERY. THE BATTERY PUMPS CHARGE FROM ONE PLATE TO THE OTHER.



WHEN THE SWITCH IS CLOSED, ELECTRICITY FLOWS, AND CHARGE IS PUMPED ONTO THE CAPACITOR. THE AMOUNT OF CHARGE PUMPED IS PROPORTIONAL TO THE BATTERY'S VOLTAGE. SO WE WRITE:

$$Q = CV$$

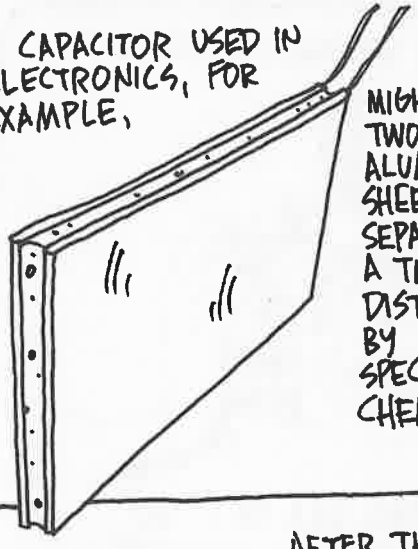
CHARGE = CONSTANT · VOLTAGE

THE CONSTANT OF PROPORTIONALITY C IS A NUMBER DEPENDING ON THE CHARACTERISTICS OF THE CAPACITOR. IT IS CALLED THE **CAPACITANCE.**

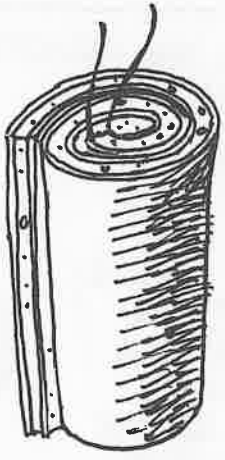
CAPACITANCE IS MEASURED IN **FARADS**, AFTER MICHAEL **FARADAY** (1791-1867). THE HIGHER THE CAPACITANCE, THE MORE CHARGE THE CAPACITOR CAN STORE.

CAPACITANCE, IN TURN, IS DIRECTLY PROPORTIONAL TO THE AREA OF THE PLATES, AND INVERSELY PROPORTIONAL TO THE SEPARATION BETWEEN THEM. THE BIGGER AND CLOSER THE PLATES, THE MORE CHARGE THEY WILL HOLD.

A CAPACITOR USED IN ELECTRONICS, FOR EXAMPLE,



MIGHT BE TWO ALUMINUM SHEETS SEPARATED A TINY DISTANCE BY SPECIAL CHEMICALS...

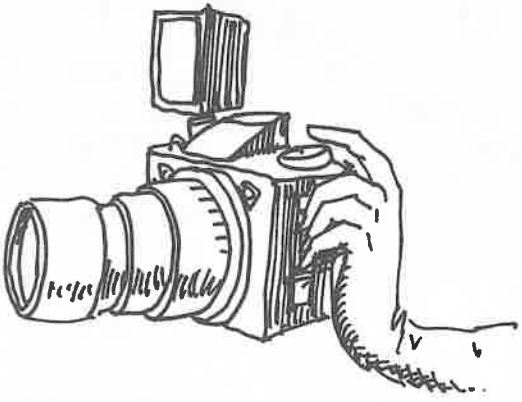


...AND ROLLED UP INTO A COMPACT TUBULAR PACKAGE.

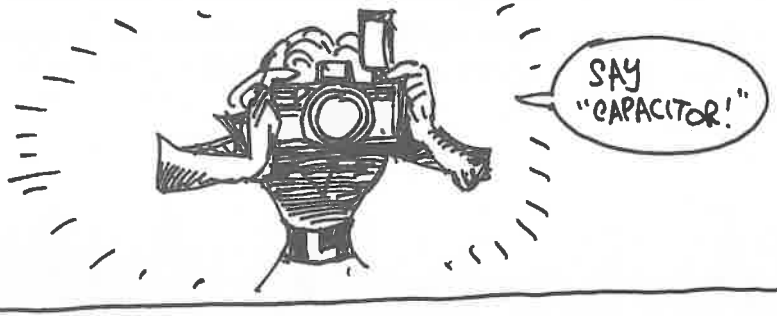
AFTER THE CAPACITOR IS CHARGED, IT CAN BE DISCONNECTED FROM THE BATTERY, AND IT WILL REMAIN CHARGED FOR MINUTES, OR EVEN HOURS, ALTHOUGH CHARGE WILL SLOWLY LEAK INTO THE AIR.

BUT, IF I NOW CAREFULLY BRING THE LEADS OF THE CAPACITOR TOGETHER... THE CHARGE FLOWS AROUND THE WIRES AND NEUTRALIZES THE PLATES. THIS IS CALLED DISCHARGING THE CAPACITOR."

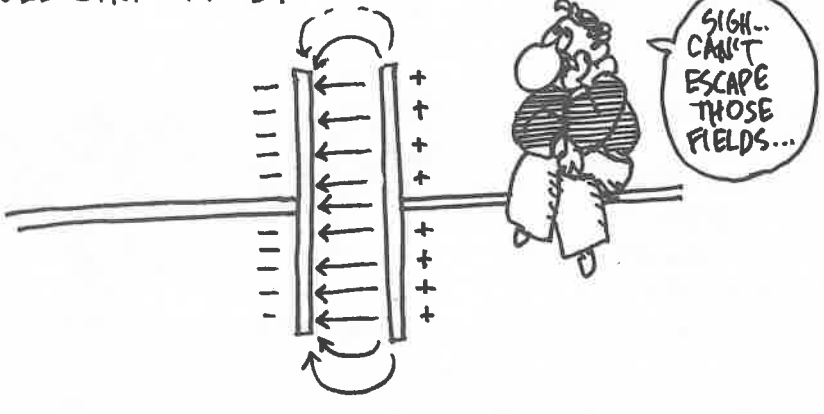
THIS SHOWS HOW CAPACITORS CAN BE USED TO STORE CHARGE AND ENERGY. FOR EXAMPLE, A PHOTOGRAPHER'S ELECTRONIC FLASH UNIT HAS A LARGE CAPACITOR TO STORE ENERGY FOR THE FLASH TUBE. THE BATTERY TAKES ABOUT 30 SECONDS TO CHARGE IT UP.



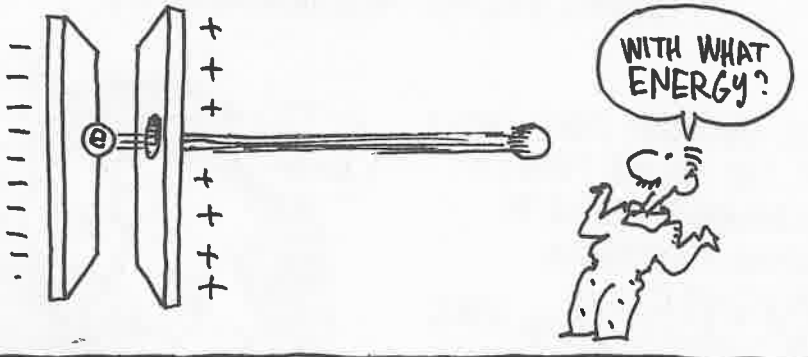
THEN, WHEN THE CHARGE IS NEEDED, ALL OF IT IS DUMPED THROUGH THE FLASH TUBE IN AN INSTANT!



WHEN THE CAPACITOR IS CHARGED, POSITIVE AND NEGATIVE CHARGES FACE EACH OTHER AND HOLD EACH OTHER IN PLACE ACROSS THE INSULATOR — AND OF COURSE THERE IS AN ELECTRIC FIELD!

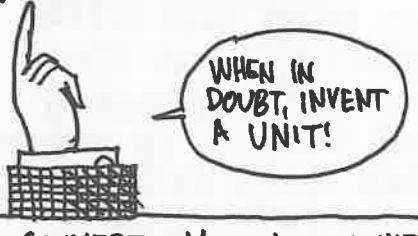


IF AN ELECTRON IS RELEASED NEAR THE NEGATIVE PLATE, THE ELECTRIC FIELD WILL ACCELERATE IT TOWARD THE POSITIVE PLATE. IN FACT, IF WE MAKE A SMALL HOLE IN THE POSITIVE PLATE, THE ELECTRON WILL ZIP THROUGH:



HERE WE MAKE UP A NEW ENERGY UNIT: THE

ELECTRON VOLT (eV).



IT'S THE ENERGY OF ONE ELECTRON IF THE PLATES ARE CHARGED TO ONE VOLT. IF THE PLATES HAVE 100 VOLTS, THE ELECTRON WILL HAVE 100 eV...

TO CONVERT eV TO JOULES, WE USE THE DEFINITION POTENTIAL = ENERGY / CHARGE:

1 eV = CHARGE OF ELECTRON
X
1 VOLT

$= 1.6 \times 10^{-19}\,C \times 1\,J/C$

$= \mathbf{1.6 \times 10^{-19}}$ JOULES

(THAT'S .000000000000000000016 !)

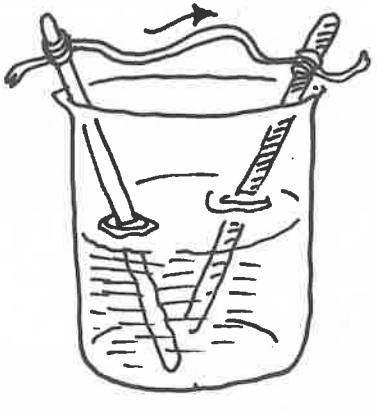
USING MODERN HI-TECH, WE CAN NOW ACCELERATE CHARGES TO MILLIONS OF ELECTRON VOLTS. BUT AT THESE ENERGIES, ELECTRONS ARE GOING CLOSE TO THE SPEED OF LIGHT, AND RELATIVITY THEORY MUST BE USED TO DESCRIBE THEM.

◦CHAPTER 15◦
ELECTRIC CURRENTS

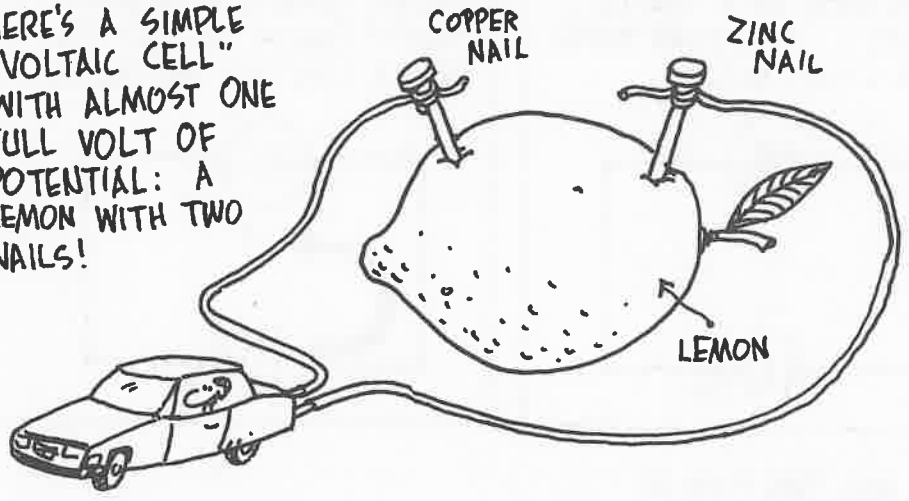
THE GREATEST ACHIEVEMENT OF THE ITALIAN PHYSICIST ALESSANDRO GIUSEPPE ANTONIO ANASTASIO **VOLTA**, ASIDE FROM REMEMBERING HIS OWN NAME, WAS THE INVENTION OF THE ELECTRIC BATTERY IN 1794.

VOLTA FOUND THAT IF YOU DIP TWO DIFFERENT METALS IN A CHEMICAL BATH, A DIFFERENCE IN POTENTIAL WILL APPEAR BETWEEN THEM.

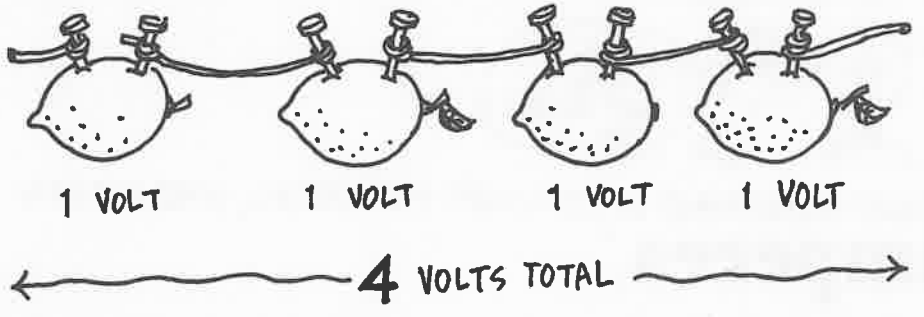
THIS MEANS THAT CHARGE "WANTS TO" MOVE FROM ONE METAL TERMINAL TO THE OTHER. IF YOU CONNECTED THEM WITH A WIRE, CHARGE WOULD FLOW THROUGH IT.



HERE'S A SIMPLE "VOLTAIC CELL" WITH ALMOST ONE FULL VOLT OF POTENTIAL: A LEMON WITH TWO NAILS!

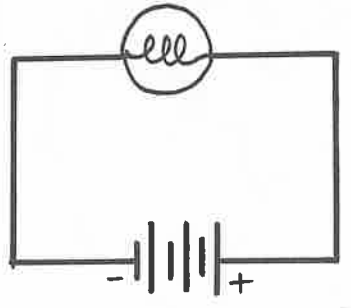


VOLTA ALSO FOUND THAT BY CONNECTING CELLS IN SERIES, THE POTENTIALS ADD UP TO GIVE LARGE VOLTAGES:

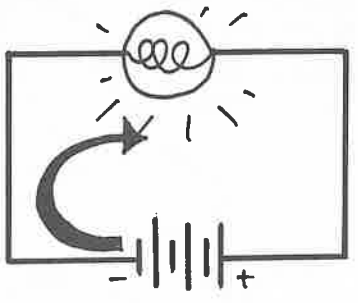


A FLASHLIGHT "BATTERY" IS ACTUALLY A SINGLE CHEMICAL CELL. A TRUE BATTERY, LIKE THE ONE IN YOUR CAR, CONSISTS OF SEVERAL CELLS CONNECTED IN SERIES, AS ABOVE. THEIR ELECTRICAL SYMBOLS ARE:

LET'S HOOK UP A SIMPLE CIRCUIT: A BATTERY WIRED TO A LIGHT BULB.



THE BATTERY CONTINUALLY "PUMPS" CHARGE AROUND THE CIRCUIT, LIGHTING THE BULB.



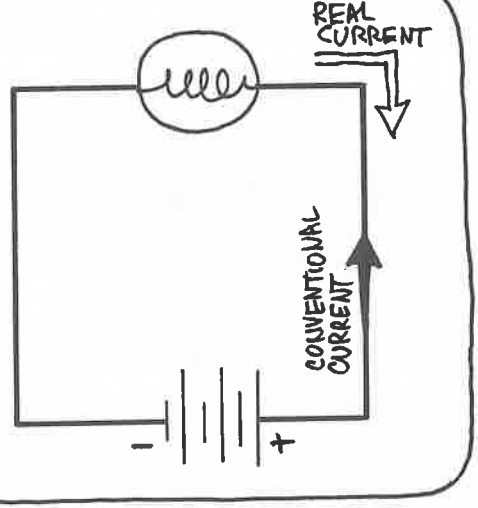
WE CALL THIS FLOW OF CHARGE THE

CURRENT.

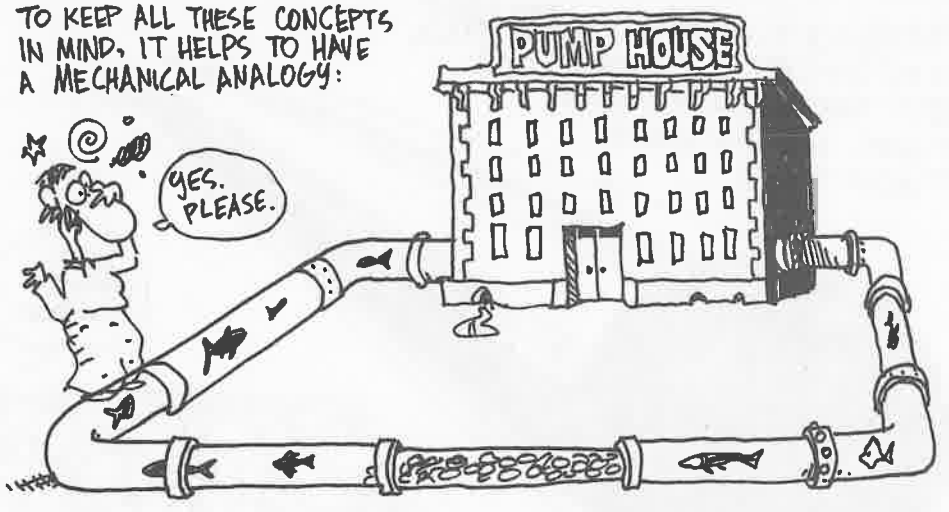
CURRENT IS MEASURED IN COULOMBS PER SECOND, ALSO KNOWN AS:

amperes.

WE OFTEN DRAW AN ARROW ALONG THE WIRE, LEADING FROM THE BATTERY'S POSITIVE TERMINAL TO THE NEGATIVE, AS IF POSITIVE CHARGES FLOWED THAT WAY. THIS IS CALLED "CONVENTIONAL CURRENT." AS OPPOSED TO REAL CURRENT, WHICH IS A FLOW OF NEGATIVE ELECTRONS IN THE OPPOSITE DIRECTION. IN MOST ELECTRICAL EFFECTS, THERE IS NO WAY TO DISTINGUISH BETWEEN THESE TWO POSSIBILITIES.



TO KEEP ALL THESE CONCEPTS IN MIND, IT HELPS TO HAVE A MECHANICAL ANALOGY:

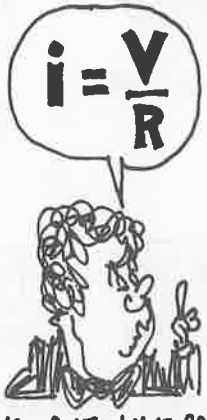


IMAGINE THAT ELECTRIC CURRENT IS LIKE WATER FLOWING THROUGH A PIPE. THEN WE HAVE THESE CORRESPONDENCES:

ELECTRICITY	WATER
COULOMB OF CHARGE	LITER OF WATER
AMPERE	ONE LITER/SEC FLOW
BATTERY	PUMP
VOLTAGE	PUMP PRESSURE
WIRE	PIPE

THE LAMP FILAMENT IS LIKE A SECTION OF PIPE FILLED WITH GRAVEL THAT **RESISTS** THE FLOW OF WATER. IN FACT, THE FRICTION OF FLOWING WATER EVEN HEATS THE GRAVEL!

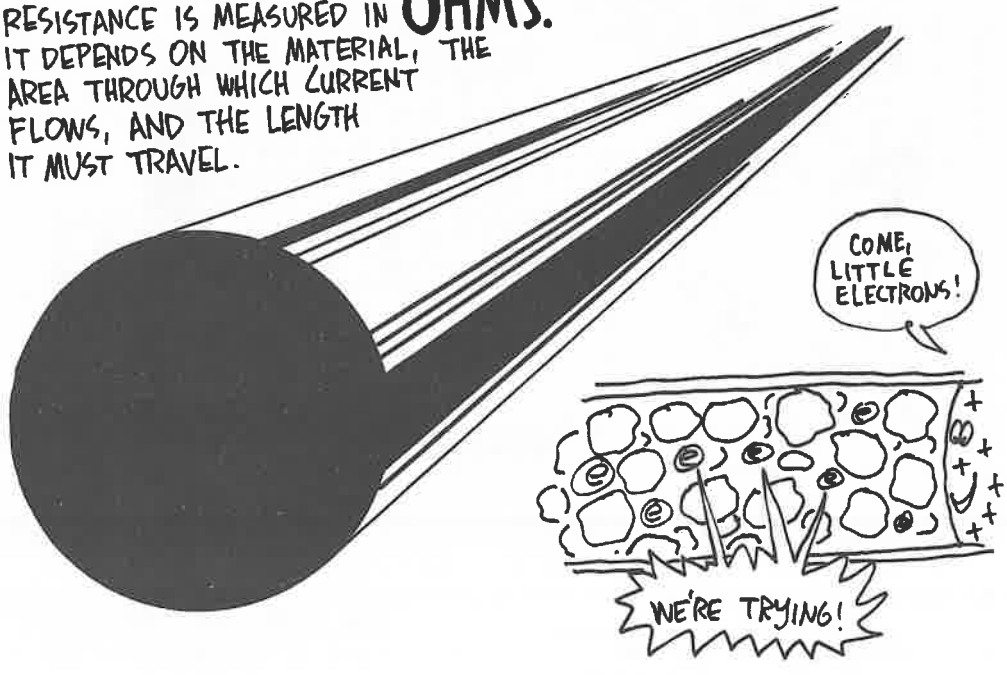
TO GET A LARGE FLOW, OR CURRENT, A HIGH PRESSURE, OR VOLTAGE, IS REQUIRED. GEORGE **OHM** (1789-1854) SUMMARIZED THIS RELATION AS **OHM'S LAW:**



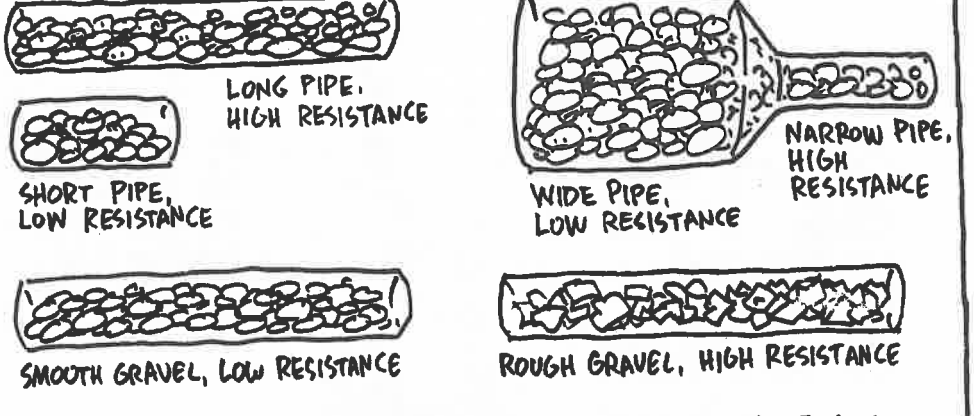
CURRENT, **i**, EQUALS VOLTAGE, **V**, DIVIDED BY RESISTANCE **R**. THE HIGHER THE VOLTAGE, THE MORE CURRENT FLOWS THROUGH A GIVEN RESISTANCE.

(OHM'S LAW IS NOT UNIVERSALLY TRUE, LIKE COULOMB'S LAW, BUT IS APPROXIMATELY TRUE IN MANY SITUATIONS.)

RESISTANCE IS MEASURED IN **OHMS.** IT DEPENDS ON THE MATERIAL, THE AREA THROUGH WHICH CURRENT FLOWS, AND THE LENGTH IT MUST TRAVEL.



THINK AGAIN OF WATER FLOWING THROUGH A PIPEFUL OF GRAVEL. A SECTION OF PIPE TWICE AS LONG HAS TWICE THE RESISTANCE... A WIDER PIPE HAS LESS RESISTANCE, BECAUSE IT OFFERS MORE SPACES FOR WATER TO FLOW... AND RESISTANCE DEPENDS ON THE TYPE OF GRAVEL.



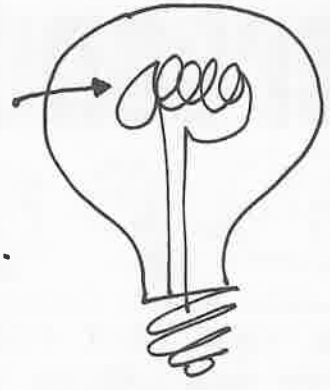
LIKEWISE, AN ELECTRIC WIRE'S RESISTANCE IS PROPORTIONAL TO ITS LENGTH AND INVERSELY PROPORTIONAL TO ITS CROSS-SECTIONAL AREA.

AND, LIKE DIFFERENT TYPES OF GRAVEL, DIFFERENT MATERIALS HAVE DIFFERENT INTRINSIC **RESISTIVITY**. GOOD CONDUCTORS HAVE LOW RESISTIVITY:

GOOD CONDUCTORS WITH LOW RESISTIVITY:
SILVER,
GOLD,
COPPER,
ALUMINUM

POOR CONDUCTORS WITH HIGH RESISTIVITY:
PLASTIC,
PAPER,
CLOTH

A LAMP FILAMENT IS LIKELY TO BE MADE OF **TUNGSTEN**, WHICH HAS A MUCH HIGHER RESISTIVITY THAN COPPER — HENCE A GREATER RESISTANCE THAN THE SAME SIZE COPPER WIRE.



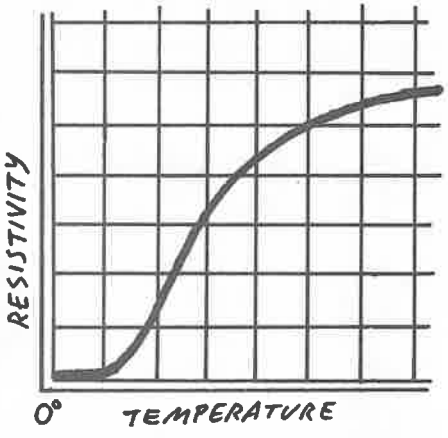
(YOU WANT HIGH RESISTANCE IN A LIGHT BULB, SO THAT IT "DISSIPATES" ELECTRIC ENERGY AS LIGHT!)

RESISTIVITY ALSO CHANGES WITH TEMPERATURE. FOR MOST MATERIALS, IT RISES SLOWLY WITH TEMPERATURE, AS VIBRATING MOLECULES INTERFERE WITH THE FLOW OF CHARGE.

FOR SOME MATERIALS, LIKE MERCURY AND ALUMINUM, THE RESISTIVITY FALLS TO

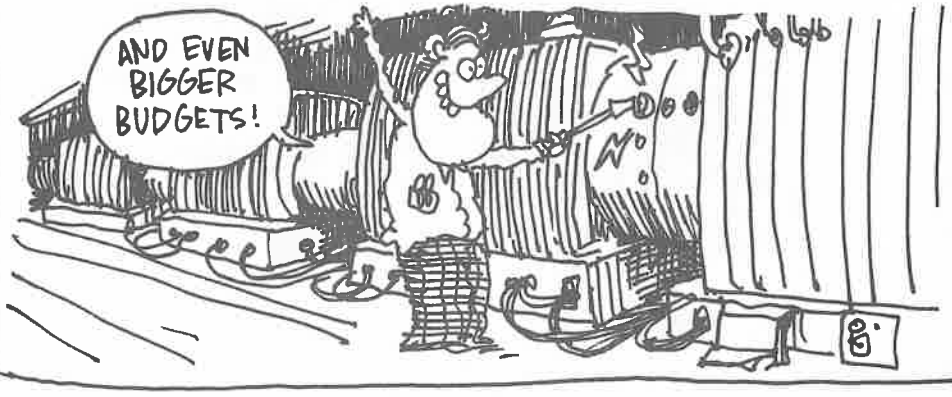
ZERO

AT VERY COLD TEMPERATURES. NEAR ABSOLUTE ZERO (−273° CENTIGRADE), THESE MATERIALS CONDUCT ELECTRICITY WITHOUT ANY RESISTANCE AT ALL. THEN THEY ARE CALLED



superconductors.

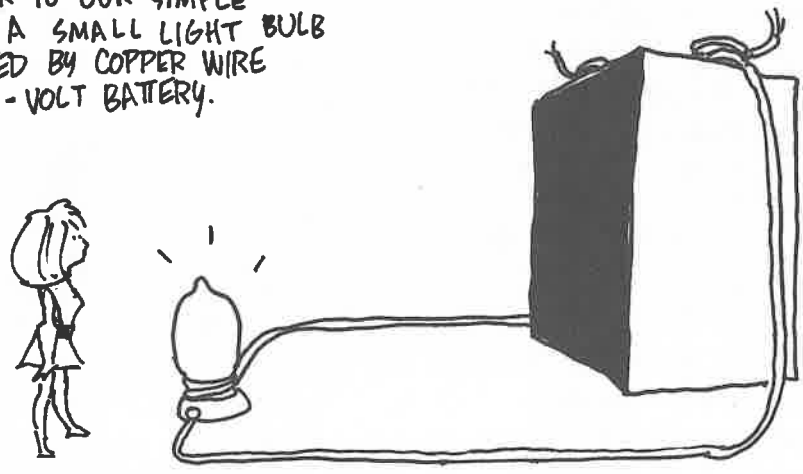
THE WONDERFUL THING ABOUT SUPERCONDUCTORS IS THAT THEY CAN CARRY HUGE CURRENTS WITHOUT ANY LOSS TO HEAT. THESE CURRENTS CAN EVEN PERSIST FOR YEARS WITHOUT LOSS OF ENERGY. SUPERCONDUCTORS, THOUGH EXPENSIVE, ARE USED IN PARTICLE ACCELERATORS, WHERE SUPERSTRONG ELECTROMAGNETS REQUIRE GIANT ELECTRIC CURRENTS.



IN 1986, SCIENTISTS DISCOVERED SEVERAL NEW SUPERCONDUCTING COMPOUNDS THAT LOSE THEIR RESISTIVITY AT MUCH HIGHER TEMPERATURES, AROUND -180° C. THIS MAY SOUND COLD, BUT IT'S A WARM BATH COMPARED WITH ABSOLUTE ZERO.

THESE COMPOUNDS CAN BE CHILLED WITH INEXPENSIVE LIQUID NITROGEN... SO WE MAY SEE SOME AMAZING COMMERCIAL APPLICATIONS IN THE COMING YEARS, SUCH AS LEVITATING TRAINS...

NOW BACK TO OUR SIMPLE CIRCUIT, A SMALL LIGHT BULB CONNECTED BY COPPER WIRE TO A 6-VOLT BATTERY.



THE LAMP FILAMENT MIGHT HAVE 6 OHMS OF RESISTANCE, IN WHICH CASE, BY OHM'S LAW, THE CURRENT WOULD BE

$$i = V/R = \frac{6 \text{ VOLTS}}{6 \text{ OHMS}} = 1 \text{ AMPERE}$$

YOU FORGOT THE RESISTANCE OF THE WIRE...

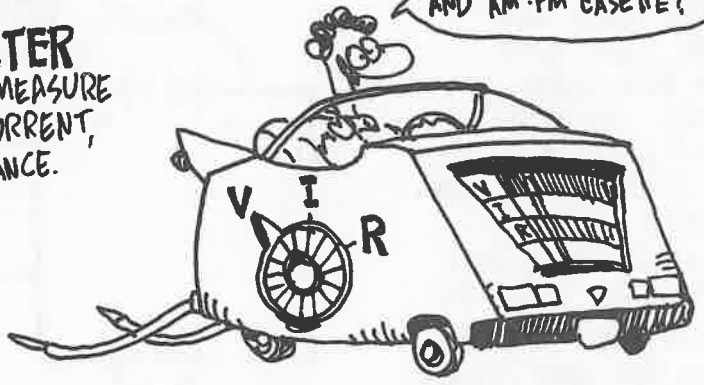
(COPPER WIRE'S RESISTANCE IS NEGLIGIBLE — LESS THAN $\frac{1}{100}$ OHM — CONTRIBUTING LITTLE TO THE OVERALL RESISTANCE*)

THE QUESTION IS, HOW WOULD YOU MEASURE THESE QUANTITIES IN THE CIRCUIT?

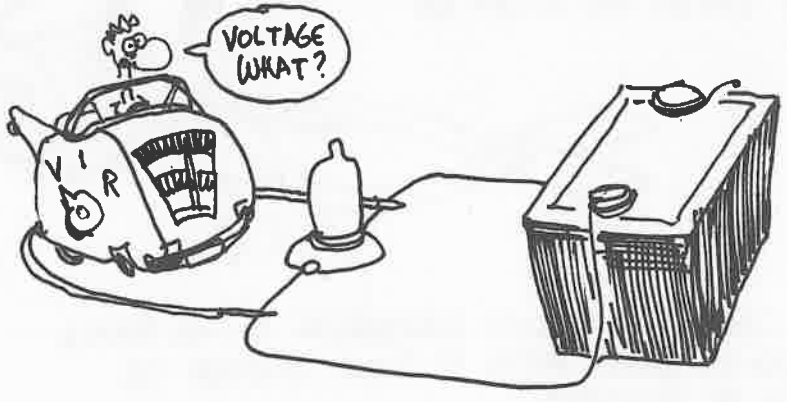
1. REMOVE BULB.
2. INSERT FINGER IN SOCKET.
3. MEASURE RESULTANT HAIR CURL..?

*UNLESS THE WIRE IS VERY LONG OR VERY THIN.

FOR AS LITTLE AS TEN DOLLARS, YOU CAN BUY A **MULTIMETER** THAT WILL MEASURE VOLTAGE, CURRENT, AND RESISTANCE.

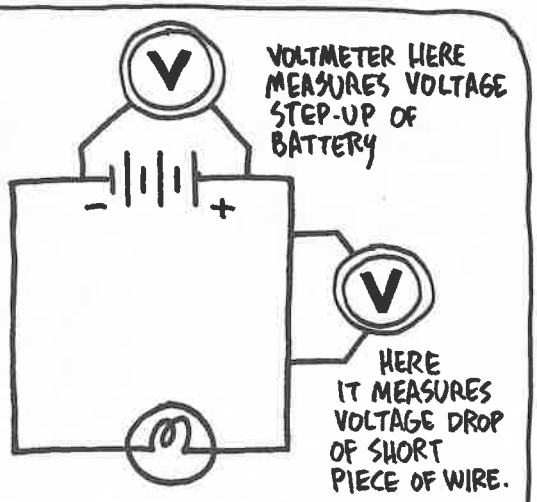


TO MEASURE VOLTAGE, TOUCH THE METER'S LEADS **ACROSS** THE LAMP OR BATTERY. TOUCHING IT ACROSS THE LAMP MEASURES THE **VOLTAGE DROP** OF THE LAMP.



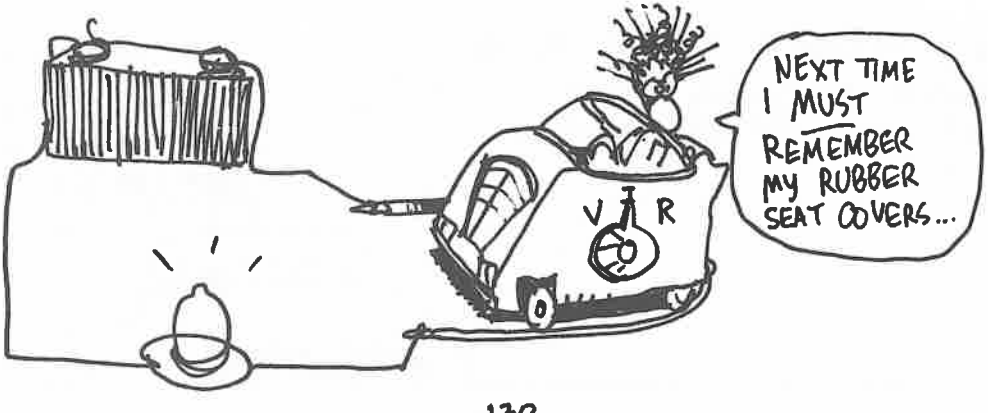
THE VOLTAGE "DROP" REFERS TO THE ENERGY PER CHARGE THAT IS GOING INTO HEAT AND LIGHT.

IF YOU TOUCHED THE LEADS TO THE WIRE ON THE SAME SIDE OF THE LAMP, YOU'D GET A NEAR-ZERO READING. IT TAKES ALMOST NO VOLTAGE TO PUSH CURRENT THROUGH A COPPER WIRE. AND MEASURING ACROSS THE BATTERY GIVES ITS VOLTAGE "STEP-UP," THE ENERGY PER UNIT CHARGE PUMPED INTO THE CIRCUIT BY THE BATTERY.



TO MEASURE **CURRENT**, YOU MUST BREAK THE CIRCUIT AND INSERT THE AMMETER.

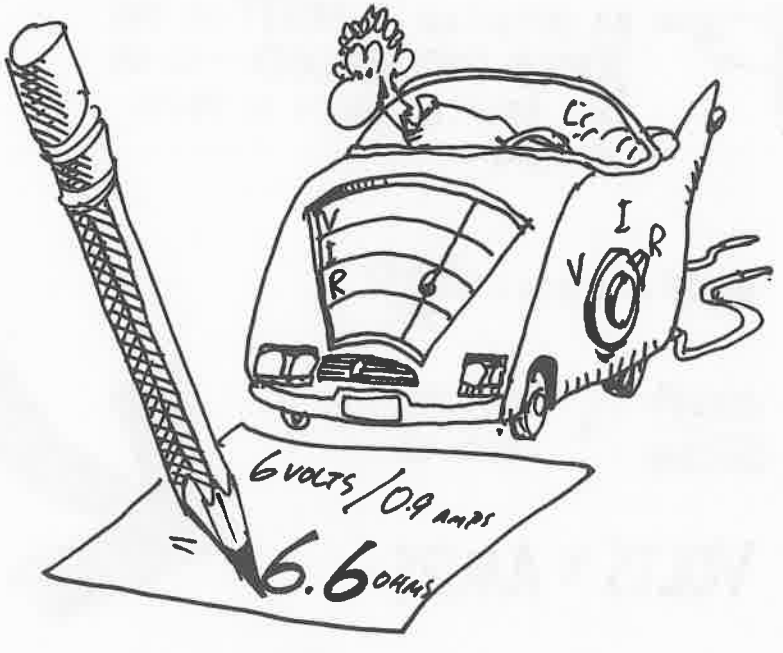
THE SAME CURRENT IS FLOWING EVERYWHERE IN THIS SIMPLE CIRCUIT, AND WE MUST MAKE IT FLOW THROUGH THE AMMETER TO BE MEASURED.



YOU COULD MEASURE THE LAMP FILAMENT'S RESISTANCE DIRECTLY, BY TAKING IT OUT OF THE CIRCUIT AND TESTING IT WITH THE OHMMETER SETTING OF THE MULTIMETER.

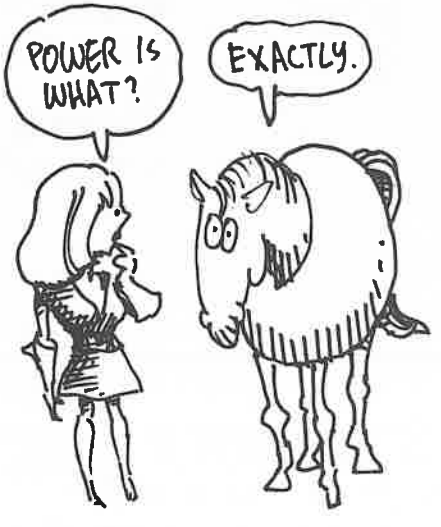
OR YOU COULD USE THE PREVIOUS VOLTAGE AND CURRENT READINGS TO CALCULATE THE RESISTANCE WITH OHM'S LAW.

THESE TWO MEASUREMENTS WOULD ACTUALLY GIVE SOMEWHAT DIFFERENT RESULTS, SINCE WHEN THE BULB IS IN CIRCUIT, THE FILAMENT IS AT HIGH TEMPERATURE (AND HIGHER RESISTANCE), WHEREAS WHEN IT IS MEASURED WITH THE METER, THE FILAMENT IS COOL.

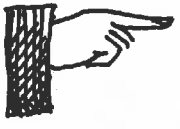


ANOTHER FAMILIAR ELECTRICAL UNIT IS THE

WATT, THE UNIT OF POWER.



POWER IS DEFINED AS **ENERGY** PER UNIT OF TIME. IT MEASURES HOW FAST ENERGY IS PRODUCED OR CONSUMED. POWER APPLIES ALSO TO MECHANICAL SYSTEMS, AS IN A POWERFUL CAR, WHICH CAN ACCELERATE RAPIDLY. A HIGH-POWERED LIGHT BULB PUTS OUT A LOT OF LIGHT PER SECOND.



BY DEFINITION, A **WATT** IS ONE **JOULE PER SECOND** — SO WE CAN RELATE WATTS TO VOLTS AND AMPS.

$$\text{POWER} = \text{WATTS} = \frac{\text{JOULES}}{\text{SEC}} =$$

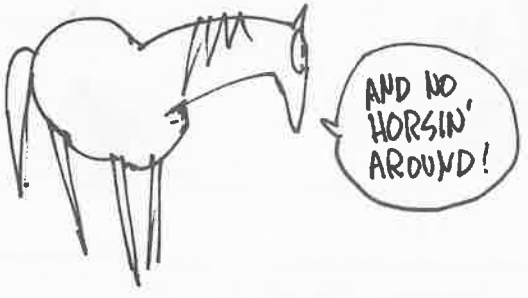
$$\frac{\text{JOULES}}{\text{COULOMB}} \times \frac{\text{COULOMBS}}{\text{SECOND}} =$$

VOLTS × AMPS

THE PRODUCT OF **VOLTAGE** TIMES **CURRENT** IS **POWER:**

$$P = Vi$$

WATTS = VOLTS x AMPS



IN THE CASE OF OUR 6-OHM BULB ATTACHED TO A 6-VOLT BATTERY, WE HAVE ONE AMP OF CURRENT, AND THE POWER IS

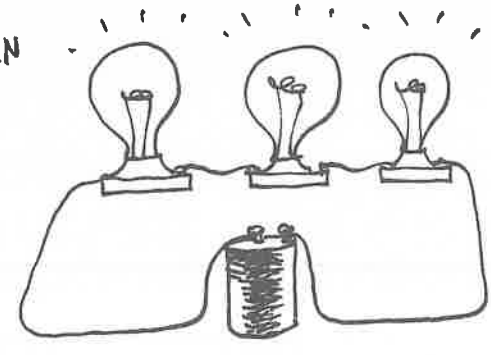
$P = 6 \text{ VOLTS} \times 1 \text{ AMP}$

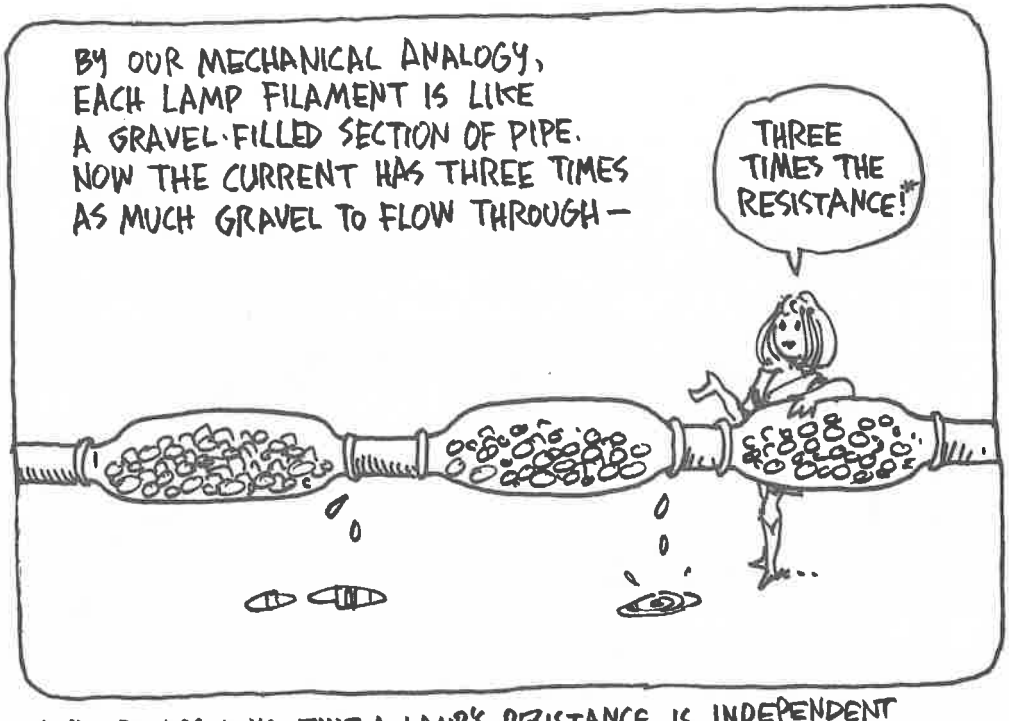
$= 6 \text{ WATTS.}$

CHAPTER 16

SERIES AND PARALLEL

I NOW PUT THREE EQUAL LIGHT BULBS IN **SERIES** WITH A BATTERY. THIS MEANS THEY ARE WIRED TOGETHER ONE AFTER THE OTHER.

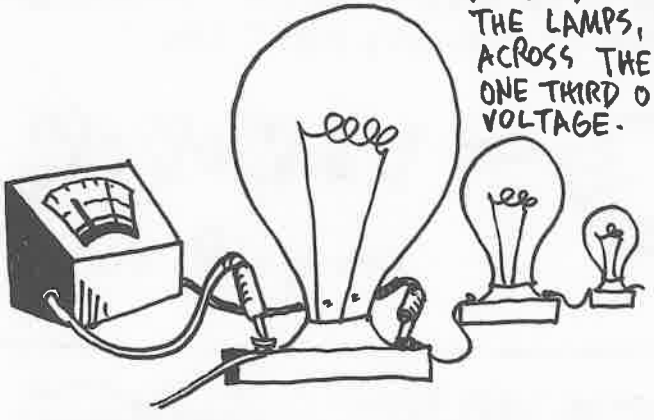




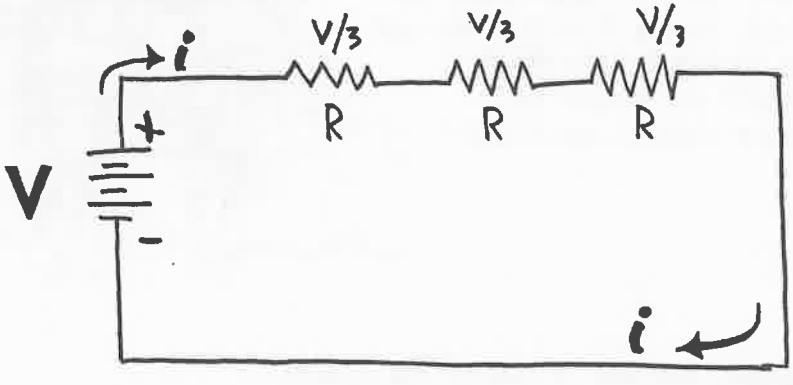
*WE ARE ASSUMING THAT A LAMP'S RESISTANCE IS INDEPENDENT OF CURRENT THROUGH THE LAMP, WHICH IS REALLY NOT THE CASE, SINCE TEMPERATURE OF THE FILAMENT DEPENDS STRONGLY ON CURRENT.

TRIPLING THE RESISTANCE MEANS THAT ONLY ONE THIRD THE CURRENT CAN FLOW. THE CURRENT MUST BE THE SAME IN EACH LIGHT, OF COURSE: THERE IS NOWHERE ELSE FOR THE CHARGE TO GO, AND IT DOESN'T ACCUMULATE IN THE CIRCUIT.

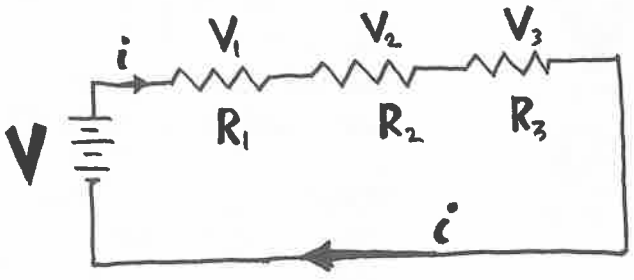
WHEN I TOUCH THE LEADS OF A VOLTMETER ACROSS ONE THE LAMPS, THE VOLTAGE DROP ACROSS THE LAMP IS ONE THIRD OF THE BATTERY VOLTAGE.



THE LAMPS DIVIDE UP THE VOLTAGE, AND THE SUM OF THE VOLTAGE DROPS ACROSS THE SERIES COMPONENTS MUST EQUAL THE BATTERY VOLTAGE.



IN THE MORE GENERAL CASE, WITH UNEQUAL RESISTANCES IN SERIES,



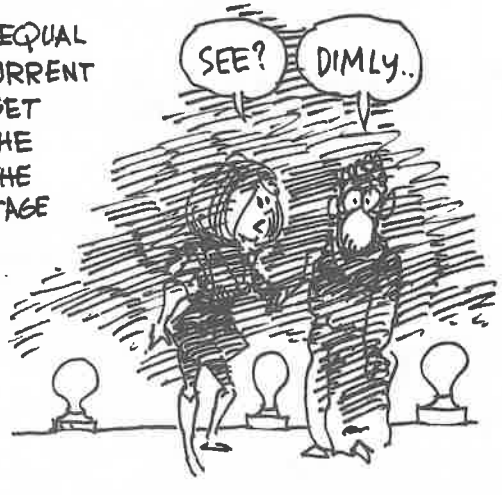
THE VOLTAGE DROPS V_1, V_2, AND V_3 REPRESENT ENERGY CONSUMED BY THE LAMPS,* ENERGY CONVERTED FROM ELECTRIC ENERGY INTO LIGHT AND HEAT.

THE TOTAL ENERGY CONSUMED BY THE LAMPS MUST EQUAL THE ENERGY PRODUCED BY THE BATTERY, SO THESE VOLTAGE DROPS MUST ADD TO THE BATTERY VOLTAGE. THIS IS CALLED THE LOOP THEOREM, OR KIRKHHOFF'S FIRST LAW:

$$V = V_1 + V_2 + V_3$$

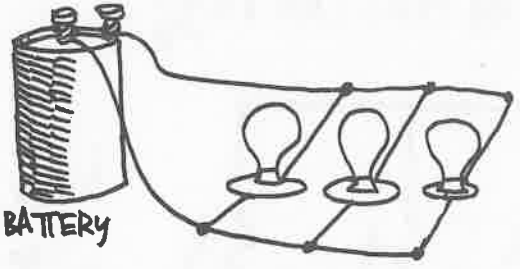
(AND $V_1 = iR_1$, ETC.)

IN SERIES, EACH OF THE THREE EQUAL LAMPS GETS ONE-THIRD THE CURRENT THAT A SINGLE LAMP WOULD GET WHEN CONNECTED ALONE TO THE BATTERY, AND AT ONE-THIRD THE VOLTAGE. SINCE POWER IS VOLTAGE TIMES CURRENT, EACH BULB IS ONE-NINTH AS BRIGHT AS ONE BULB CONNECTED ALONE!!



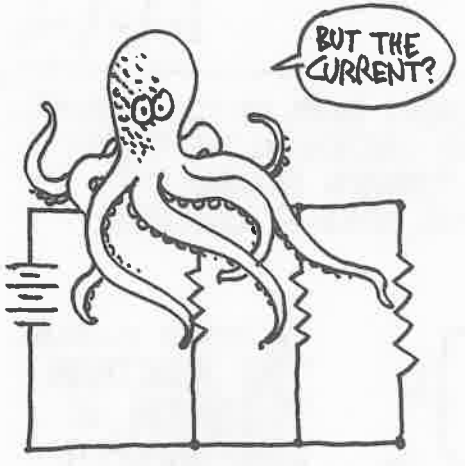
* REMEMBER, VOLTAGE IS ENERGY PER CHARGE.

NOW LET'S CONNECT THE BULBS IN **PARALLEL**:

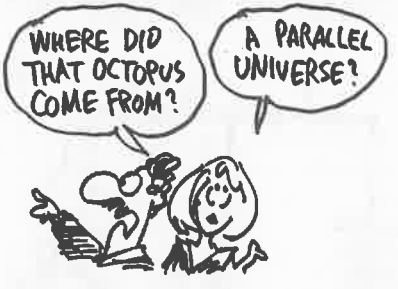


EACH LAMP IS CONNECTED DIRECTLY TO THE BATTERY, WITH NO OTHER BULB INTERVENING.

THIS WAY EVERY BULB GETS A FULL DOSE OF VOLTAGE, AND SHINES WITH ITS NORMAL BRIGHTNESS. THIS IS THE WAY A HOUSE WOULD NORMALLY BE WIRED SO THAT EVERY ELECTRIC FIXTURE GETS FULL HOUSE VOLTAGE.

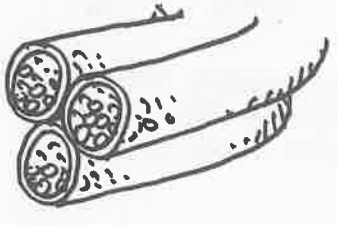


IN THE PARALLEL CIRCUIT, THE **CURRENT** HAS TO DIVIDE AND FLOW THROUGH THE THREE BRANCHES.

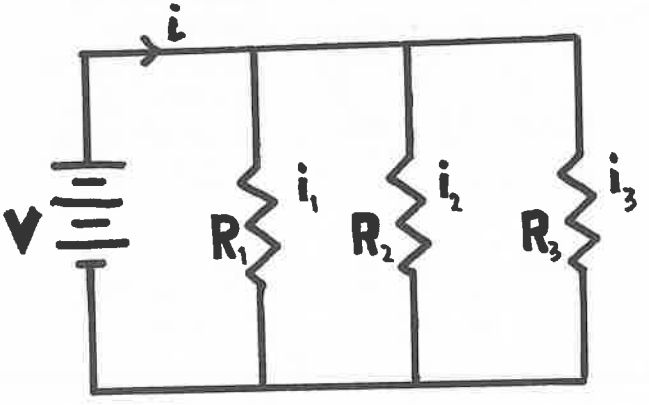


BUT THE TOTAL **RESISTANCE** OF THE CIRCUIT IS ONE THIRD THAT OF ONE BULB — THERE IS THREE TIMES AS MUCH "AREA OF GRAVEL" TO FLOW THROUGH. THIS MAKES IT EASIER!

THEN, BY OHM'S LAW, THREE TIMES AS MUCH CURRENT CAN FLOW THROUGH THE CIRCUIT AS A WHOLE.



TO SUM UP, IN PARALLEL EACH COMPONENT GETS THE SAME VOLTAGE, AND DRAWS A CURRENT i INVERSELY PROPORTIONAL TO ITS RESISTANCE, BY OHM'S LAW $i = V/R$.



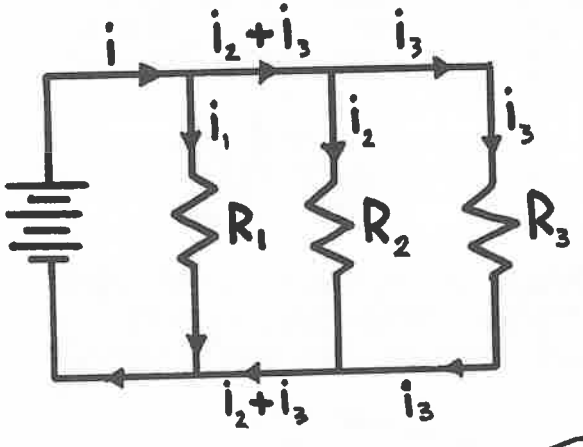
$$i_1 = \frac{V}{R_1}$$

$$i_2 = \frac{V}{R_2}$$

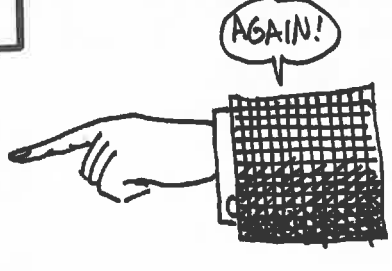
$$i_3 = \frac{V}{R_3}$$

$$i = i_1 + i_2 + i_3$$

WHAT IS THE CURRENT IN DIFFERENT PARTS OF THE CIRCUIT? THE CURRENT FLOWING INTO ANY JUNCTION IN THE CIRCUIT MUST EQUAL THE SUM OF THE CURRENTS FLOWING OUT. CURRENT IS THE FLOW OF CHARGE, WHICH IS CONSERVED.



THE RESULT IS CALLED **THE JUNCTION THEOREM**, OR **KIRCHHOFF'S SECOND LAW:**

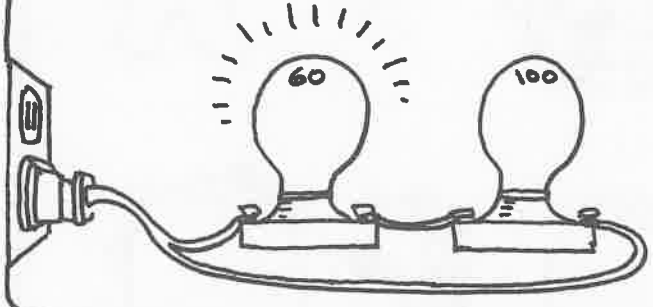


THE CURRENT FLOWING INTO ANY JUNCTION EQUALS THE SUM OF THE CURRENTS FLOWING OUT.

HERE IS AN INTERESTING

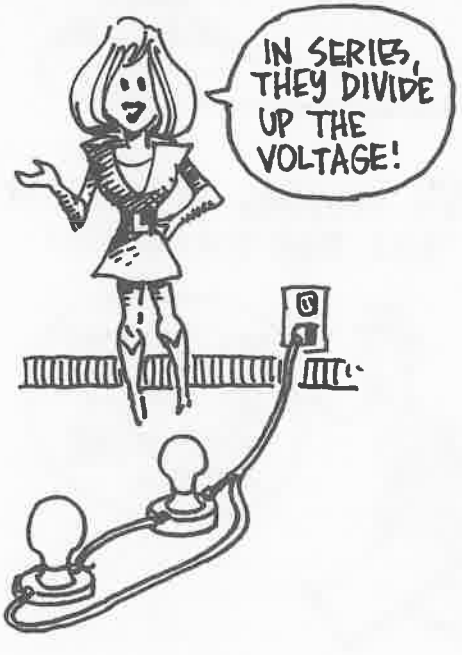
PARADOX!

I'M GOING TO HOOK UP A 60-WATT BULB AND A 100-WATT BULB IN SERIES.



THE **60** WATT BULB IS **BRIGHTER!!** WHAT'S GOING ON HERE?

FIRST, REMEMBER THAT THE WATT RATINGS ARE GOOD ONLY IF THE BULBS ARE PLUGGED IN ALONE, NOT IN SERIES.

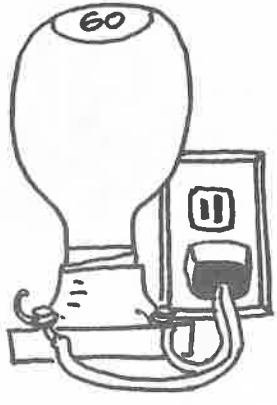


HOW MUCH VOLTAGE DOES EACH BULB IN SERIES GET? BOTH BULBS GET THE SAME CURRENT i, SO OHM'S LAW

$$V = iR$$

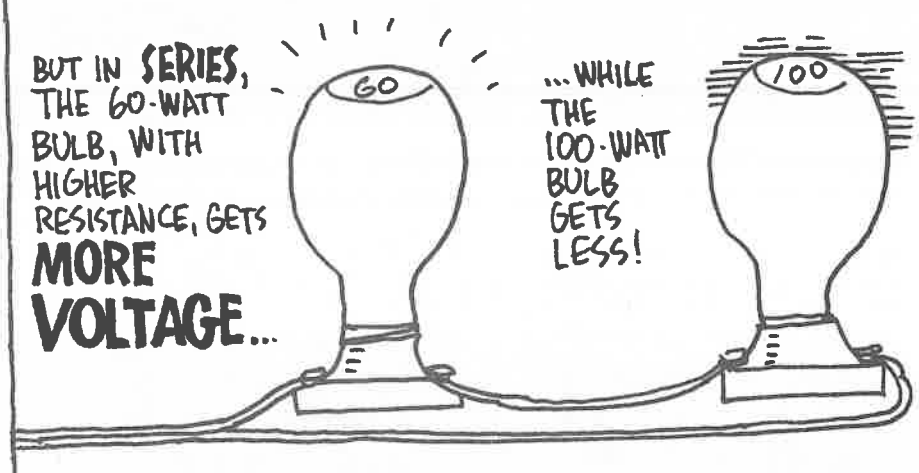
GIVES THE VOLTAGE DROP ACROSS EACH BULB.

NOW THE 60-WATT BULB HAS GREATER RESISTANCE: WHEN PLUGGED IN ALONE, IT DRAWS LESS CURRENT AND GLOWS LESS BRIGHTLY.



THE 100-WATT BULB, WITH LESS RESISTANCE, DRAWS MORE CURRENT WHEN PLUGGED IN ALONE.

BUT IN **SERIES**, THE 60-WATT BULB, WITH HIGHER RESISTANCE, GETS **MORE VOLTAGE**...



...WHILE THE 100-WATT BULB GETS LESS!

SO THE ACTUAL POWER **P=Vi** DELIVERED TO EACH LAMP IS HIGHER FOR THE 60-WATT BULB THAN FOR THE 100!