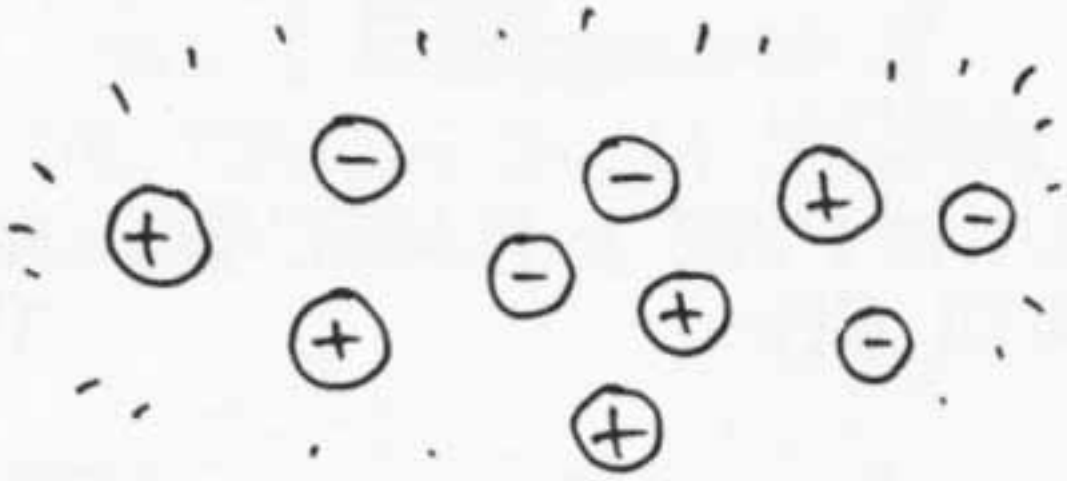
CHAPTER 12
CHARGE

WE NOW TURN FROM MECHANICS TO ELECTRICITY AND MAGNETISM. IN MECHANICS WE USED THE BASIC PROPERTY OF MATTER CALLED **MASS**. IN ELECTRICITY, THE BASIC CONCEPT IS **CHARGE**.

MECHANICAL CONCEPT



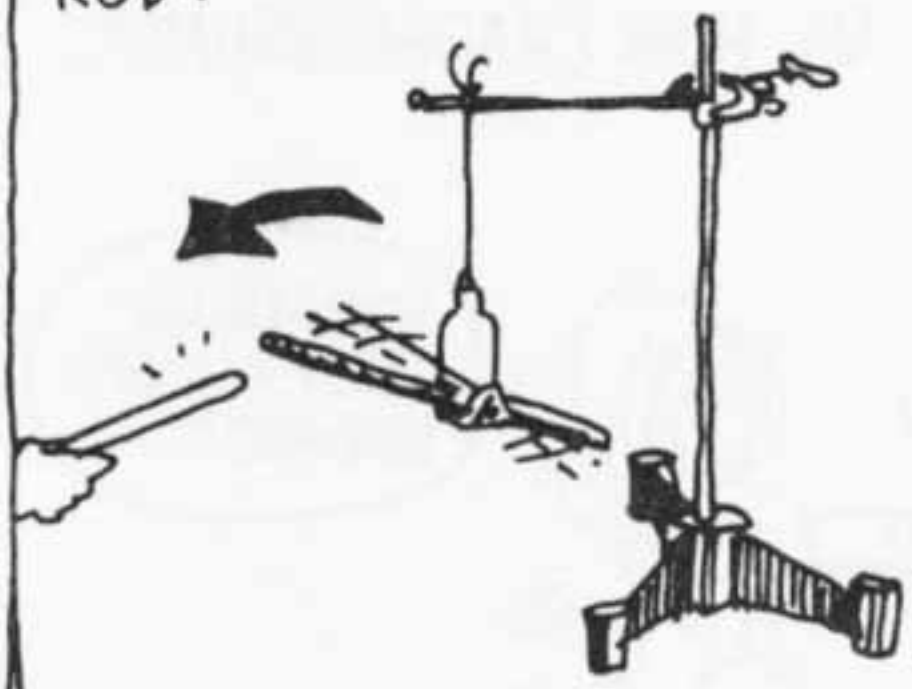
ELECTRICAL CONCEPT

NOTICE THAT MECHANICS NEVER TOLD US WHAT MASS "REALLY IS," BUT ONLY HOW IT BEHAVES. IN THE SAME WAY, CLASSICAL E&M TELLS US HOW CHARGE BEHAVES, BUT NOT WHAT IT IS.

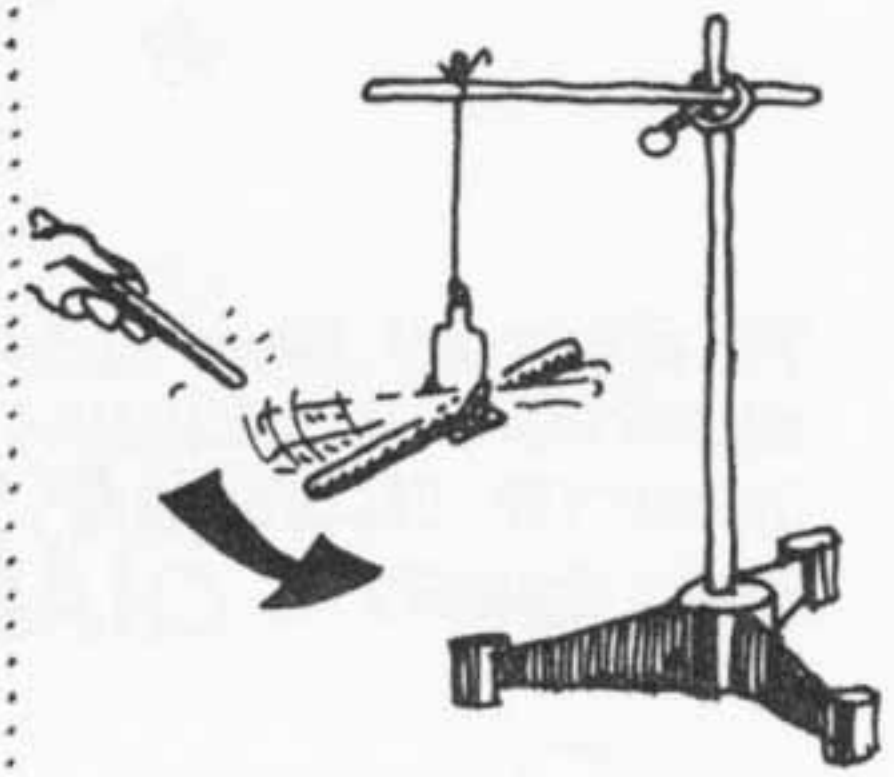
IT IS EASY TO PRODUCE A LITTLE CHARGE — JUST RUN A RUBBER COMB THROUGH YOUR HAIR, OR RUB A RUBBER ROD WITH ANIMAL FUR.

BUT IF I RUB A PLASTIC ROD WITH SILK...

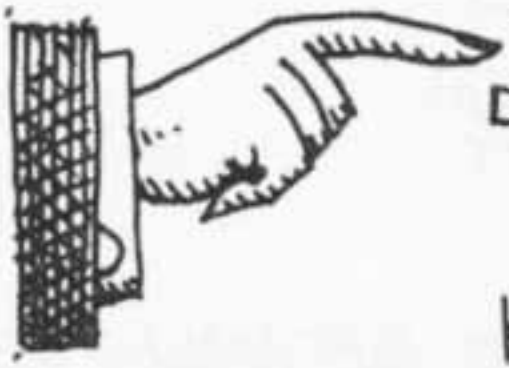
IT ATTRACTS THE RUBBER ROD!



PLACE THE CHARGED ROD IN A HANGING STIRRUP AND BRING ANOTHER, SIMILARLY CHARGED ROD NEAR — THEY **REPEL.**



FROM EXPERIMENTS LIKE THESE WE LEARN THAT



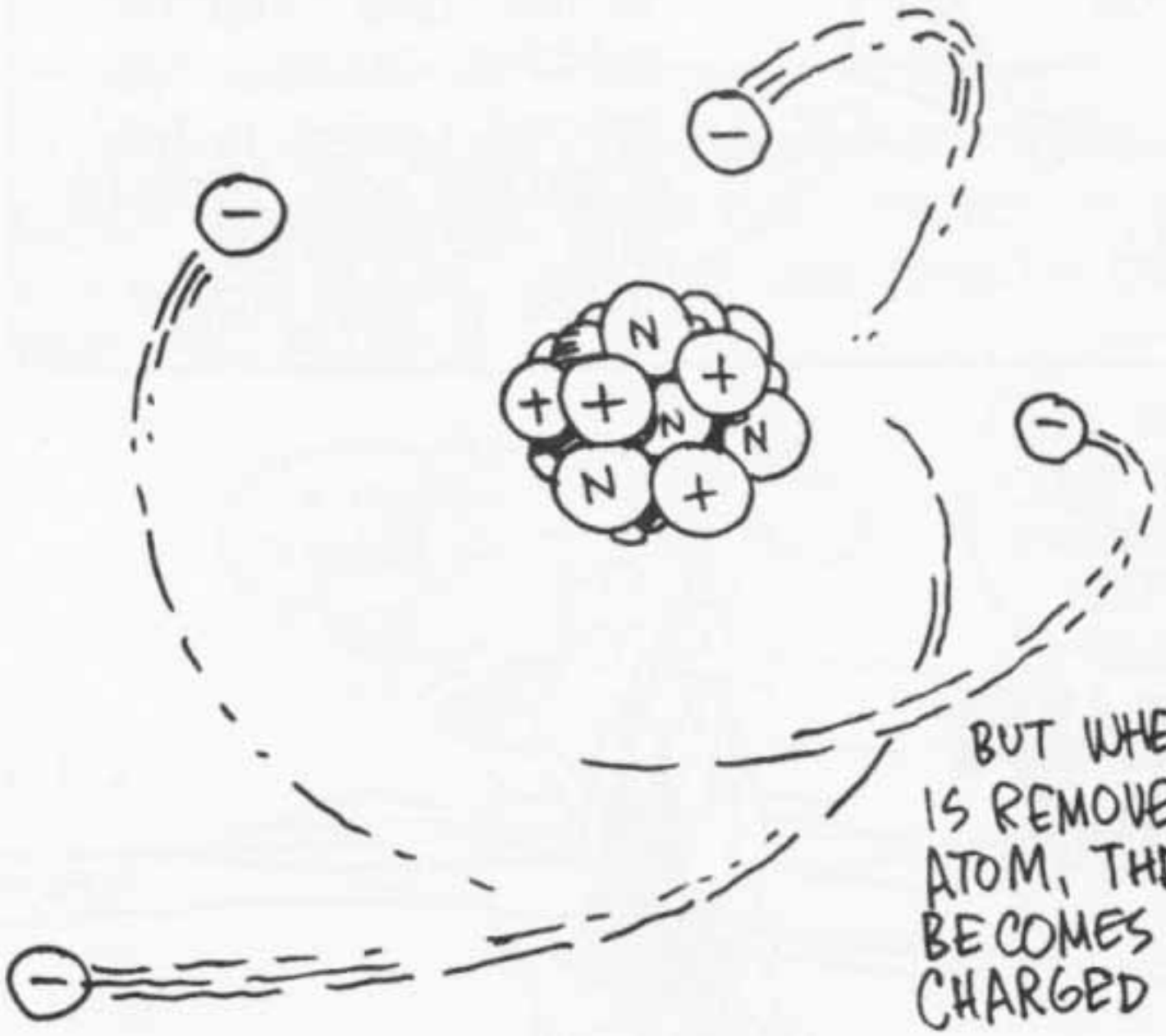
THERE ARE **TWO** KINDS OF CHARGE...

AND THAT LIKE CHARGES REPEL, AND UNLIKE CHARGES ATTRACT!!

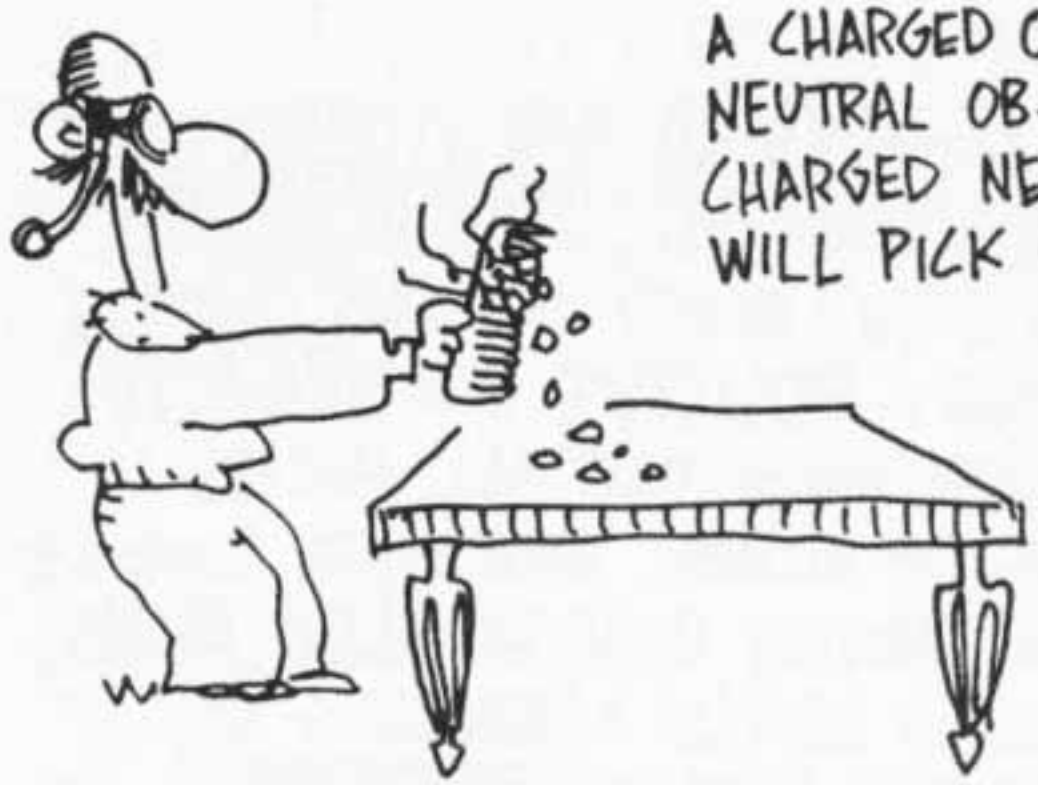
BENJAMIN FRANKLIN

(1706-1790) NAMED THE TWO KINDS OF CHARGES **POSITIVE** AND **NEGATIVE**. WE NOW KNOW THAT ALL MATTER IS MADE OF ATOMS, WHICH ARE COMPOSED OF NEGATIVELY CHARGED **ELECTRONS**, WHIRLING AROUND A NUCLEUS OF POSITIVELY CHARGED **PROTONS**, AND **NEUTRONS**, WHICH HAVE NO CHARGE.

ELECTRONS AND PROTONS HAVE EQUAL AND OPPOSITE CHARGES. NORMAL ATOMS HAVE EXACTLY ENOUGH ELECTRONS TO BALANCE THE PROTONS IN THE NUCLEUS, MAKING THE ATOM OVERALL NEUTRAL.



BUT WHEN AN ELECTRON IS REMOVED FROM AN ATOM, THE ATOM BECOMES A POSITIVELY CHARGED **ION**.



A CHARGED OBJECT WILL ALSO ATTRACT NEUTRAL OBJECTS. THIS RUBBER COMB, CHARGED NEGATIVELY BY RINGO'S HAIR, WILL PICK UP BITS OF PAPER.

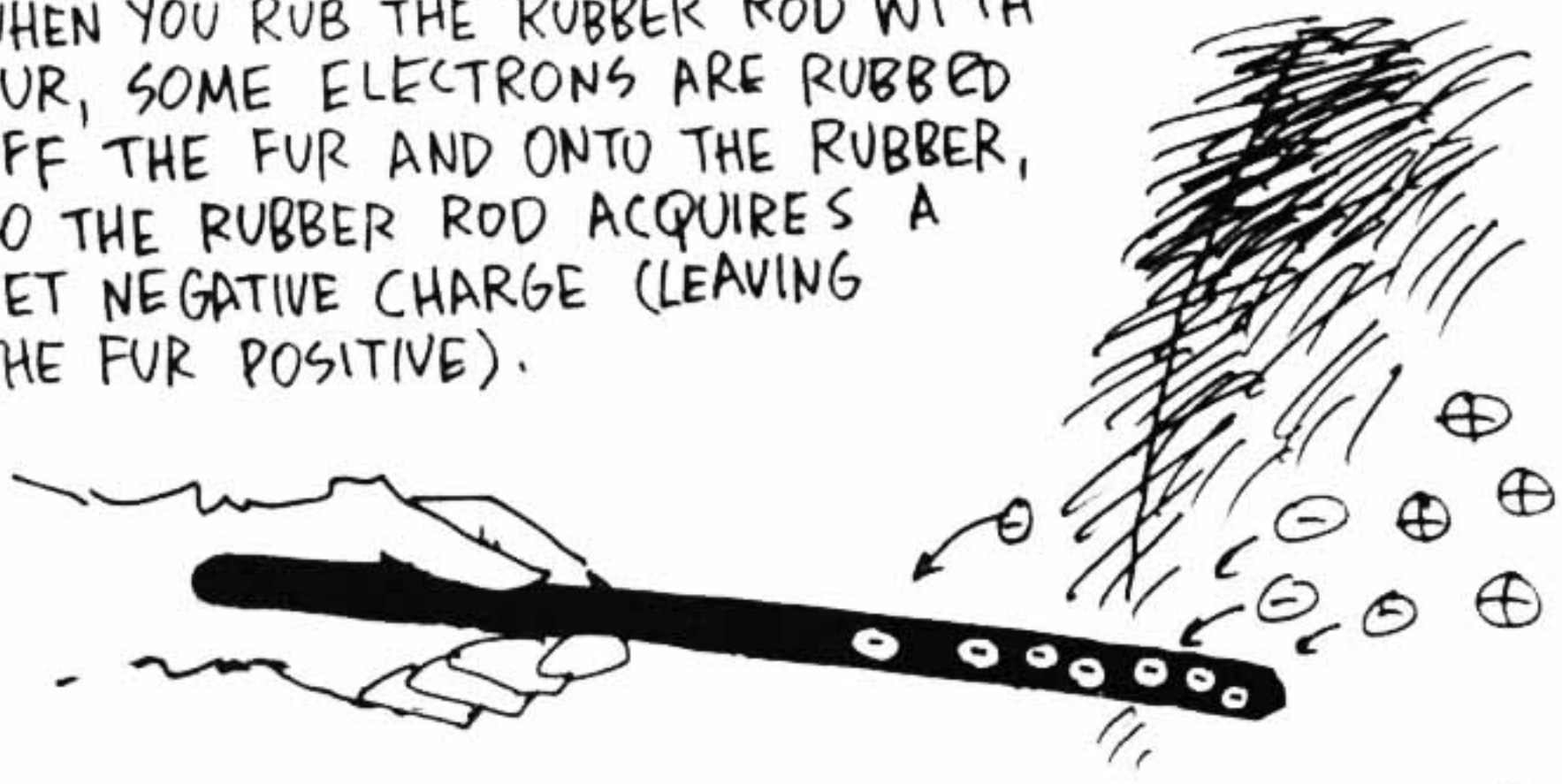
IT DOES SO BECAUSE THE PAPER BECOMES ELECTRICALLY **POLARIZED:**

THE NEGATIVE COMB REPELS ELECTRONS IN THE PAPER AND ATTRACTS THE POSITIVE NUCLEI OF THE ATOMS IN THE PAPER. THERE IS A CHARGE SHIFT IN THE PAPER! EVEN THOUGH IT IS NEUTRAL OVERALL ...

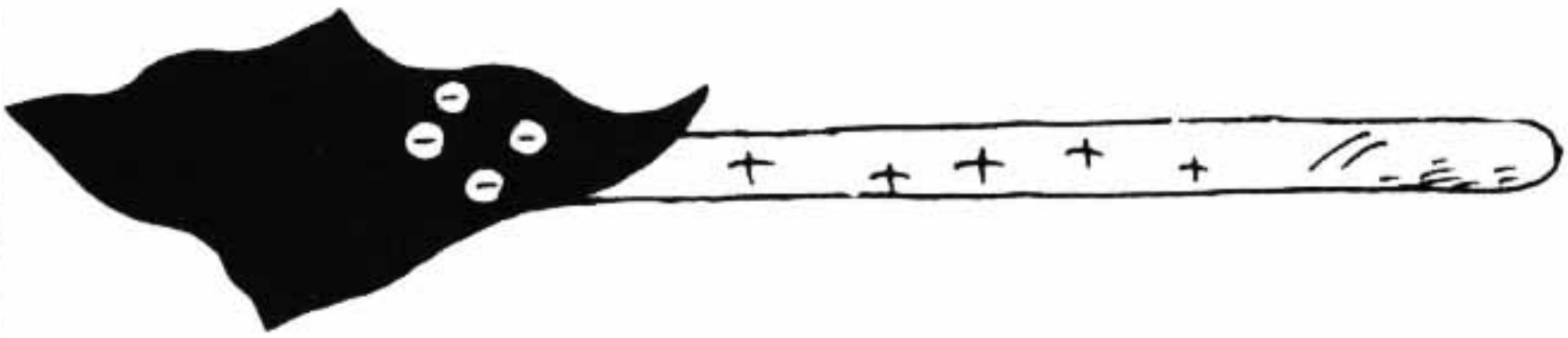
... THE POSITIVE CHARGE IN THE PAPER IS CLOSER TO THE COMB THAN THE NEGATIVE CHARGE. THE POSITIVE CHARGE IS THEN ATTRACTED MORE STRONGLY THAN THE NEGATIVE CHARGE IS REPELLED!

FROM SUCH OBSERVATIONS, WE DEDUCE THAT THE ELECTRICAL FORCE **GROWS WEAKER WITH DISTANCE.**

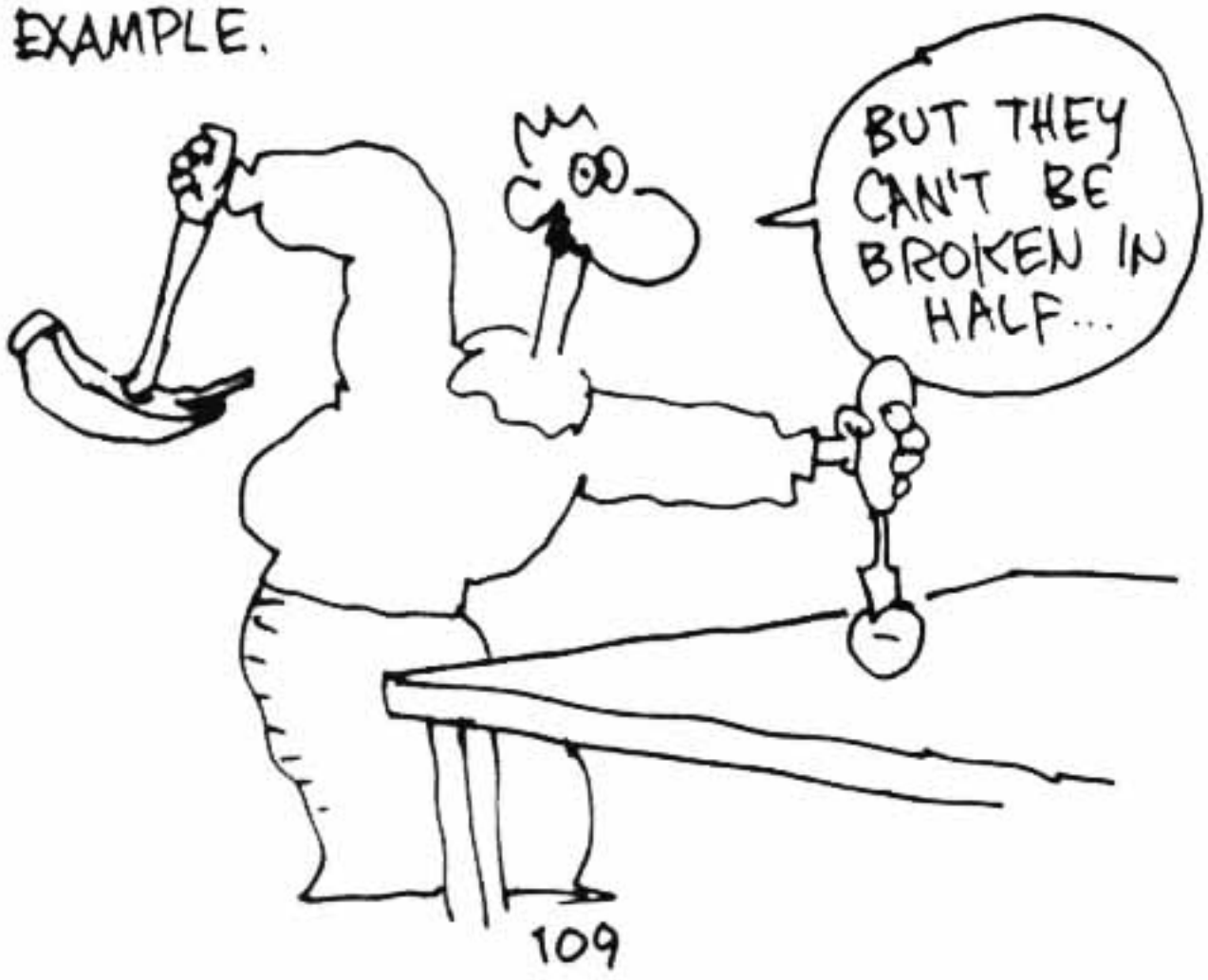
WHEN YOU RUB THE RUBBER ROD WITH FUR, SOME ELECTRONS ARE RUBBED OFF THE FUR AND ONTO THE RUBBER, SO THE RUBBER ROD ACQUIRES A NET NEGATIVE CHARGE (LEAVING THE FUR POSITIVE).

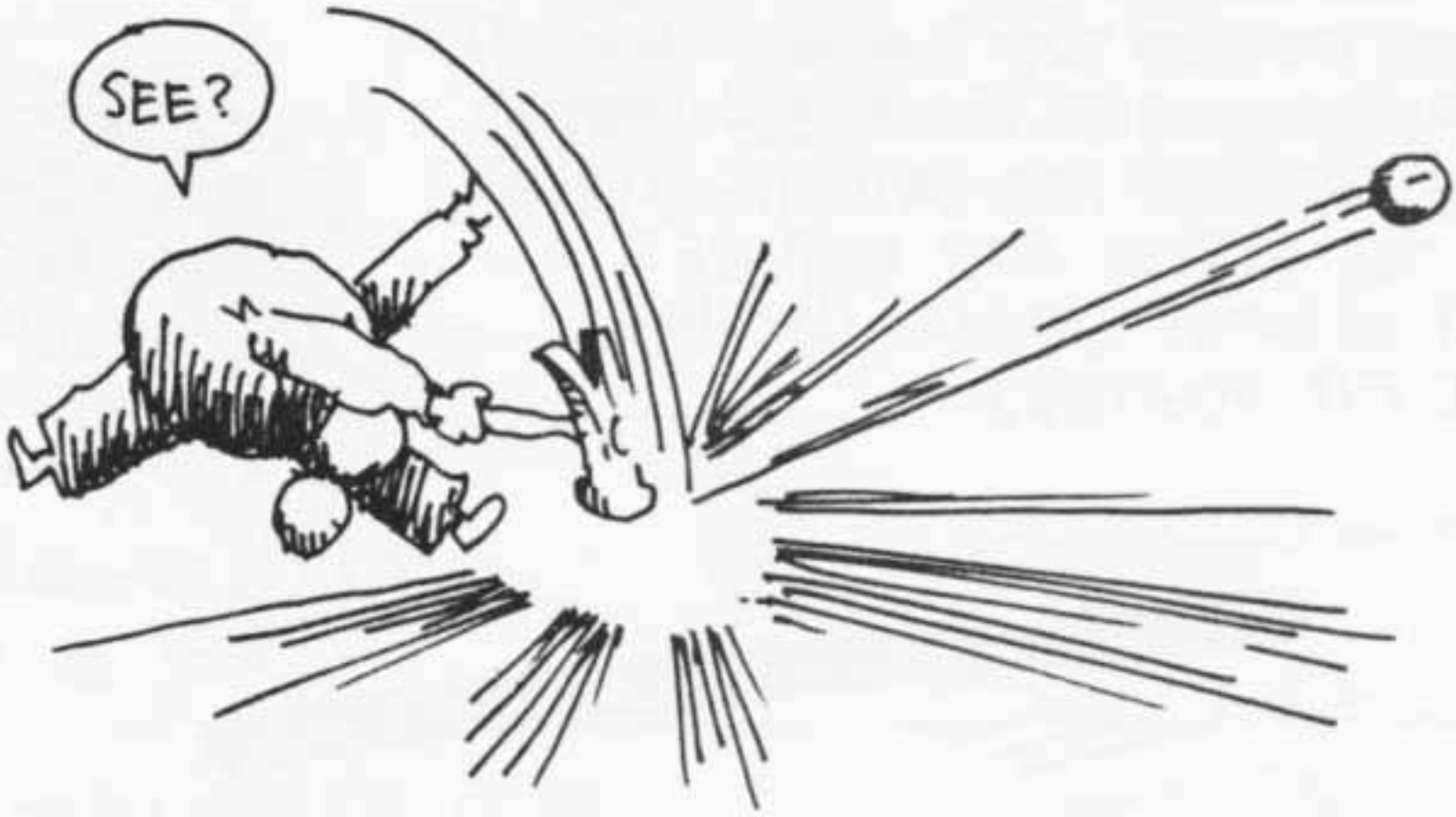


SIMILARLY, SILK RUBS ELECTRONS OFF THE PLASTIC, LEAVING THE PLASTIC WITH A NET POSITIVE CHARGE.

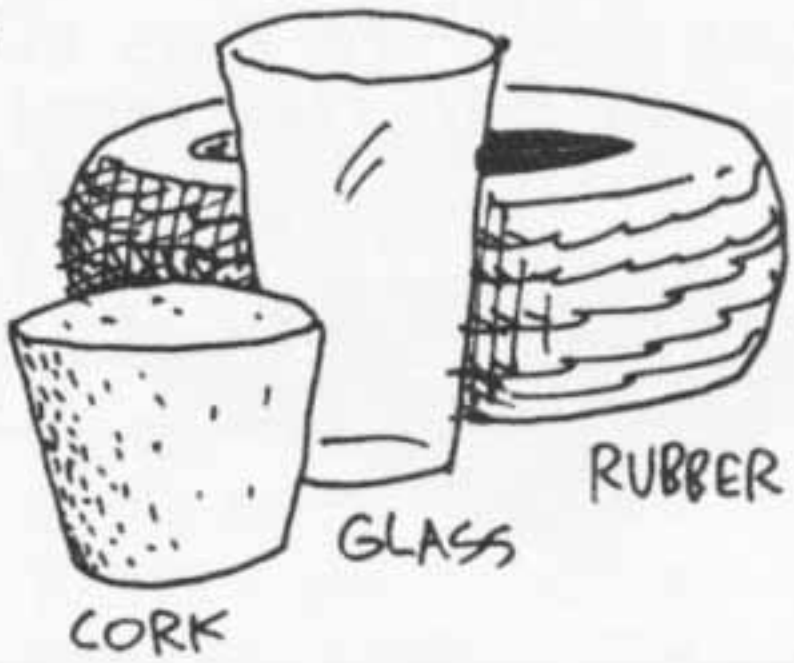


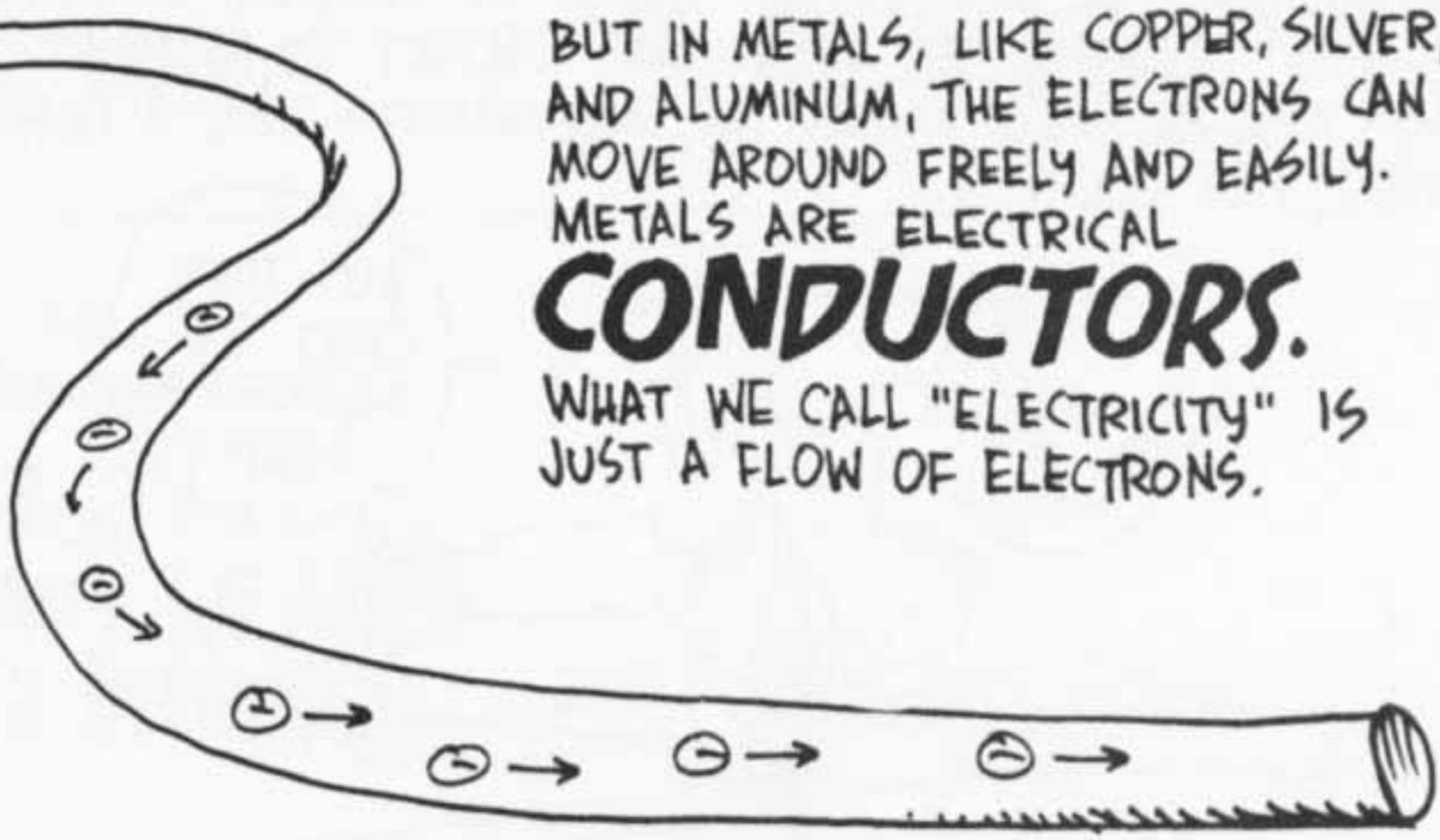
ELECTRONS ARE ELEMENTARY UNITS OF CHARGE, AND ARE EASILY TRANSFERRED FROM ONE OBJECT TO ANOTHER. THEY MAY ALSO BE PASSED ALONG THE SAME OBJECT – LIKE A COPPER WIRE, FOR EXAMPLE.





MATERIALS LIKE RUBBER, GLASS, AND PLASTIC ARE ELECTRICAL **INSULATORS**. CHARGE CAN BE RUBBED ON OR OFF THEIR SURFACES, BUT IT TENDS TO STICK THERE AND WILL NOT MOVE EASILY THROUGH THE MATERIALS.





BUT IN METALS, LIKE COPPER, SILVER, AND ALUMINUM, THE ELECTRONS CAN MOVE AROUND FREELY AND EASILY. METALS ARE ELECTRICAL **CONDUCTORS**.

WHAT WE CALL "ELECTRICITY" IS JUST A FLOW OF ELECTRONS.

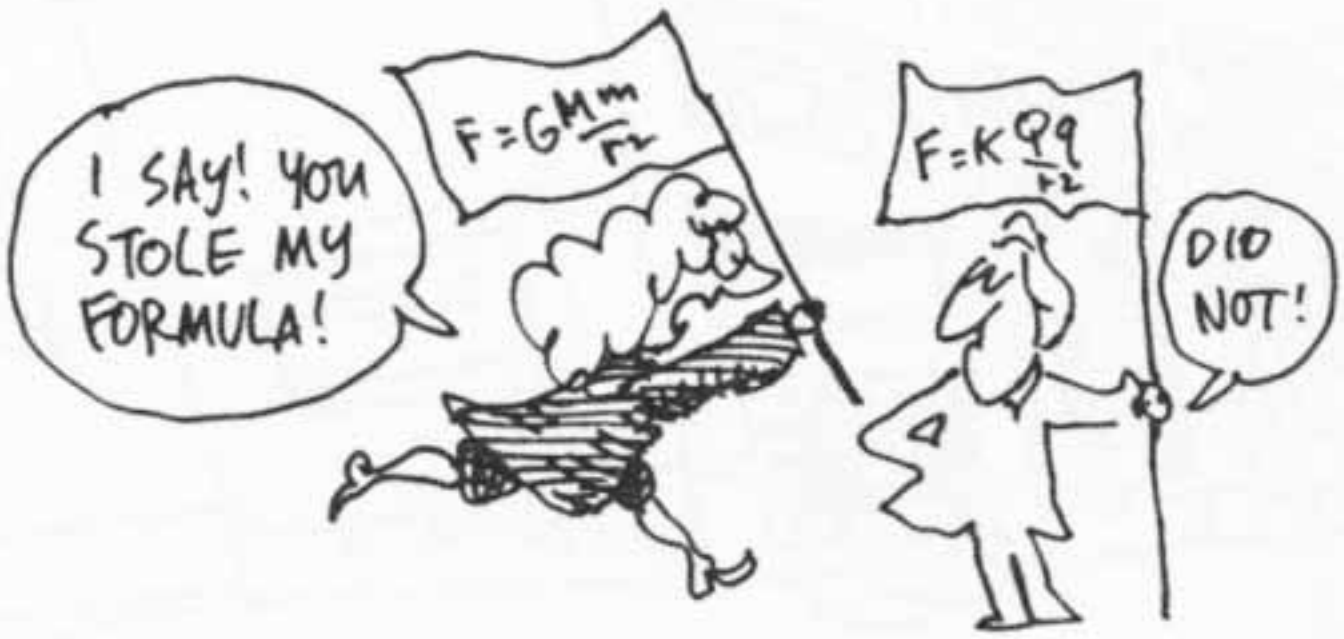
CAREFUL MEASUREMENTS BY CHARLES **COULOMB** (1736-1806) ESTABLISHED THAT THE ELECTRIC FORCE DECREASES WITH THE SQUARE OF THE DISTANCE, LIKE GRAVITY. COULOMB'S LAW FOR ELECTROSTATIC* FORCES IS VERY MUCH LIKE NEWTON'S LAW OF GRAVITY:

$$F = k\frac{Qq}{r^2}$$

*ELECTROSTATIC MEANS THAT THE CHARGES ARE STATIONARY.

IN COULOMB'S EQUATION, Q AND q ARE THE VALUES OF THE CHARGES, r IS THE DISTANCE BETWEEN THEM, AND k IS A CONSTANT, LIKE G FOR GRAVITY. IN STANDARD UNITS, $k = 9 \times 10^9$.

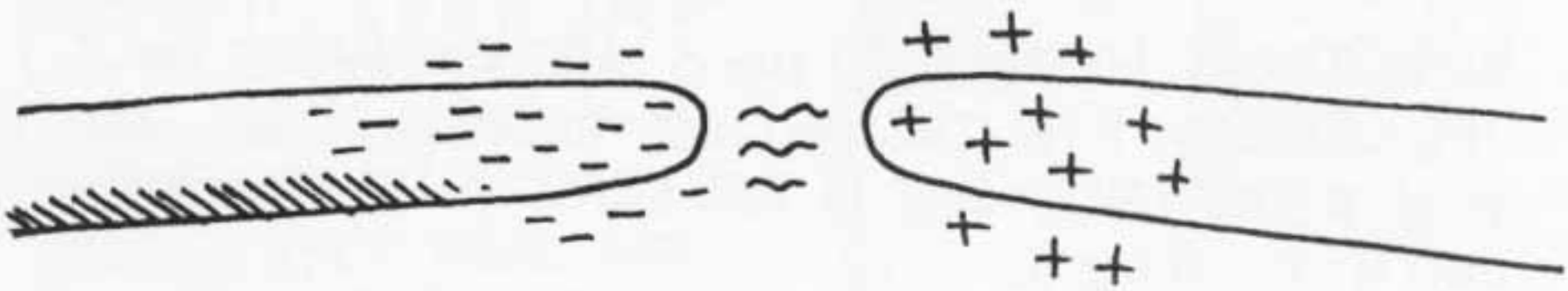
THE UNIT OF CHARGE IS THE **COULOMB**. A SINGLE ELECTRON HAS A CHARGE OF $-e = 1.6 \times 10^{-19}$ COULOMBS.



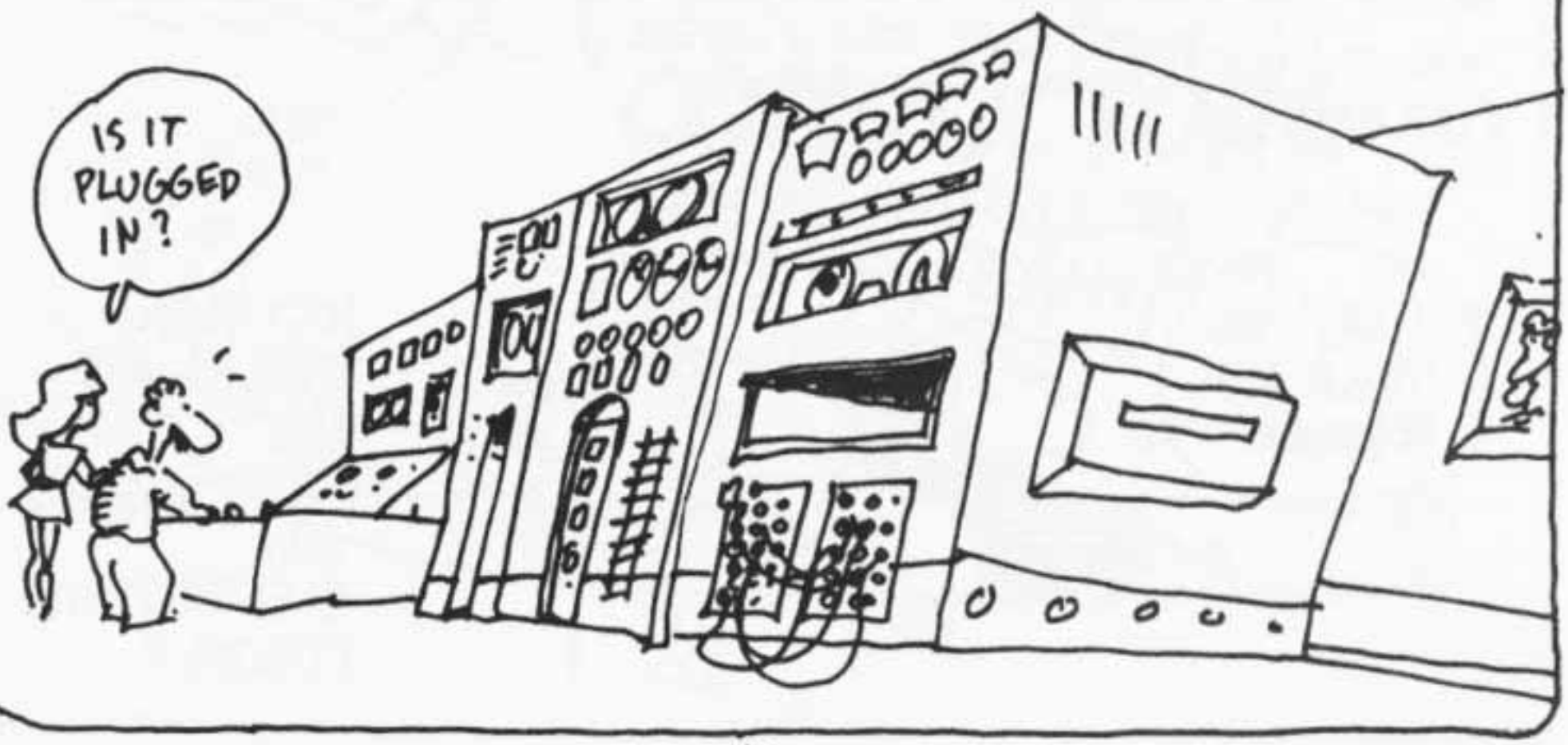
JUST HOW SIMILAR ARE THE GRAVITATIONAL AND ELECTROSTATIC FORCES?

ALTHOUGH THE LAW OF ELECTROSTATIC FORCES SEEMS VERY SIMILAR TO THE LAW OF GRAVITY, THERE ARE MAJOR DIFFERENCES BETWEEN THEM. FOR EXAMPLE, GRAVITY ALWAYS ATTRACTS, BUT ELECTRICAL FORCES CAN EITHER ATTRACT OR REPEL.

ALSO, ELECTRICAL FORCES ARE VASTLY STRONGER THAN GRAVITATIONAL FORCES. IF A (MERE!) HUNDRED BILLION ELECTRONS WERE MOVED FROM A PLASTIC ROD TO A RUBBER ONE, THERE IS A PERCEPTIBLE ATTRACTION BETWEEN THEM.



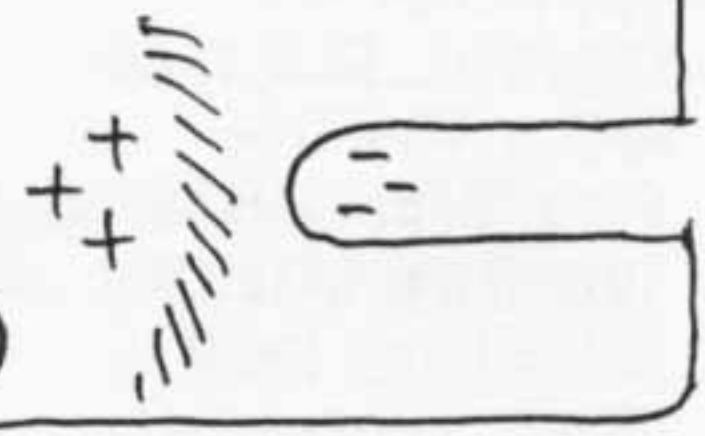
BUT EVEN WITH ALL 10^{24} ($= 10^{15}$ BILLION) ATOMS IN THE ROD PULLING GRAVITATIONALLY, THE MOST SENSITIVE INSTRUMENTS WOULD HAVE TROUBLE DETECTING IT!

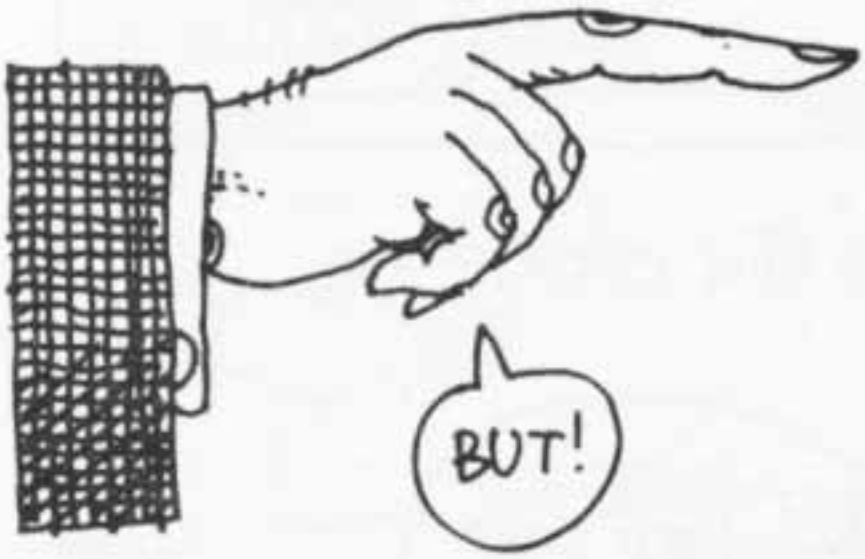


CHEW ON THIS!

CHARGE IS CONSERVED — THE NET CHARGE, THE SUM OF THE NEGATIVE AND POSITIVE CHARGES IN AN ISOLATED SYSTEM CANNOT CHANGE.

(WHEN THE NEUTRAL RUBBER WAS CHARGED BY THE ANIMAL FUR, THE POSITIVE CHARGE ON THE FUR MATCHES THE NEGATIVE CHARGE ON THE RUBBER.)

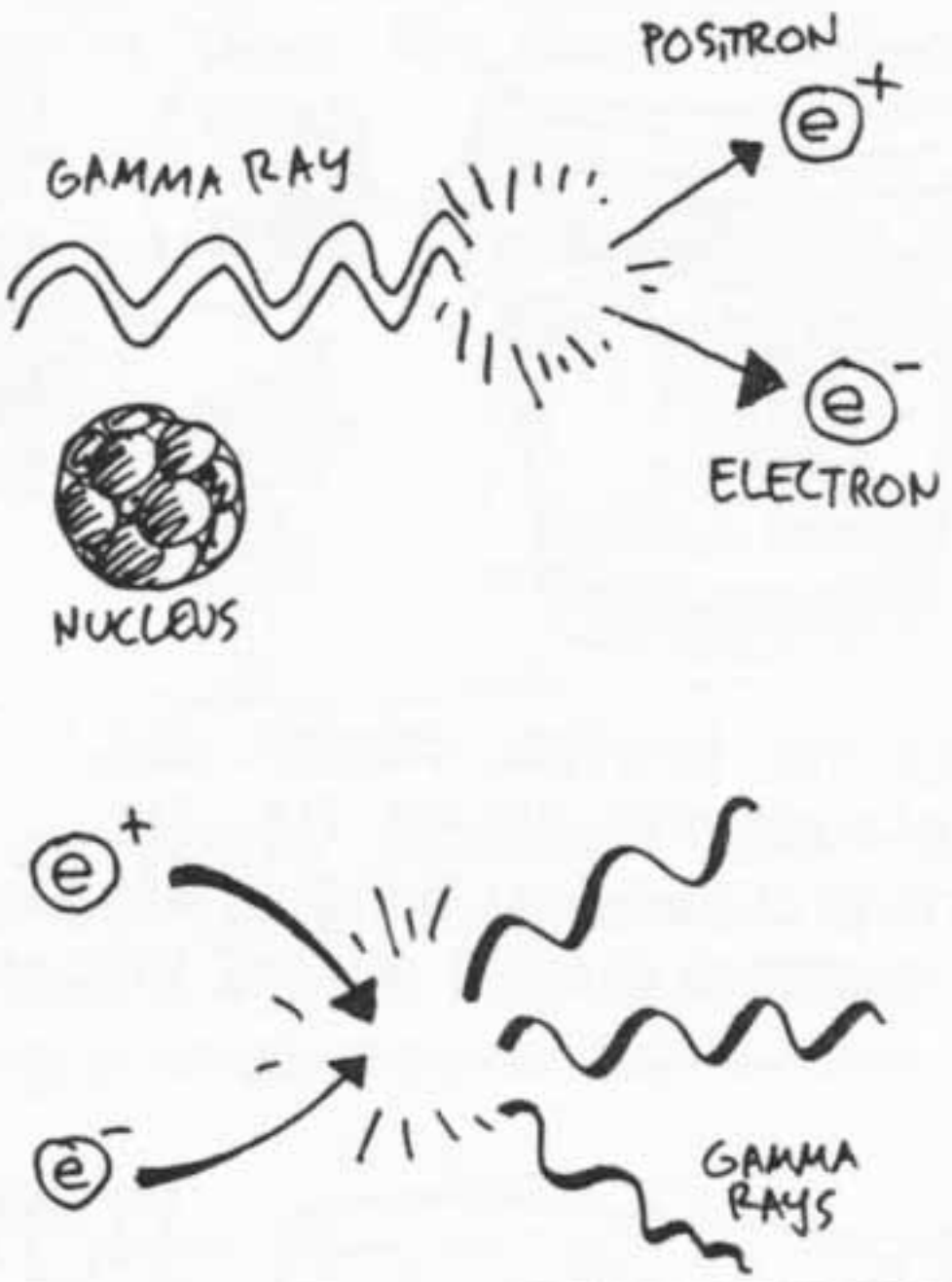




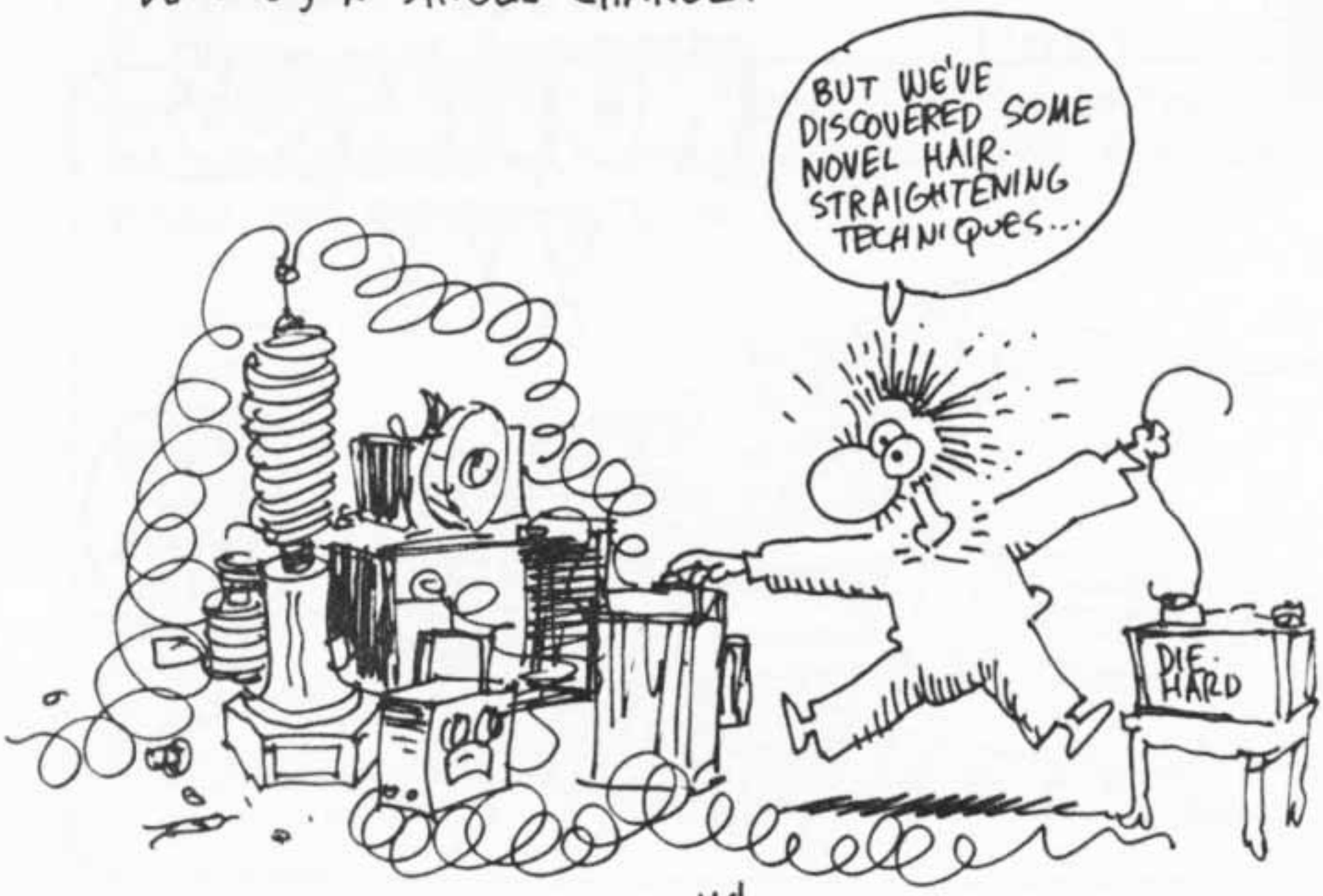
IT IS POSSIBLE TO CREATE PAIRS OF CHARGES FROM NOTHING

!!!

THIS IS DONE BY A **GAMMA RAY**, A VERY HIGH-ENERGY PARTICLE OF LIGHT. WHEN A GAMMA RAY PASSES NEAR AN ATOMIC NUCLEUS, IT MAY CREATE TWO PARTICLES — A NEGATIVE ELECTRON AND A POSITIVE POSITRON. THESE TWO MAY LATER ANNIHILATE EACH OTHER, PRODUCING MORE GAMMA RAYS.

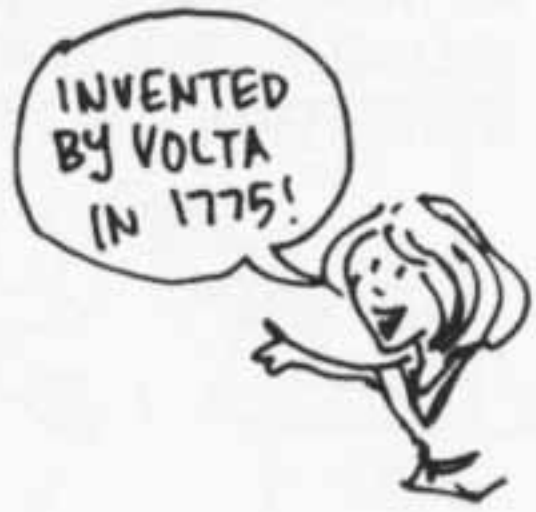


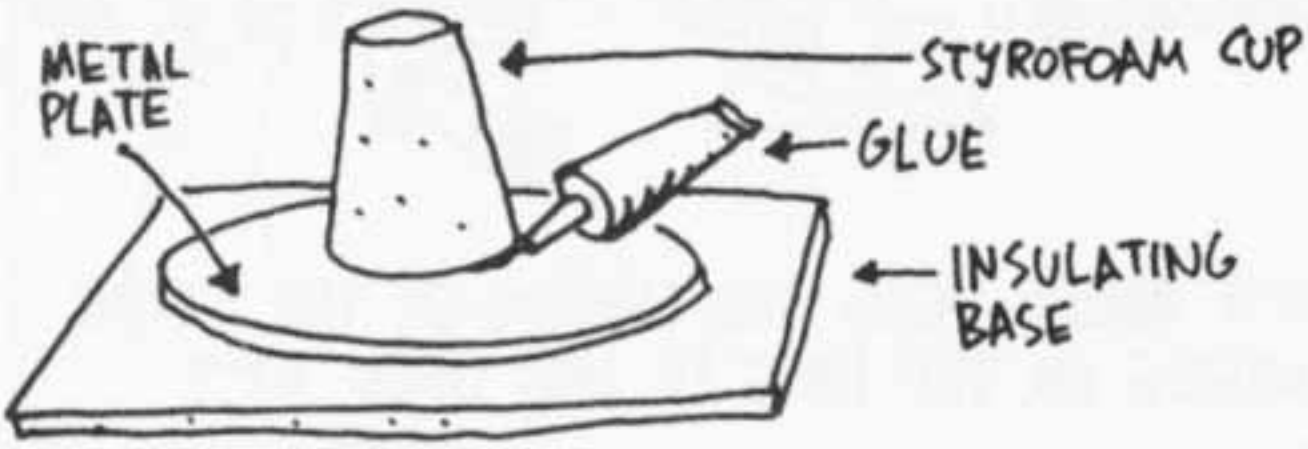
BUT NO KNOWN PHYSICAL PROCESS CAN CREATE OR DESTROY A SINGLE CHARGE!



A PIECE OF ELECTROSTATIC APPARATUS YOU CAN MAKE FOR YOURSELF IS AN

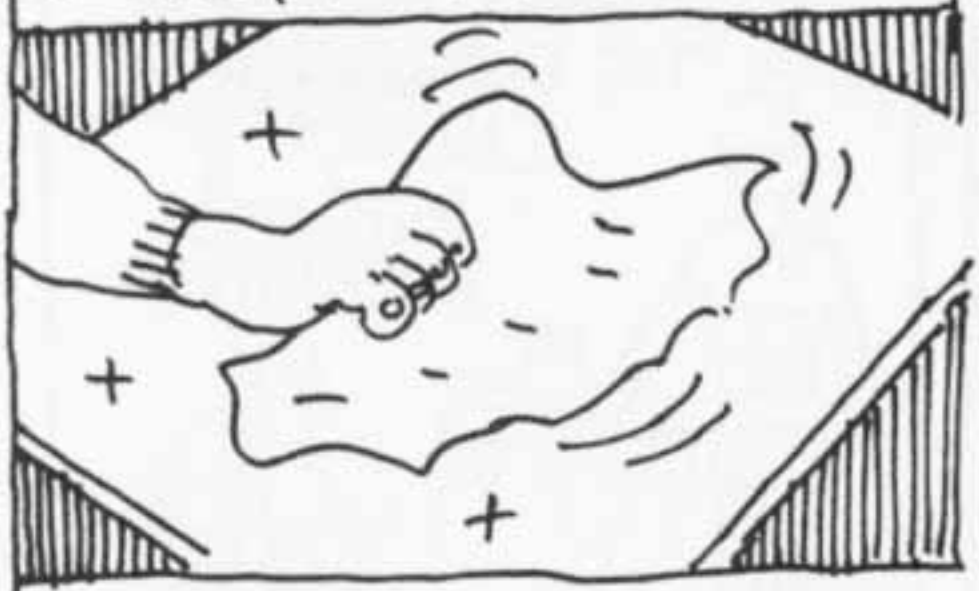
ELECTROPHORUS.



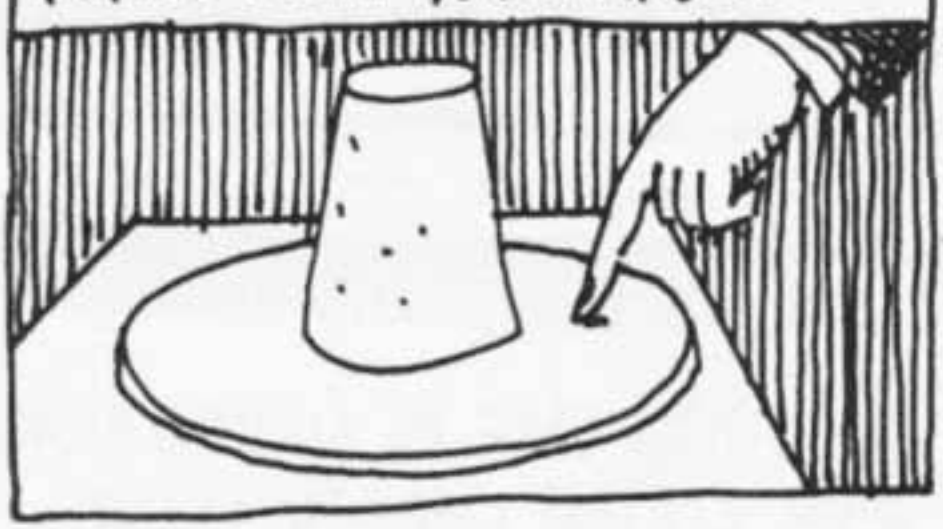


YOU'LL NEED A PLASTIC PLATE FOR THE BASE AND A METAL PIE PLATE WITH AN INSULATING HANDLE, SAY A STYROFOAM CUP, GLUED TO IT.

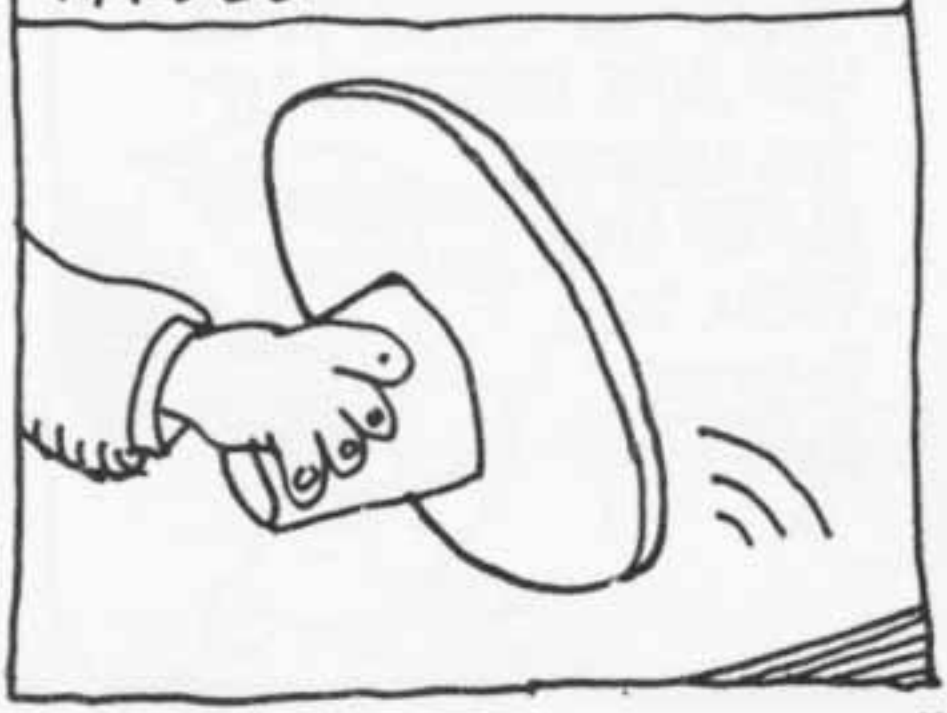
RUB THE BASE WITH SILK, FUR, OR WOOL, TO CHARGE IT.



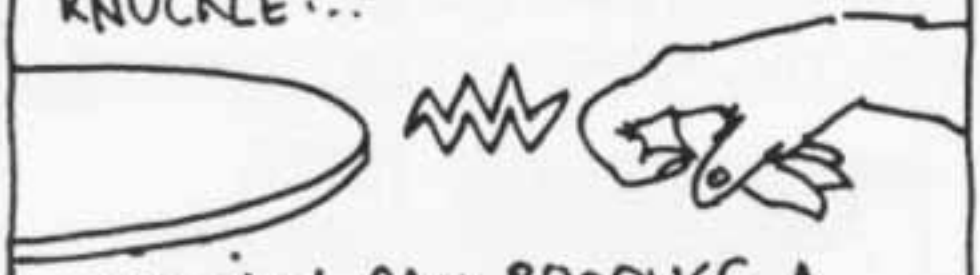
NOW PLACE THE METAL PLATE ON THE BASE, AND TOUCH THE PLATE WITH YOUR FINGER.



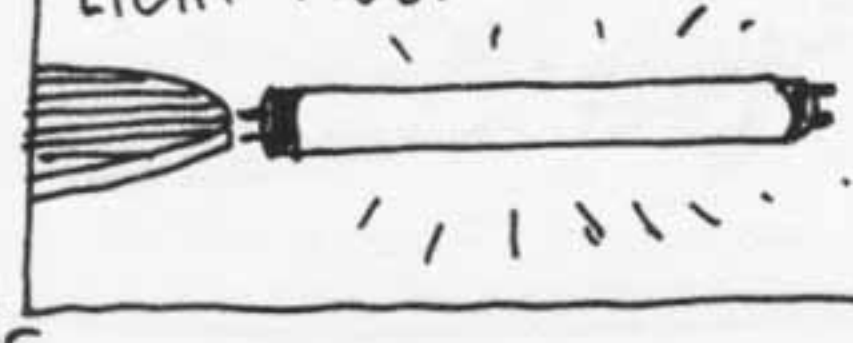
LIFT THE PLATE OFF THE BASE BY THE INSULATING HANDLE.



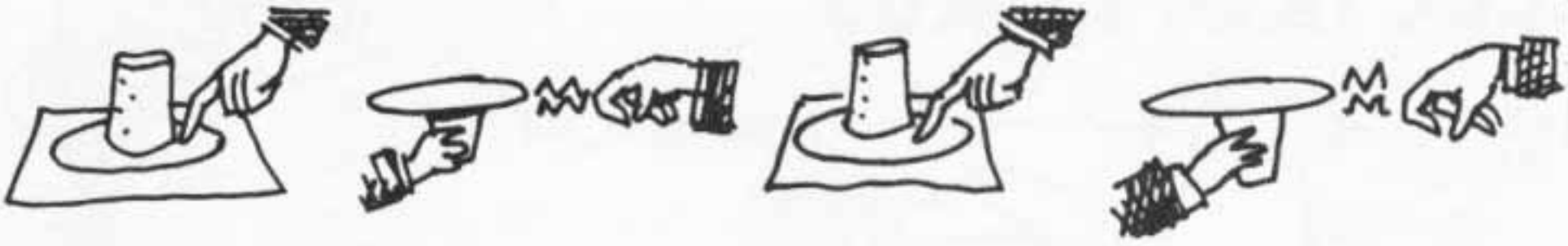
NOW YOU CAN DRAW A SPARK OFF THE PLATE WITH YOUR KNUCKLE...



...OR YOU CAN PRODUCE A FLASH IN A FLUORESCENT LIGHT TUBE.

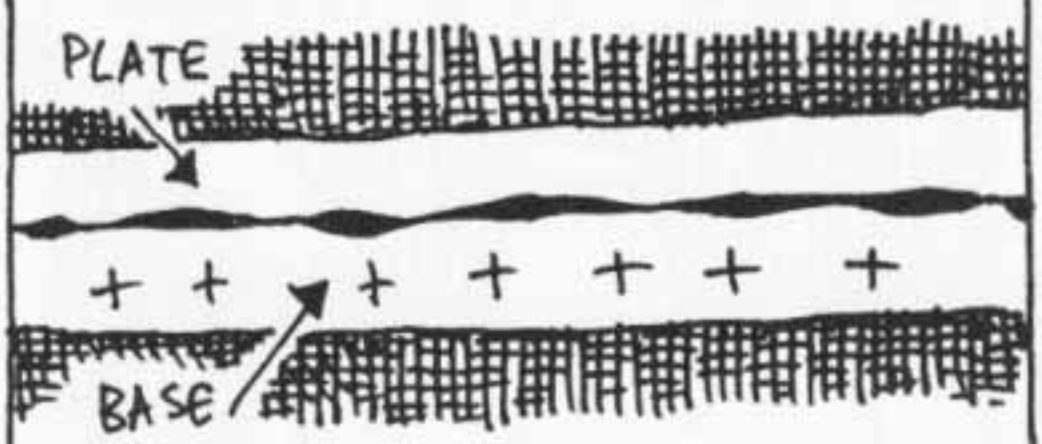


AN INTERESTING FEATURE OF THIS EXPERIMENT IS THAT YOU CAN RECHARGE THE PLATE BY TOUCHING IT WITH YOUR FINGER REPEATEDLY, WITHOUT FURTHER RUBBING OF THE BASE.

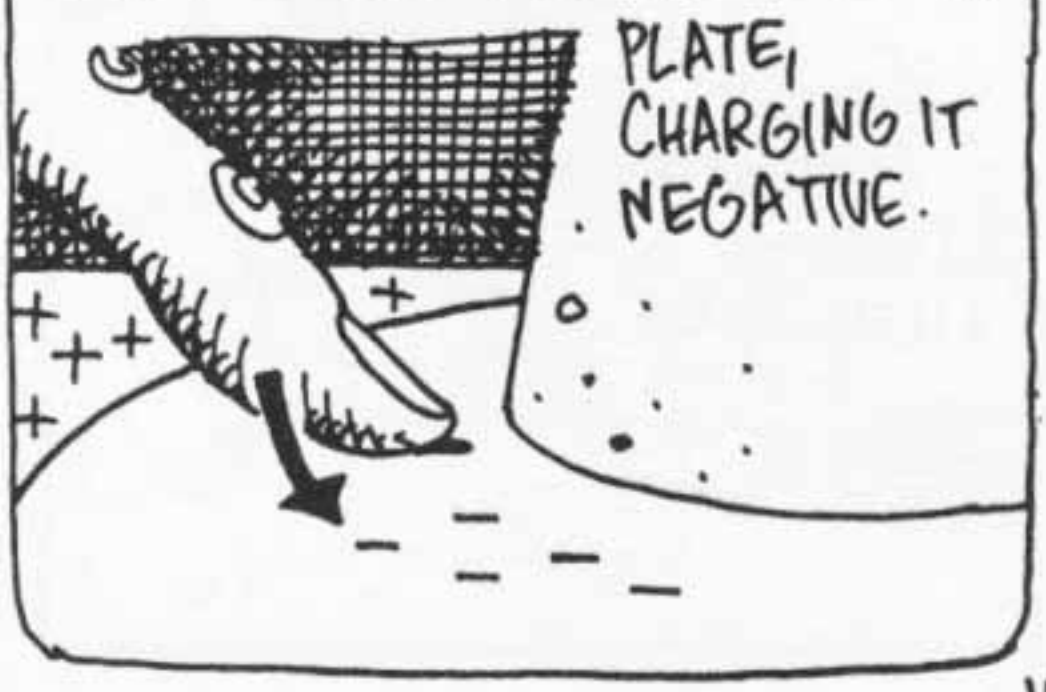


HOW DOES THIS WORK? WHERE DOES THE ENERGY OF THE SPARK COME FROM IF THE CHARGE ON THE BASE IS NOT USED UP?

THE BASE IS CHARGED POSITIVE BY RUBBING. WHEN THE PLATE IS PLACED ON THE BASE, IT ACTUALLY TOUCHES IT IN ONLY A FEW PLACES:



SINCE THE BASE IS AN INSULATOR, VERY LITTLE CHARGE FLOWS. BUT WHEN YOU TOUCH THE METAL, ELECTRONS IN YOUR BODY, ATTRACTED BY THE POSITIVE BASE, FLOW ONTO THE PLATE, CHARGING IT NEGATIVE.



YOUR BODY SERVES AS AN **ELECTRICAL GROUND**, A RESERVOIR OF POSITIVE AND NEGATIVE CHARGES. SINCE THE CHARGE ON THE PLATE COMES FROM YOU, THE EXPERIMENT CAN BE REPEATED INDEFINITELY.

AND WHERE DOES THE SPARK'S ENERGY COME FROM? IT COMES FROM THE EXTRA FORCE YOU MUST EXERT TO LIFT THE NEGATIVE PLATE AWAY FROM THE POSITIVE BASE!

·CHAPTER 13·
ELECTRIC FIELDS

THE EARTH EXERTS A FORCE ON THE MOON, A BODY THOUSANDS OF MILES AWAY. SIMILARLY, ONE ELECTRIC CHARGE EXERTS FORCES ON OTHER CHARGES WHICH ARE SEPARATED FROM IT IN SPACE.

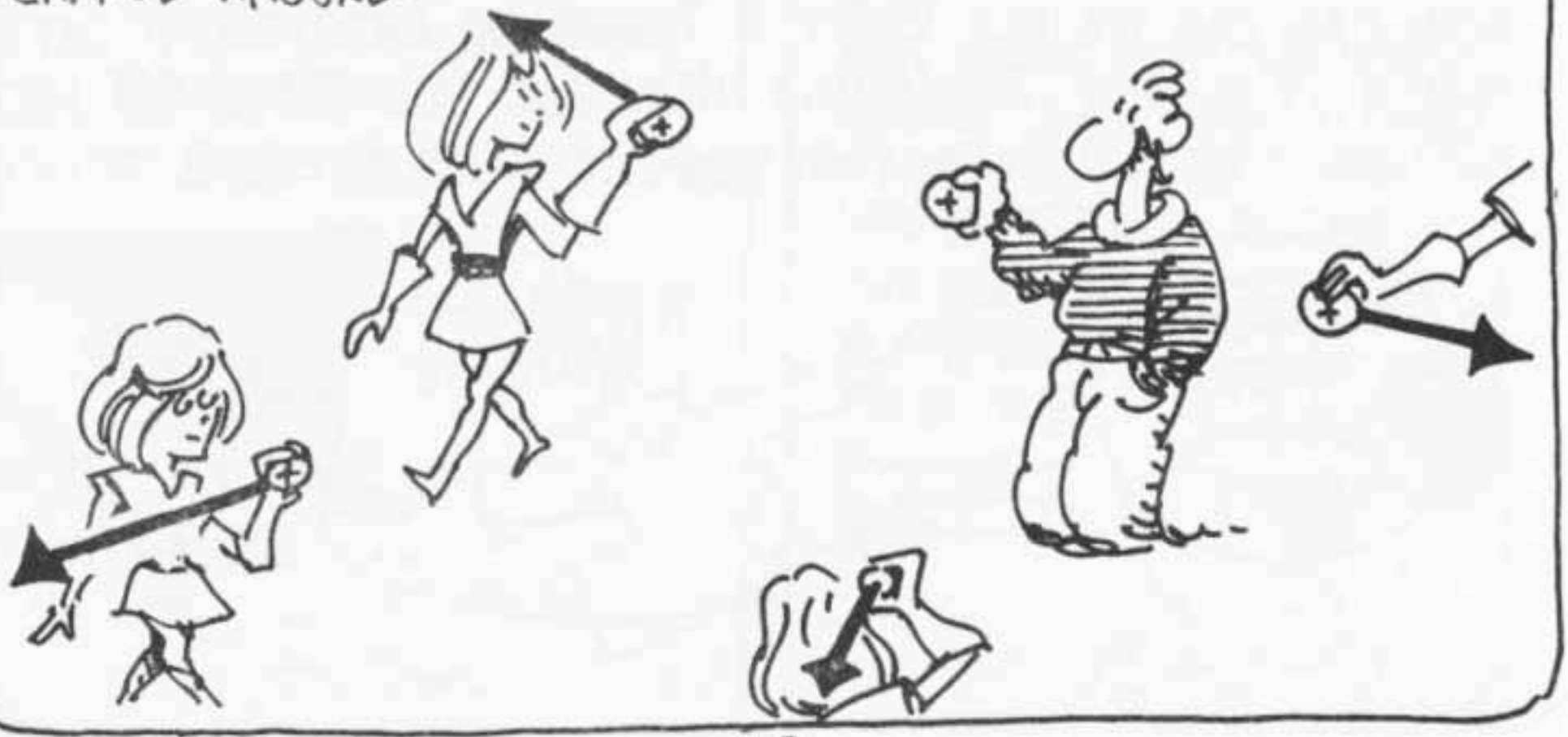
HOW CAN ONE OBJECT EXERT A FORCE ON ANOTHER WHICH IT IS NOT TOUCHING? HOW CAN THE FORCE GET ACROSS SPACE? HOW FAST DOES IT GET THERE?

A BEGINNING OF THE ANSWER IS TO IMAGINE THAT THE EARTH FILLS SPACE WITH A **GRAVITATIONAL FIELD.** IT IS THE FIELD (WHATEVER IT IS!) THAT CAUSES THE FORCES ON MASSES WITHIN IT.

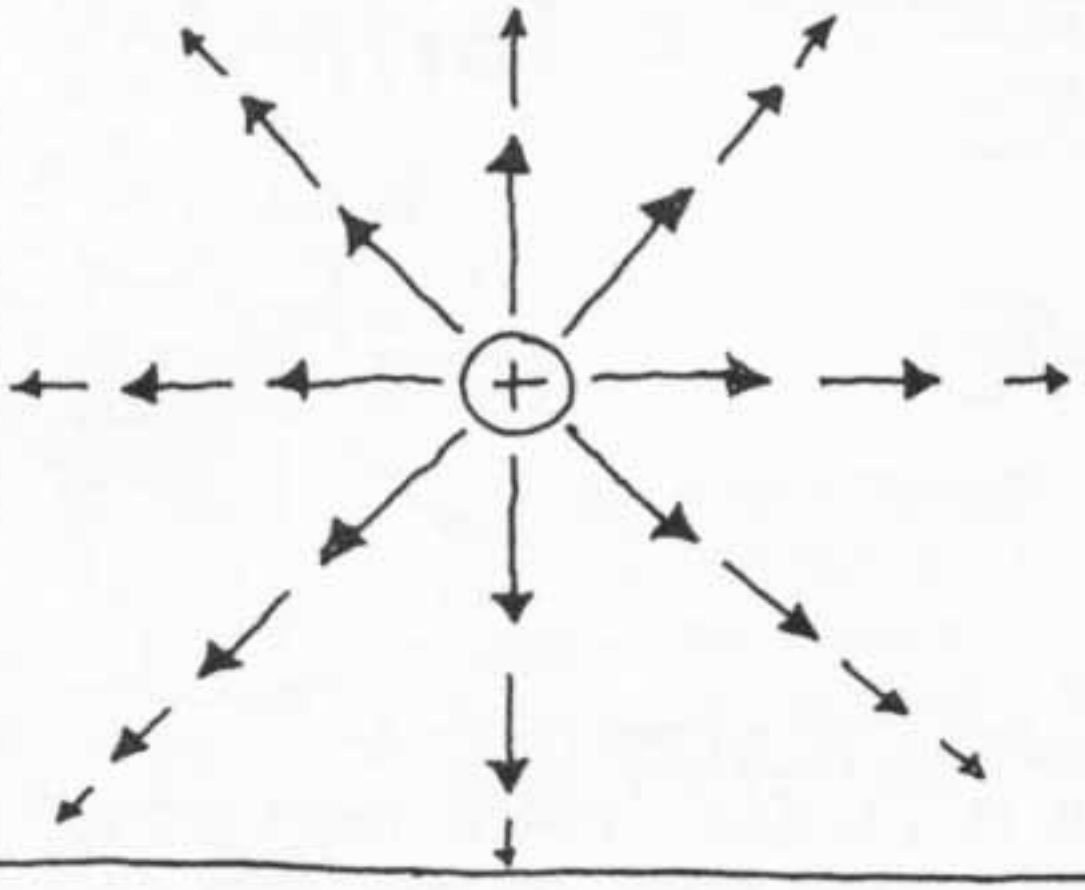
SIMILARLY, A CHARGE FILLS SPACE WITH AN **ELECTRIC FIELD.**

WHEN ANOTHER CHARGE IS IN THE ELECTRIC FIELD, ELECTRIC FORCES ACT ON IT!

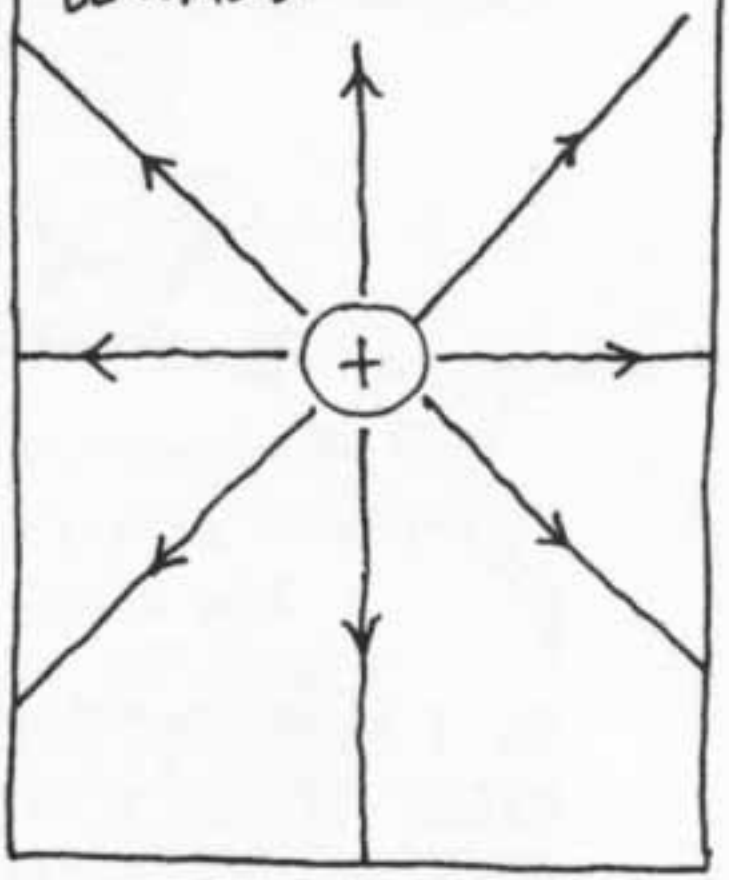
WE CAN VISUALIZE THE ELECTRIC FIELD BY IMAGINING THAT WE ARE CARRYING A SMALL POSITIVE TEST CHARGE AROUND AND MAPPING THE DIRECTION OF THE FORCE ON IT. HERE, RINGO HAS A SINGLE POSITIVE CHARGE, AND I'M MOVING THE TEST CHARGE AROUND.



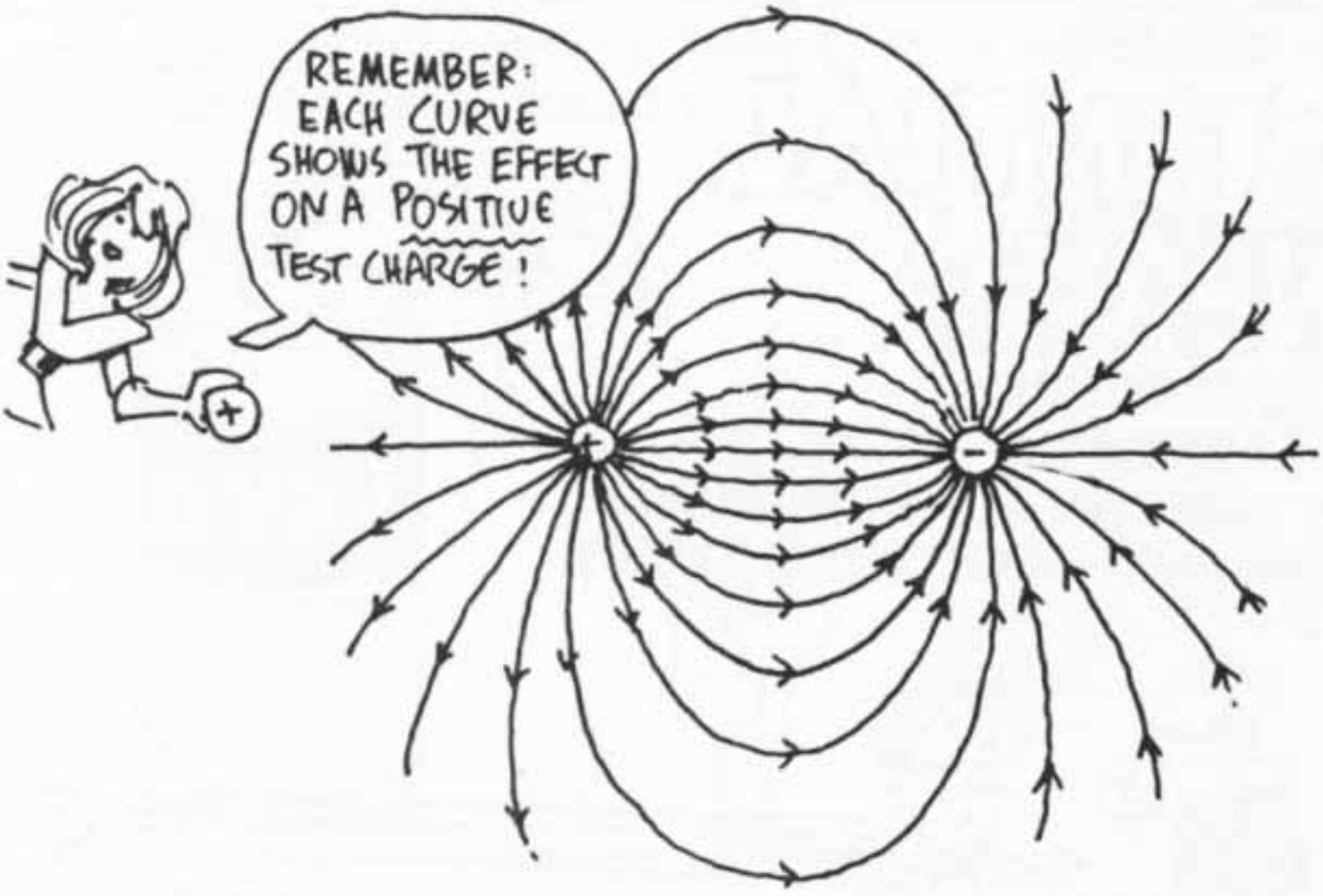
IF WE DRAW ARROWS IN THE DIRECTION OF THE FORCE, WITH LENGTH PROPORTIONAL TO ITS STRENGTH, WE GET A PICTURE OF THE ELECTRIC FIELD OF RINGO'S CHARGE:



AND IF WE CONNECT THE ARROWS WITH **FIELD LINES**, THE PICTURE BECOMES:

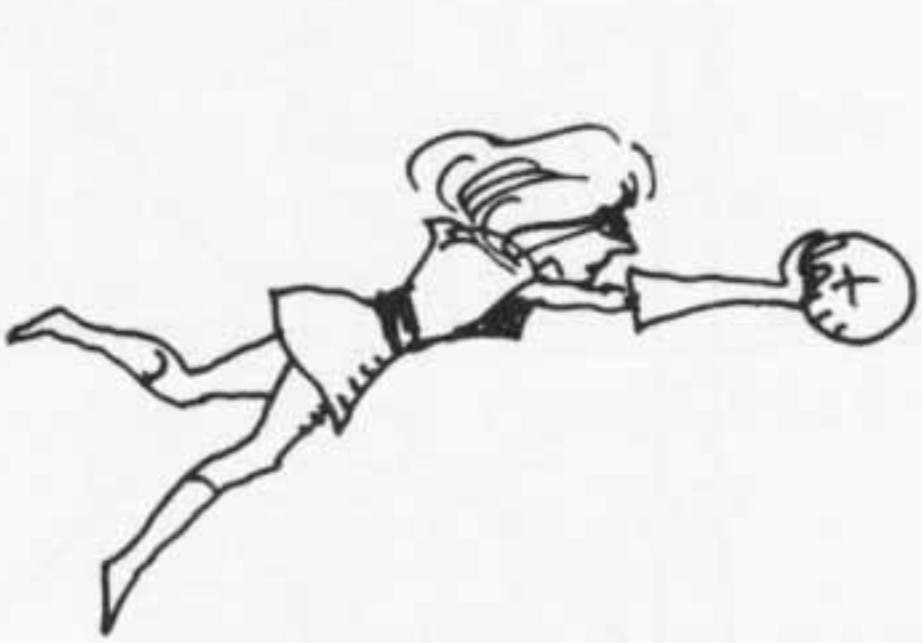


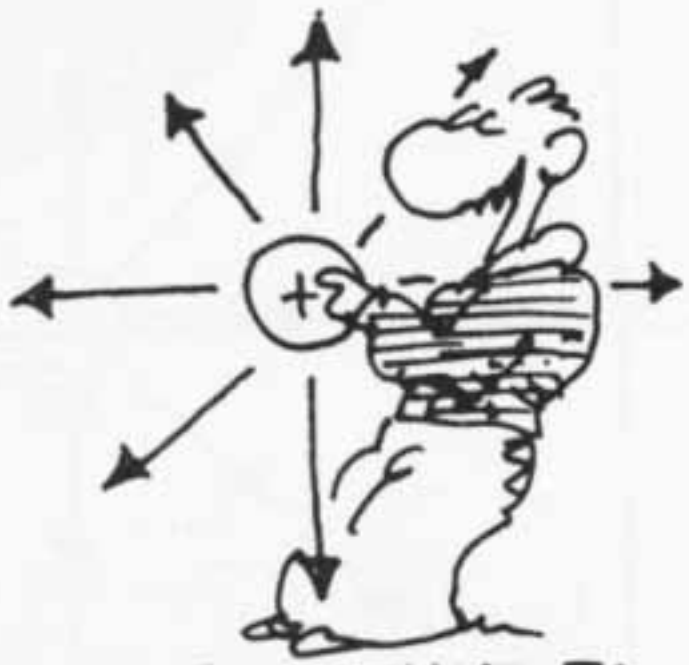
FIELD LINES GIVE A VERY CONVINCING PICTURE OF ELECTRIC FIELDS; FOR EXAMPLE, FOR TWO ATTRACTING CHARGES:



THE FIELD LINES BEGIN AT THE POSITIVE CHARGE AND END AT THE NEGATIVE CHARGE: THE NEGATIVE CHARGE PULLS A POSITIVE TEST CHARGE IN FROM ANY DIRECTION.

SINCE THE ELECTRIC FIELD EXERTS FORCES ON CHARGES, THERE IS ENERGY ASSOCIATED WITH THE POSITION OF A PARTICLE IN THE FIELD. HERE RINGO HOLDS A POSITIVE CHARGE, AND, STARTING FAR AWAY, I BRING A SMALL POSITIVE TEST CHARGE IN CLOSE TO IT.



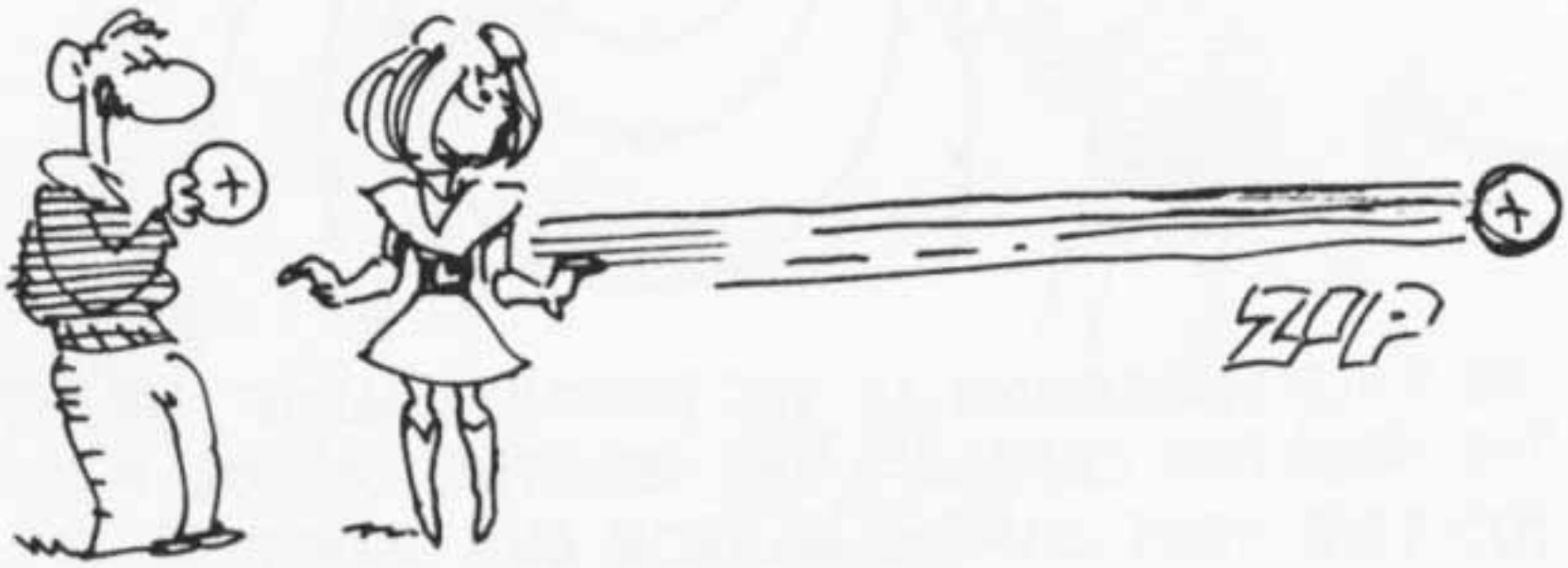


AS I MOVE IN, THE CHARGE IS REPELLED, SO I HAVE TO EXERT FORCE TO PUSH IT CLOSER. FORCE TIMES DISTANCE EQUALS **WORK** — I DO WORK ON THE TEST CHARGE.

WE SAY THAT THE WORK GOES INTO THE

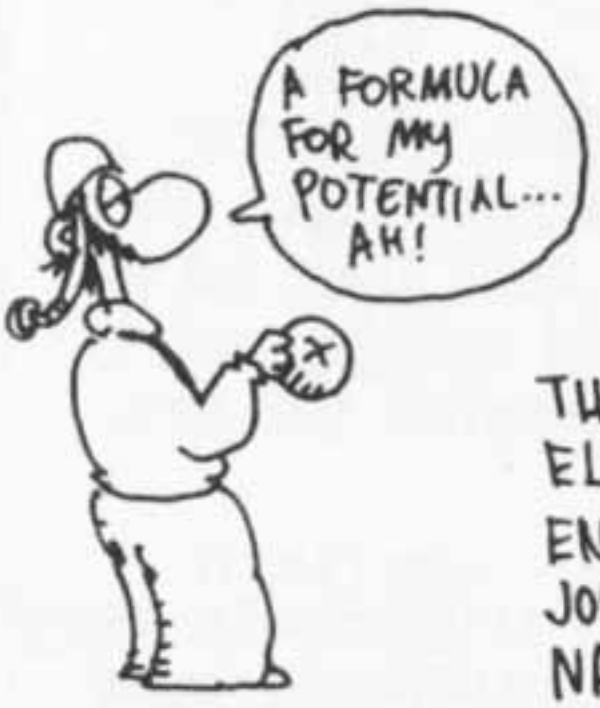
POTENTIAL ENERGY

OF THE TEST CHARGE.
IF I RELEASE THE CHARGE, IT FLIES AWAY, AND POTENTIAL ENERGY IS CONVERTED INTO KINETIC ENERGY.



WE WOULD LIKE TO ATTRIBUTE THE POTENTIAL ENERGY SOLELY TO THE ELECTRIC FIELD OF RINGO'S CHARGE, SO WE DIVIDE OUT MY TEST CHARGE AND WRITE:

$$\text{Potential} = \frac{\text{POTENTIAL ENERGY}}{\text{CHARGE}}$$



THIS EQUATION DEFINES A NEW QUANTITY, THE ELECTRIC POTENTIAL.* POTENTIAL MEASURES ENERGY PER CHARGE. ITS UNITS ARE JOULES PER COULOMB, WHICH WE GIVE A NAME ALL ITS OWN, THE **VOLT**.

$$1\ \text{Volt} = 1\ \frac{\text{JOULE}}{\text{COULOMB}}$$

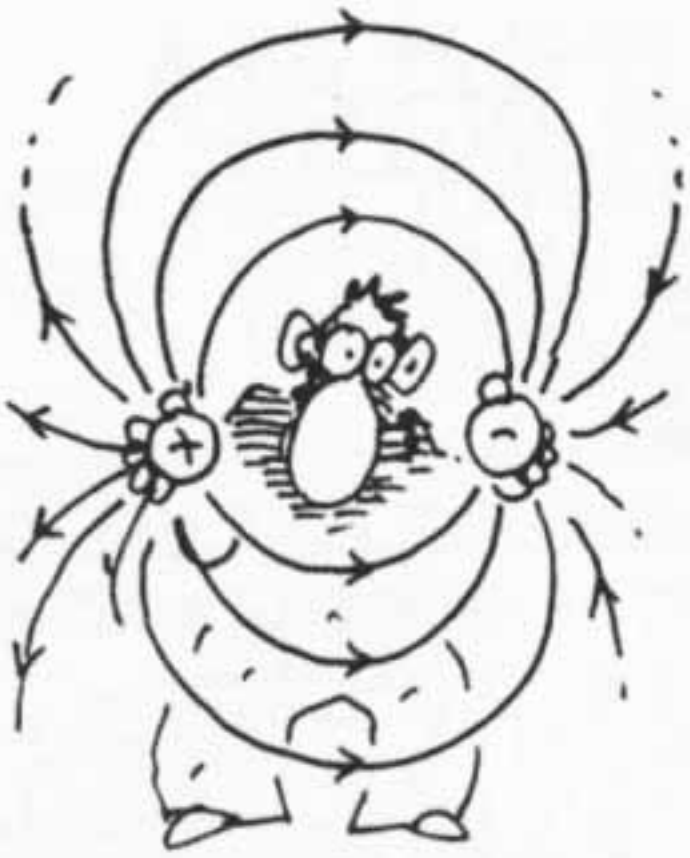
AS WITH ANY NEW DEFINITION IN PHYSICS, IT IS IMPORTANT TO UNDERSTAND THE BASIC CONCEPT.

IF A BATTERY IS RATED AT 6 VOLTS, THAT MEANS IT IS PREPARED TO GIVE 6 JOULES OF ENERGY TO EVERY COULOMB THAT IS MOVED FROM ONE TERMINAL TO THE OTHER.

* THERE IS ALSO A GRAVITATIONAL POTENTIAL. IF P.E. = mgh, THEN $\frac{\text{P.E.}}{m} = gh$ IS THE ABILITY OF THE GRAVITATIONAL FIELD TO TRANSMIT ENERGY TO ANY MASS AT HEIGHT h.

O.K... SO HERE'S A CHARGE... BUT I STILL DON'T GET IT...

WHAT IS A CHARGE, ANYWAY?? I MEAN, IT MUST BE SOMETHING — MUSN'T IT...?



AND THIS ELECTRIC "FIELD," WHAT'S THAT?

HOW CAN IT "CARRY" A FORCE? HOW CAN SOME IDEA THAT "FILLS SPACE" CARRY ANYTHING??

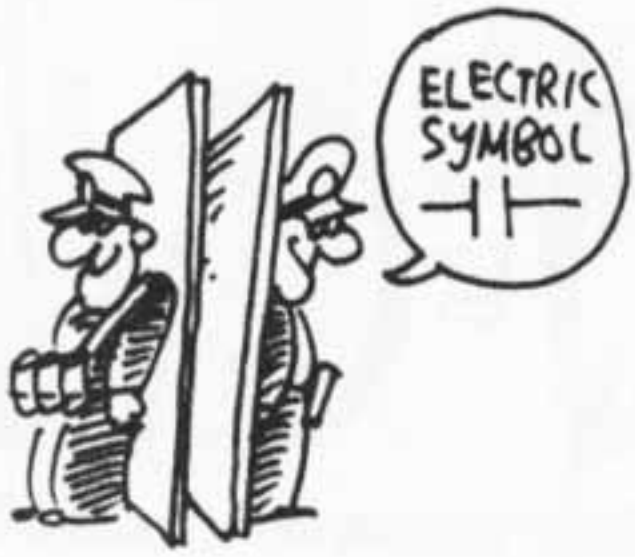
I'M JUST AS CONFUSED AS EVER!!

HMM...

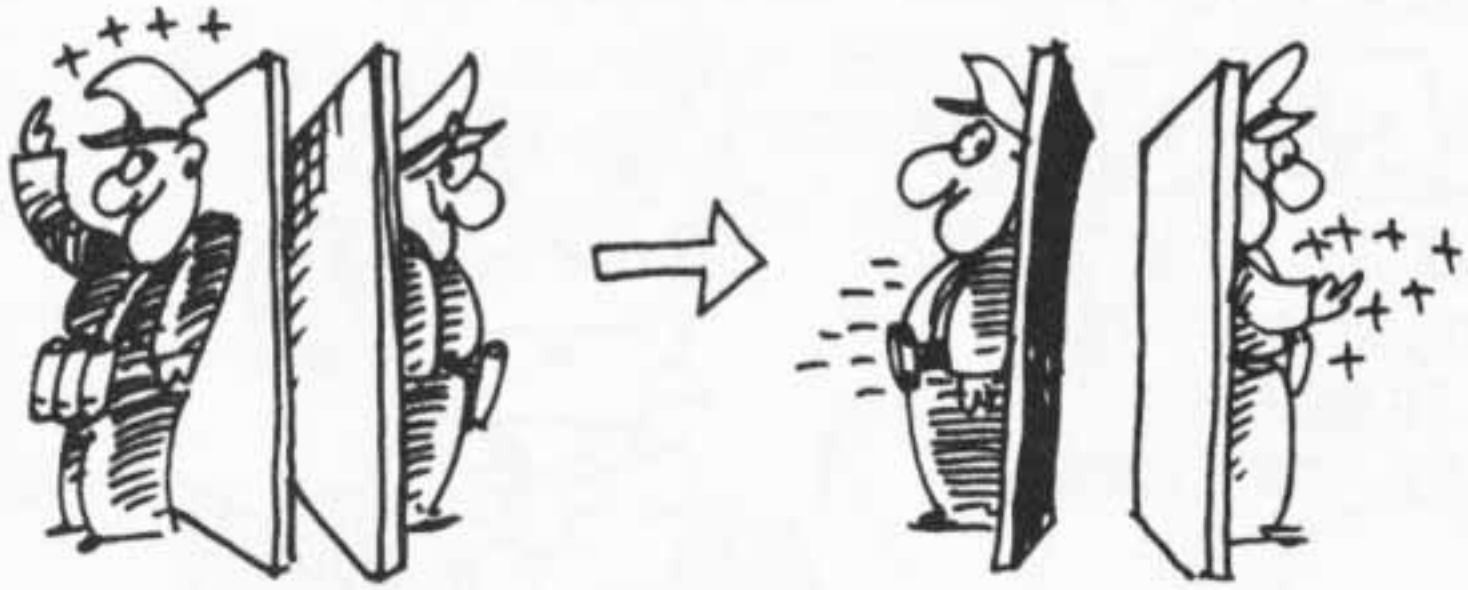
SORRY, RINGO, OLD BOY, BUT YOU HAVE A POINT... CLASSICAL E&M NEVER ANSWERS THOSE QUESTIONS. IT ONLY DESCRIBES HOW CHARGES AND FIELDS BEHAVE... BUT IF YOU CAN HANG ON UNTIL THE END OF THE BOOK, I'LL TELL YOU A LITTLE ABOUT WHAT QUANTUM THEORY SAYS CHARGES AND FIELDS "REALLY ARE..."

CHAPTER 14
CAPACITORS

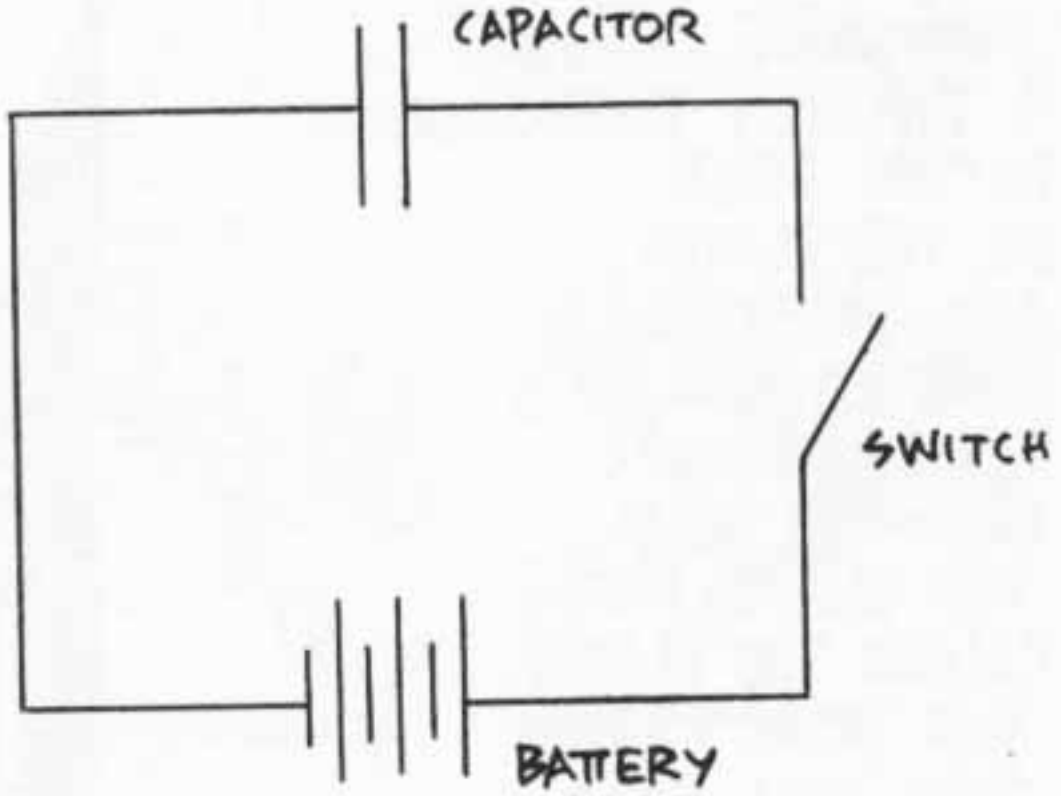
A CAPACITOR CONSISTS OF TWO CONDUCTORS SEPARATED BY AN INSULATOR, FOR EXAMPLE, TWO METAL PLATES WITH AIR BETWEEN THEM.



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:

$$Q = CV$$

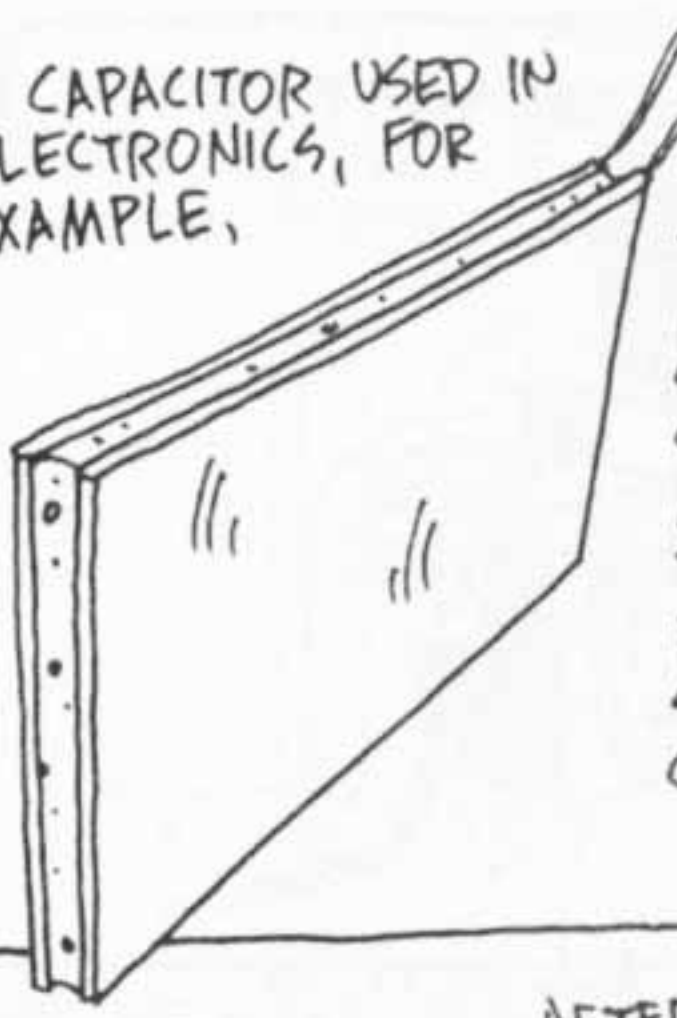
CHARGE = CONSTANT · VOLTAGE

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

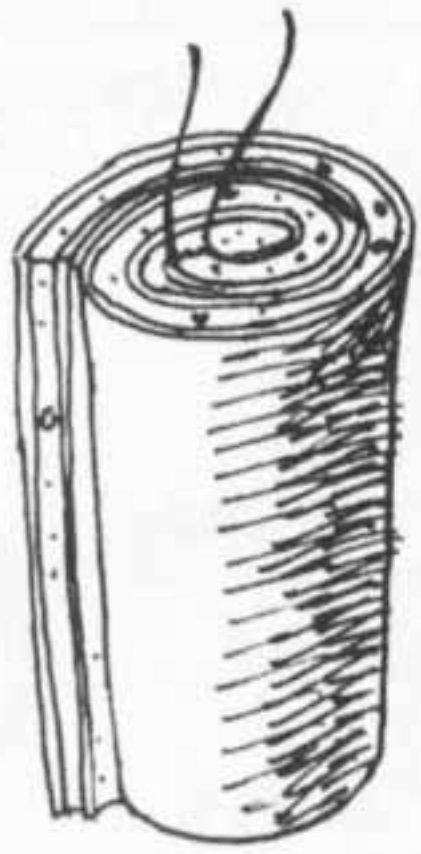
CAPACITANCE IS MEASURED IN **FARADS**, AFTER MICHAEL **FARADAY** (1791-1867). THE HIGHER THE CAPACITANCE, THE MORE CHARGE THE CAPACITOR CAN STORE.

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...

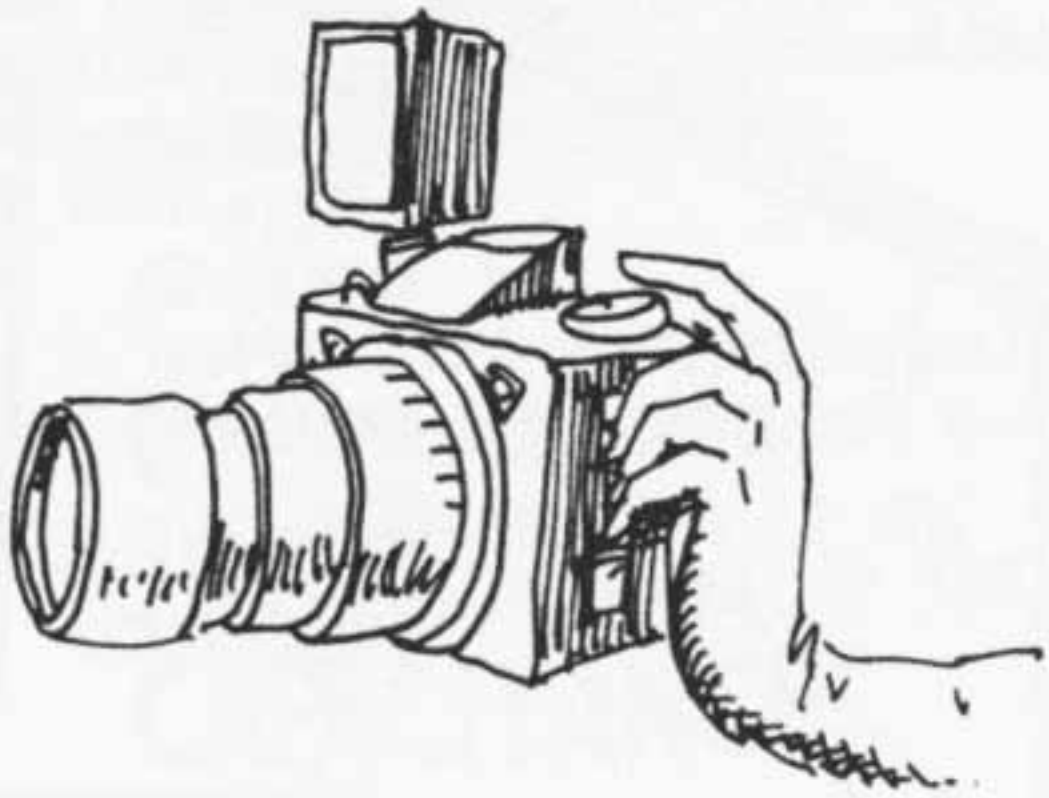


...AND ROLLED UP INTO A COMPACT TUBULAR PACKAGE.

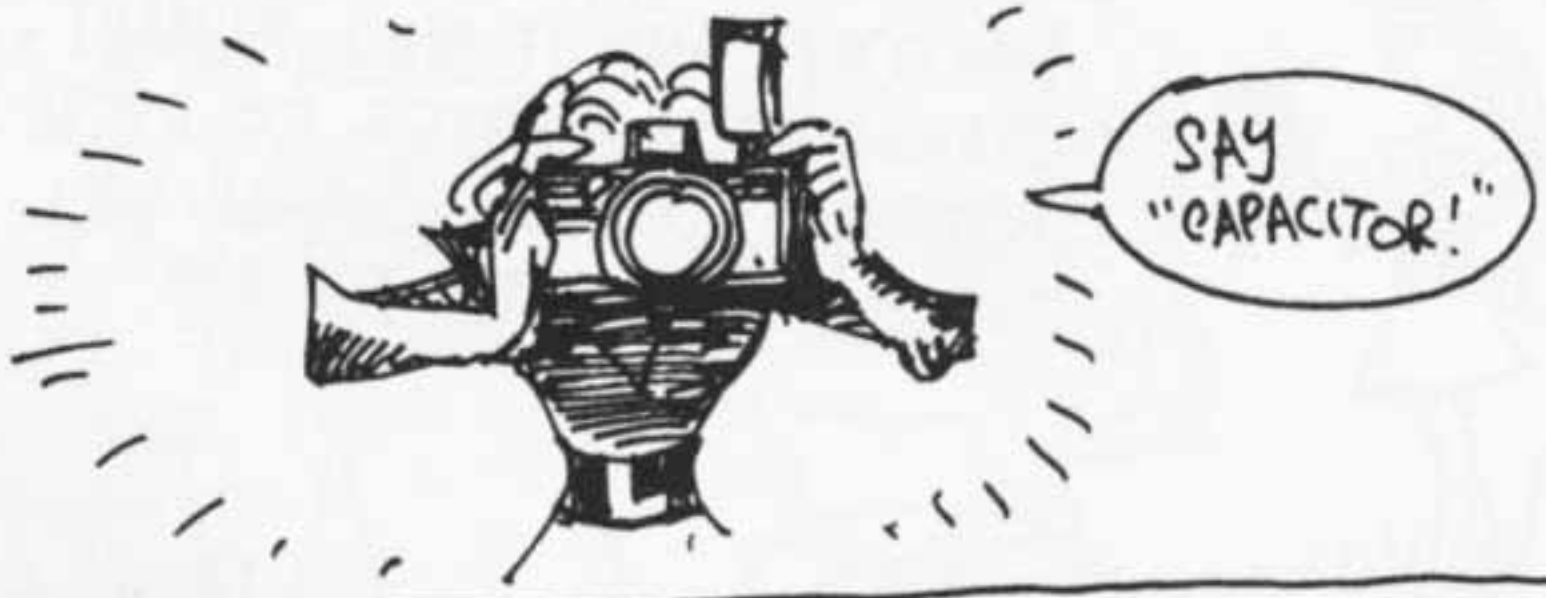
AFTER THE CAPACITOR IS CHARGED, IT CAN BE DISCONNECTED FROM THE BATTERY, AND IT WILL REMAIN CHARGED FOR MINUTES, OR EVEN HOURS, ALTHOUGH CHARGE WILL SLOWLY LEAK INTO THE AIR.

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."

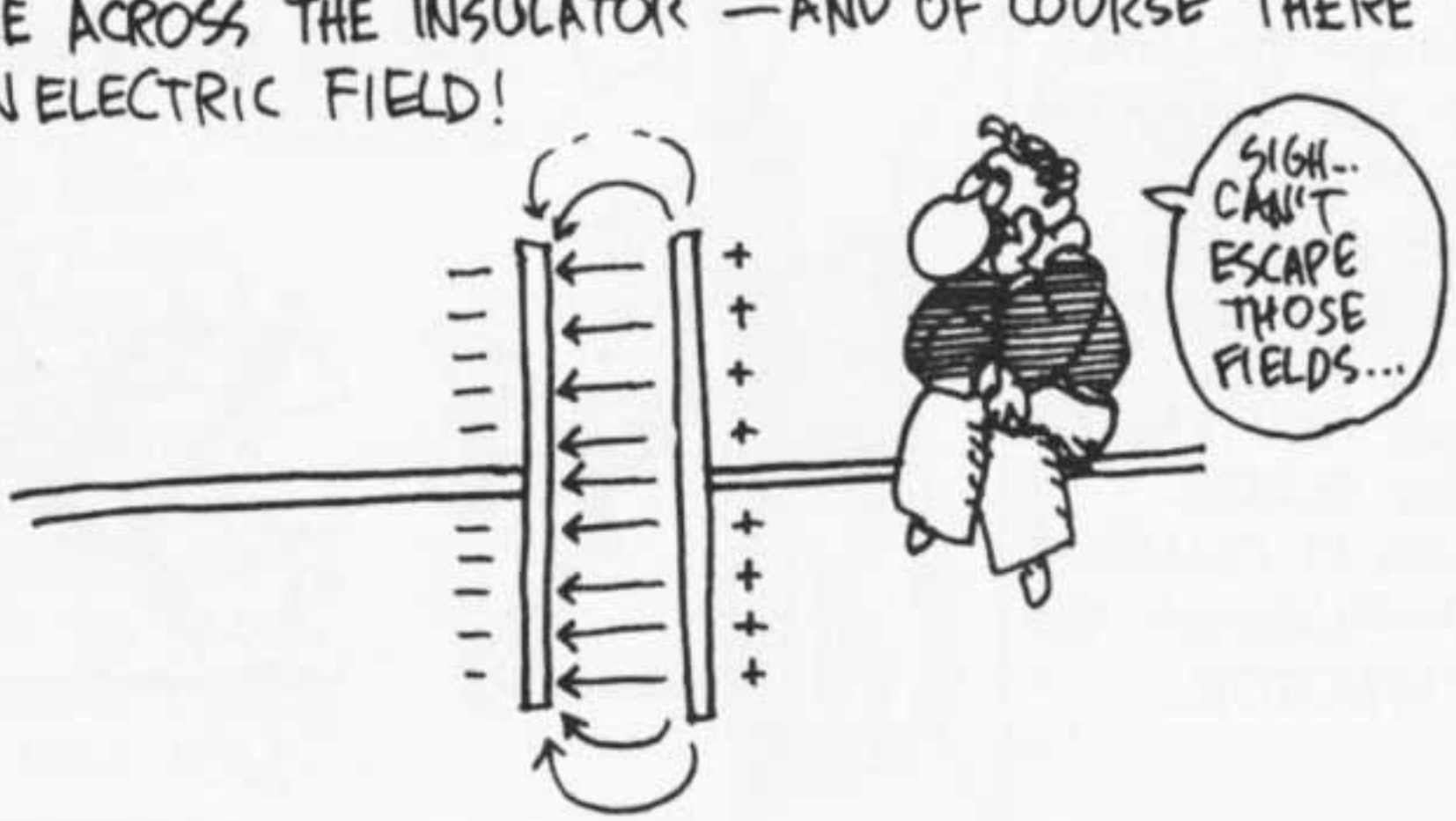
THIS SHOWS HOW CAPACITORS CAN BE USED TO STORE CHARGE AND ENERGY. FOR EXAMPLE: A PHOTOGRAPHER'S ELECTRONIC FLASH UNIT HAS A LARGE CAPACITOR TO STORE ENERGY FOR THE FLASH TUBE. THE BATTERY TAKES ABOUT 30 SECONDS TO CHARGE IT UP.



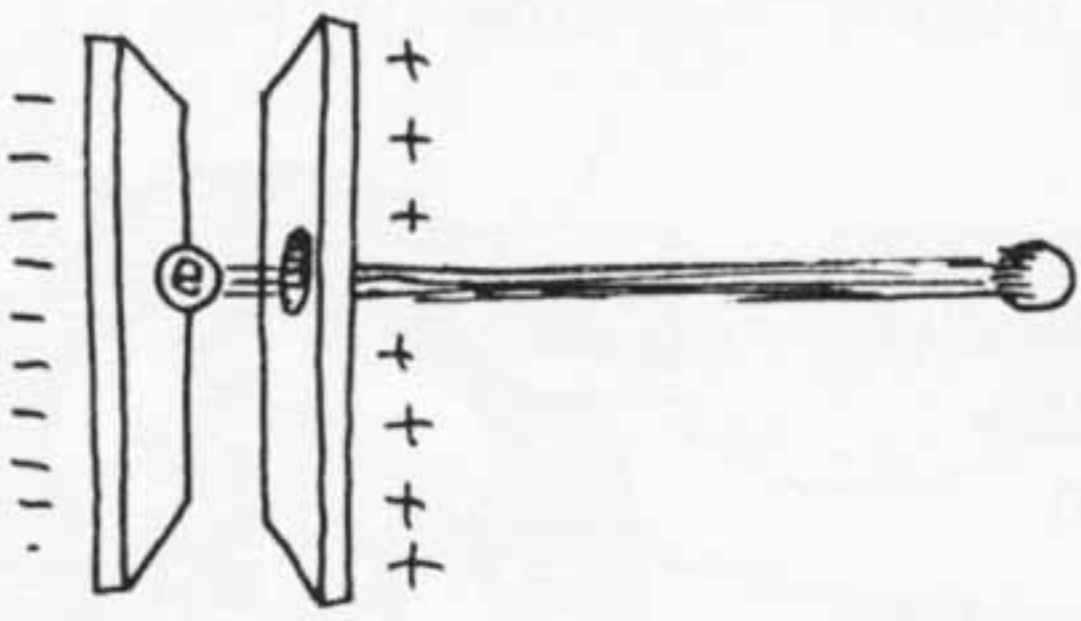
THEN, WHEN THE CHARGE IS NEEDED, ALL OF IT IS DUMPED THROUGH THE FLASH TUBE IN AN INSTANT!



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!

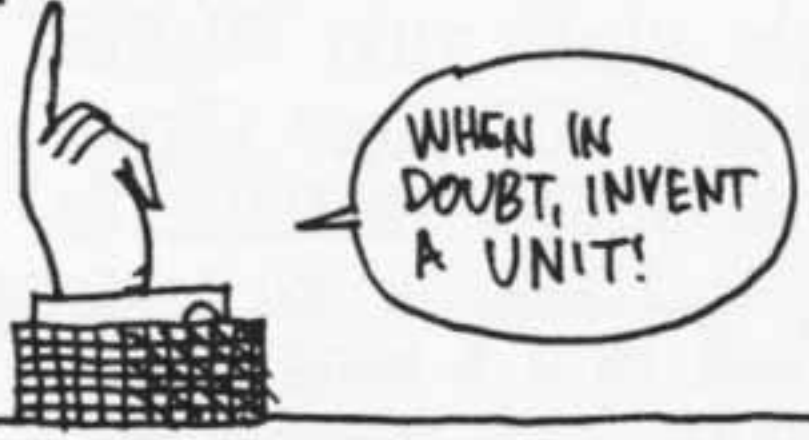


IF AN ELECTRON IS RELEASED NEAR THE NEGATIVE PLATE, THE ELECTRIC FIELD WILL ACCELERATE IT TOWARD THE POSITIVE PLATE. IN FACT, IF WE MAKE A SMALL HOLE IN THE POSITIVE PLATE, THE ELECTRON WILL ZIP THROUGH:



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 .0000000000000000016!)

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.

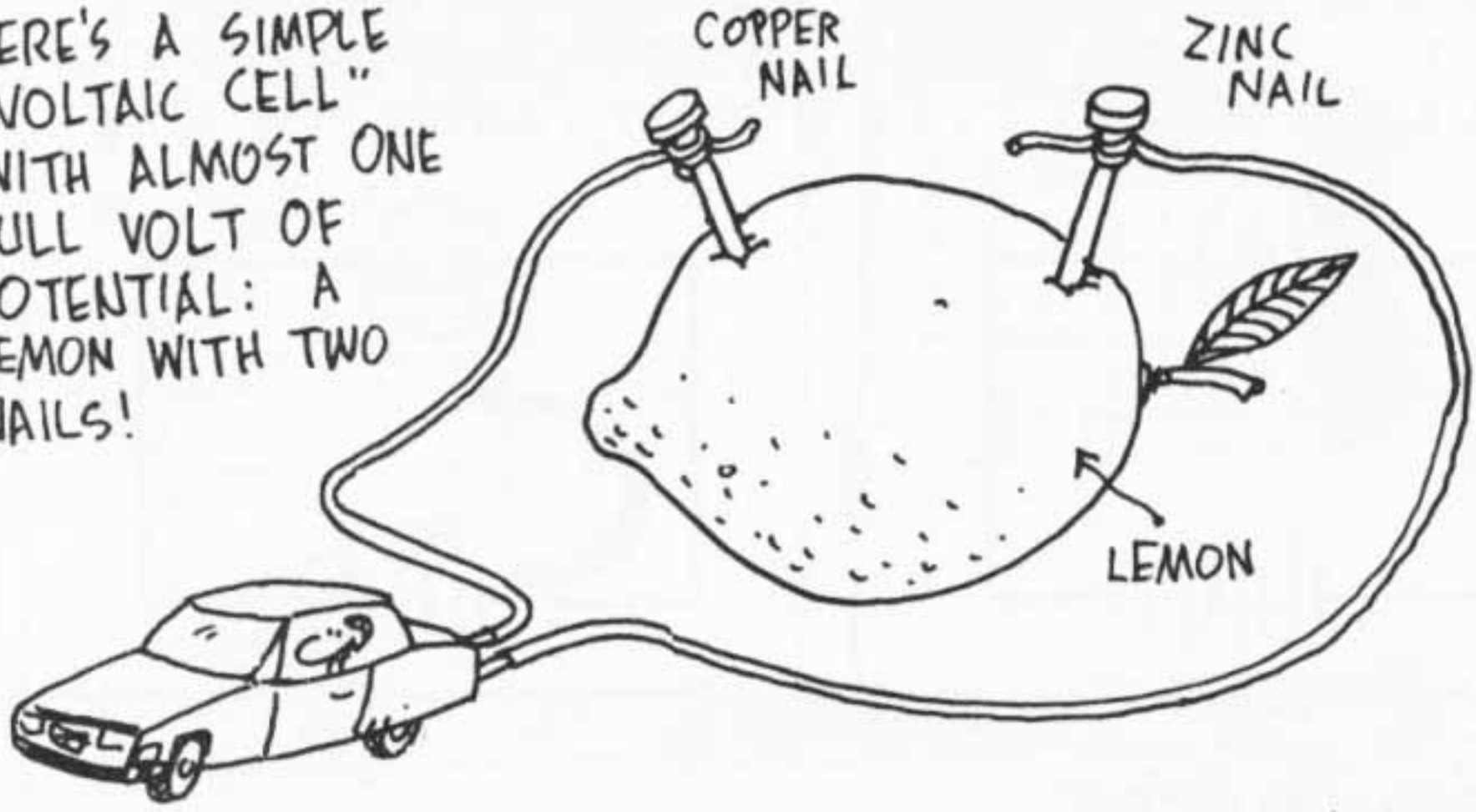
◦CHAPTER 15◦
ELECTRIC CURRENTS

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.

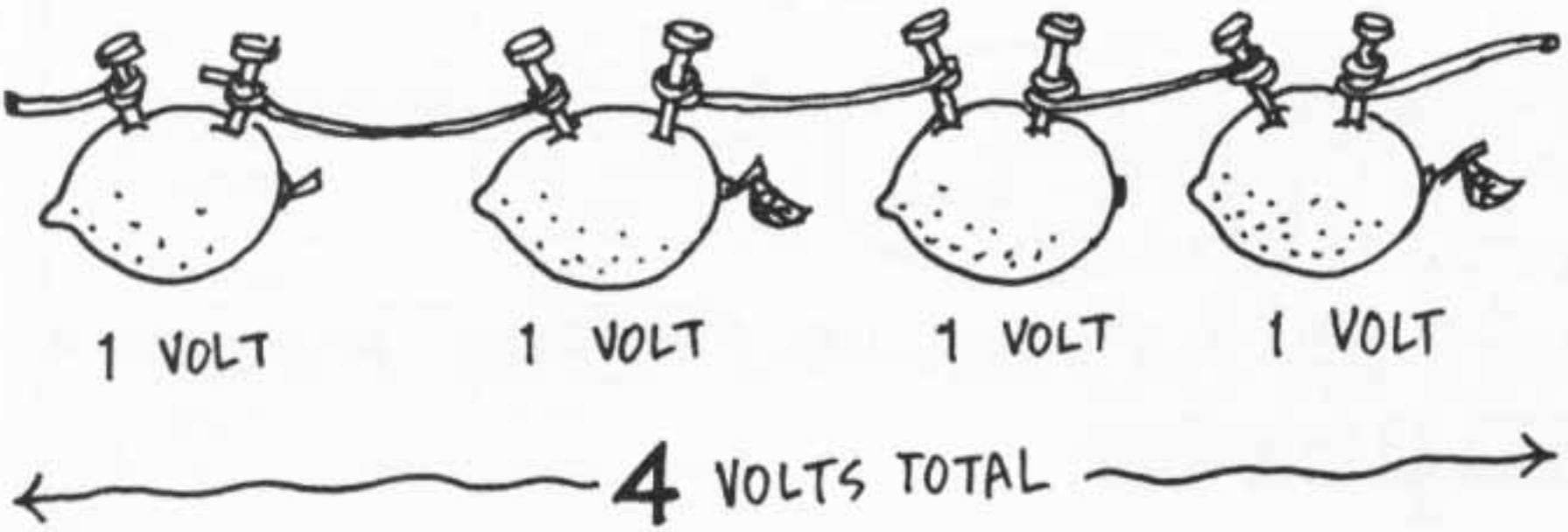
VOLTA FOUND THAT IF YOU DIP TWO DIFFERENT METALS IN A CHEMICAL BATH, A DIFFERENCE IN POTENTIAL WILL APPEAR BETWEEN THEM.

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.

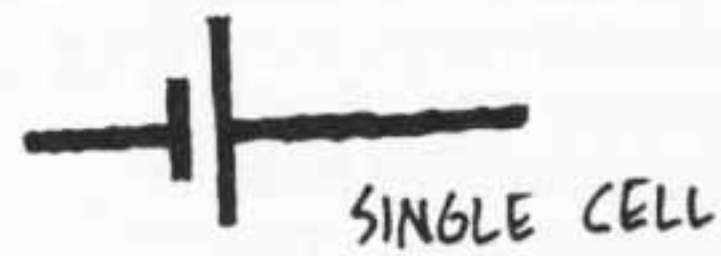
HERE'S A SIMPLE "VOLTAIC CELL" WITH ALMOST ONE FULL VOLT OF POTENTIAL: A LEMON WITH TWO NAILS!



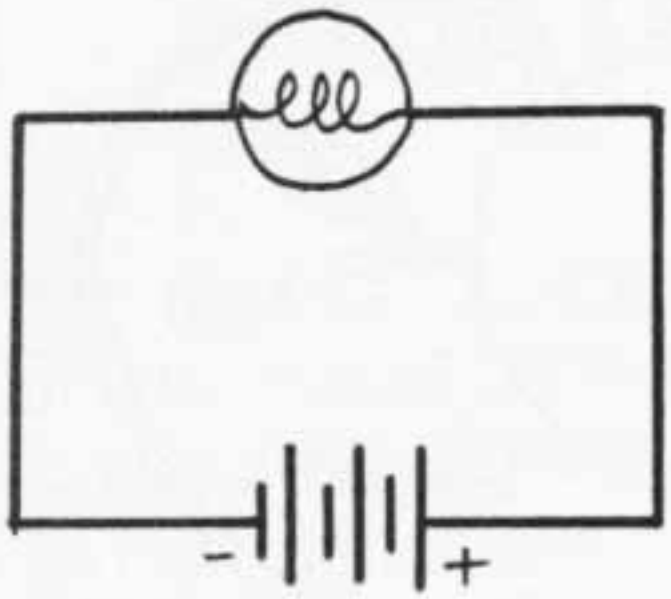
VOLTA ALSO FOUND THAT BY CONNECTING CELLS IN SERIES, THE POTENTIALS ADD UP TO GIVE LARGE VOLTAGES:



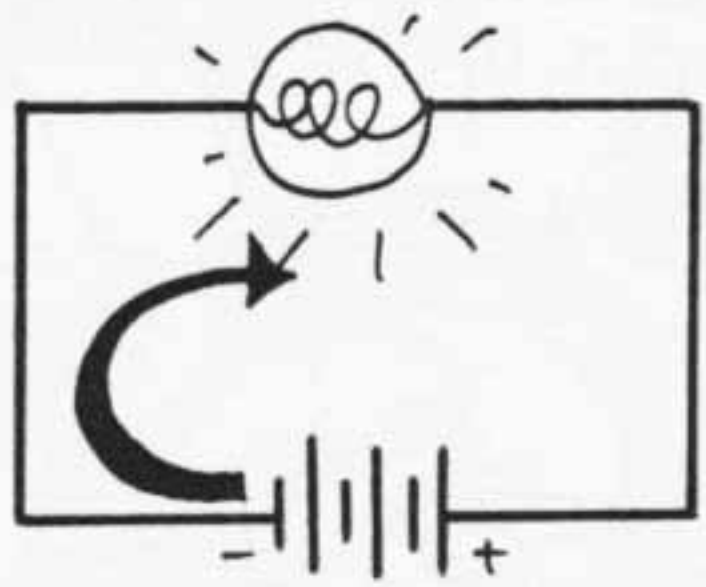
A FLASHLIGHT "BATTERY" IS ACTUALLY A SINGLE CHEMICAL CELL. A TRUE BATTERY, LIKE THE ONE IN YOUR CAR, CONSISTS OF SEVERAL CELLS CONNECTED IN SERIES, AS ABOVE. THEIR ELECTRICAL SYMBOLS ARE:



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.



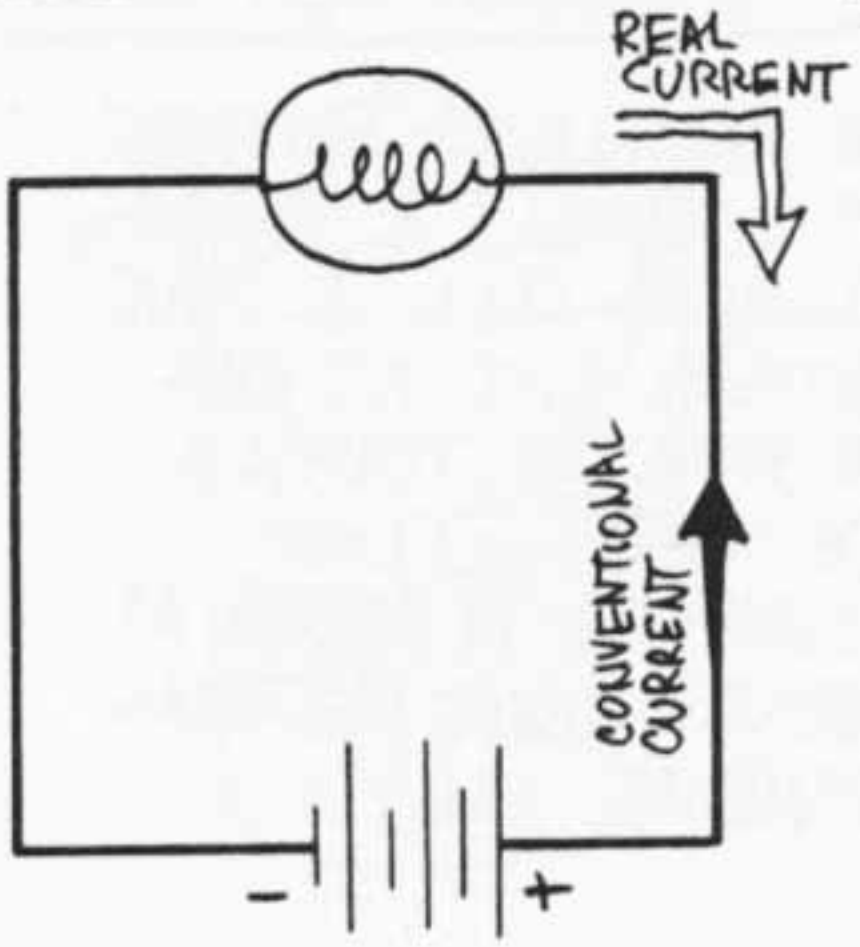
WE CALL THIS FLOW OF CHARGE THE

CURRENT.

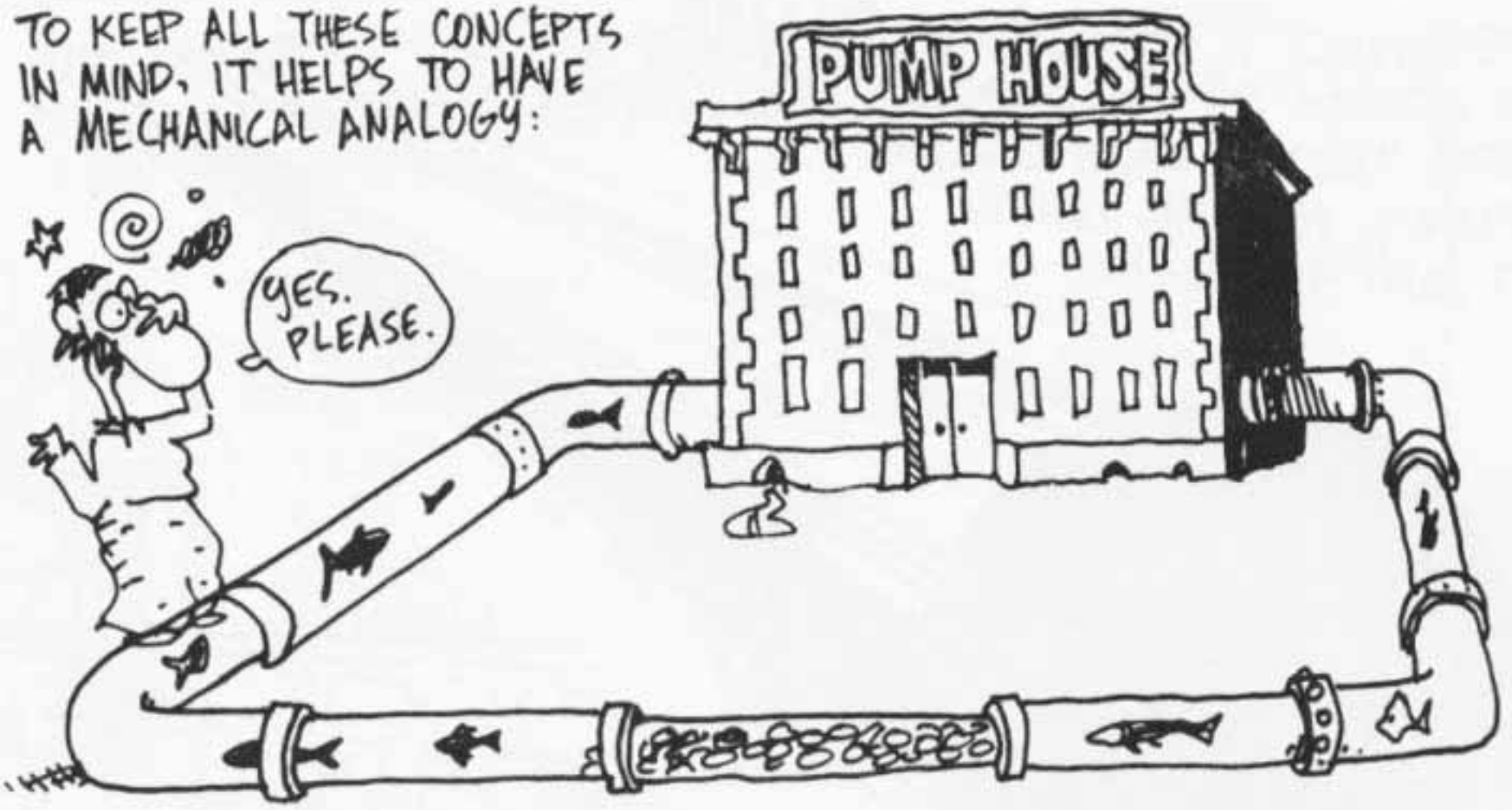
CURRENT IS MEASURED IN COULOMBS PER SECOND, ALSO KNOWN AS:

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

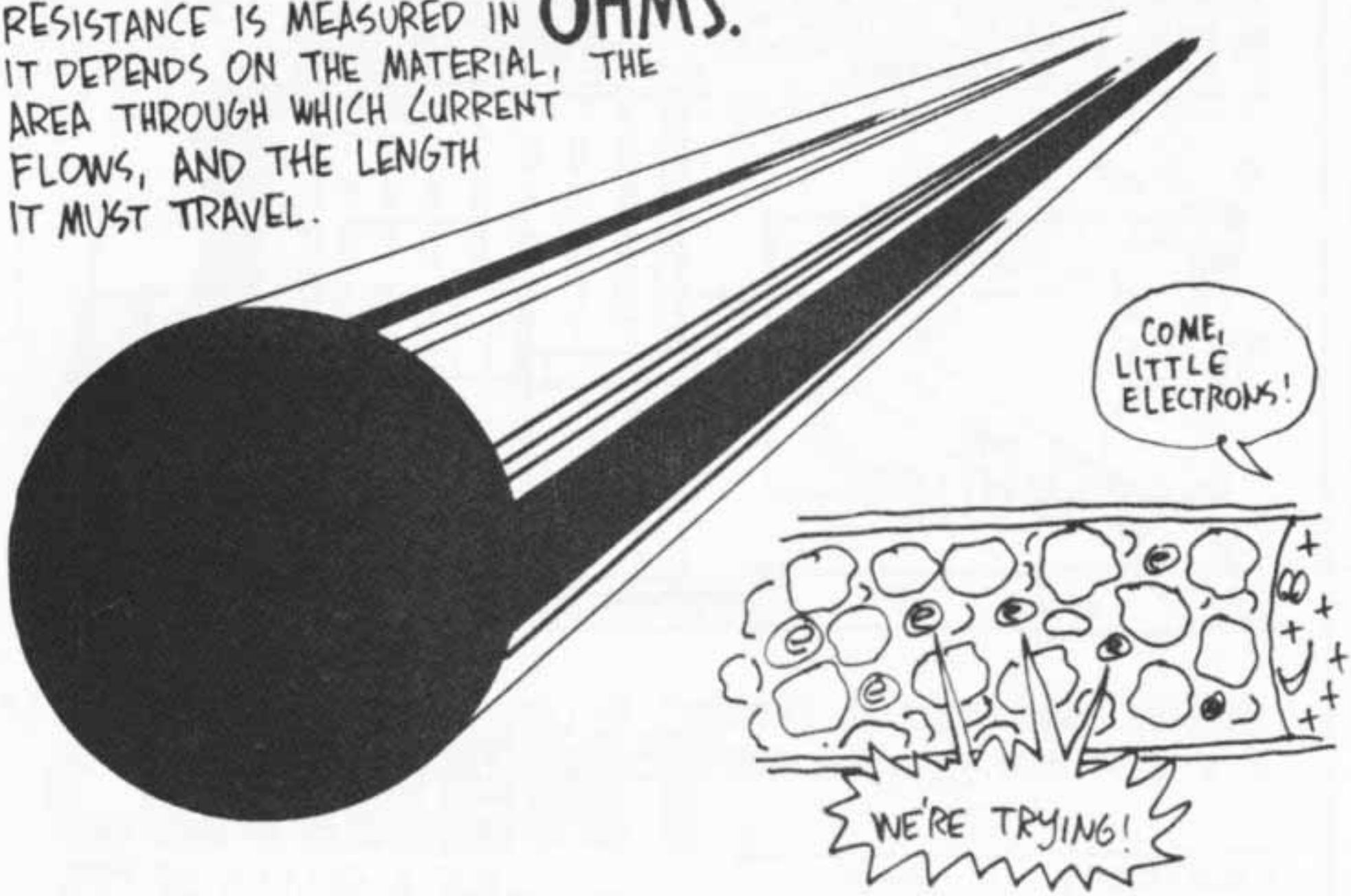
THE LAMP FILAMENT IS LIKE A SECTION OF PIPE FILLED WITH GRAVEL THAT **RESISTS** THE FLOW OF WATER. IN FACT, THE FRICTION OF FLOWING WATER EVEN HEATS THE GRAVEL!

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:

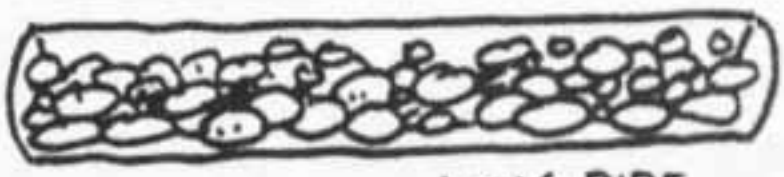
CURRENT, **i**, EQUALS VOLTAGE, **V**, DIVIDED BY RESISTANCE **R**. THE HIGHER THE VOLTAGE, THE MORE CURRENT FLOWS THROUGH A GIVEN RESISTANCE.

(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.

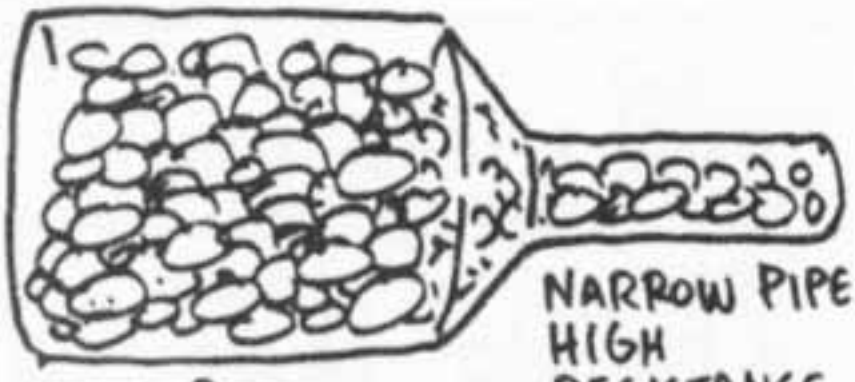


THINK AGAIN OF WATER FLOWING THROUGH A PIPEFUL OF GRAVEL. A SECTION OF PIPE TWICE AS LONG HAS TWICE THE RESISTANCE... A WIDER PIPE HAS LESS RESISTANCE, BECAUSE IT OFFERS MORE SPACES FOR WATER TO FLOW... AND RESISTANCE DEPENDS ON THE TYPE OF GRAVEL.



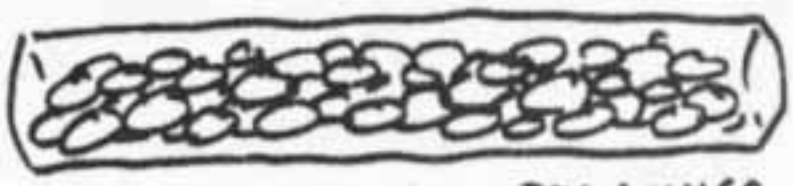
LONG PIPE, HIGH RESISTANCE

SHORT PIPE, LOW RESISTANCE



WIDE PIPE, LOW RESISTANCE

NARROW PIPE, HIGH RESISTANCE



SMOOTH GRAVEL, LOW RESISTANCE

ROUGH GRAVEL, HIGH RESISTANCE

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.

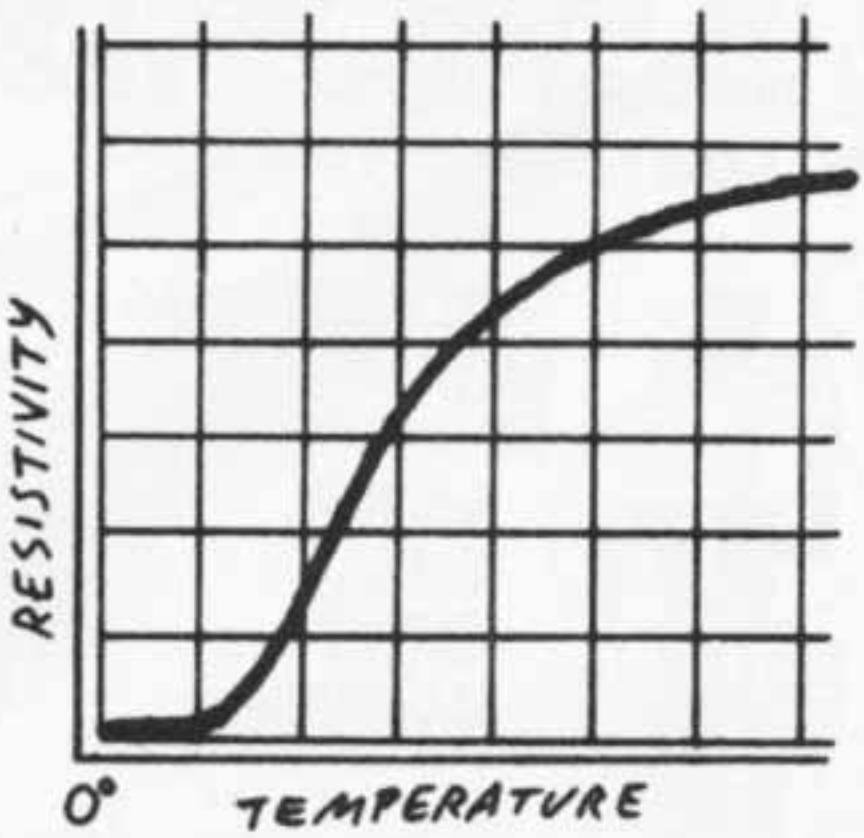
(YOU WANT HIGH RESISTANCE IN A LIGHT BULB, SO THAT IT "DISSIPATES" ELECTRIC ENERGY AS LIGHT!)

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

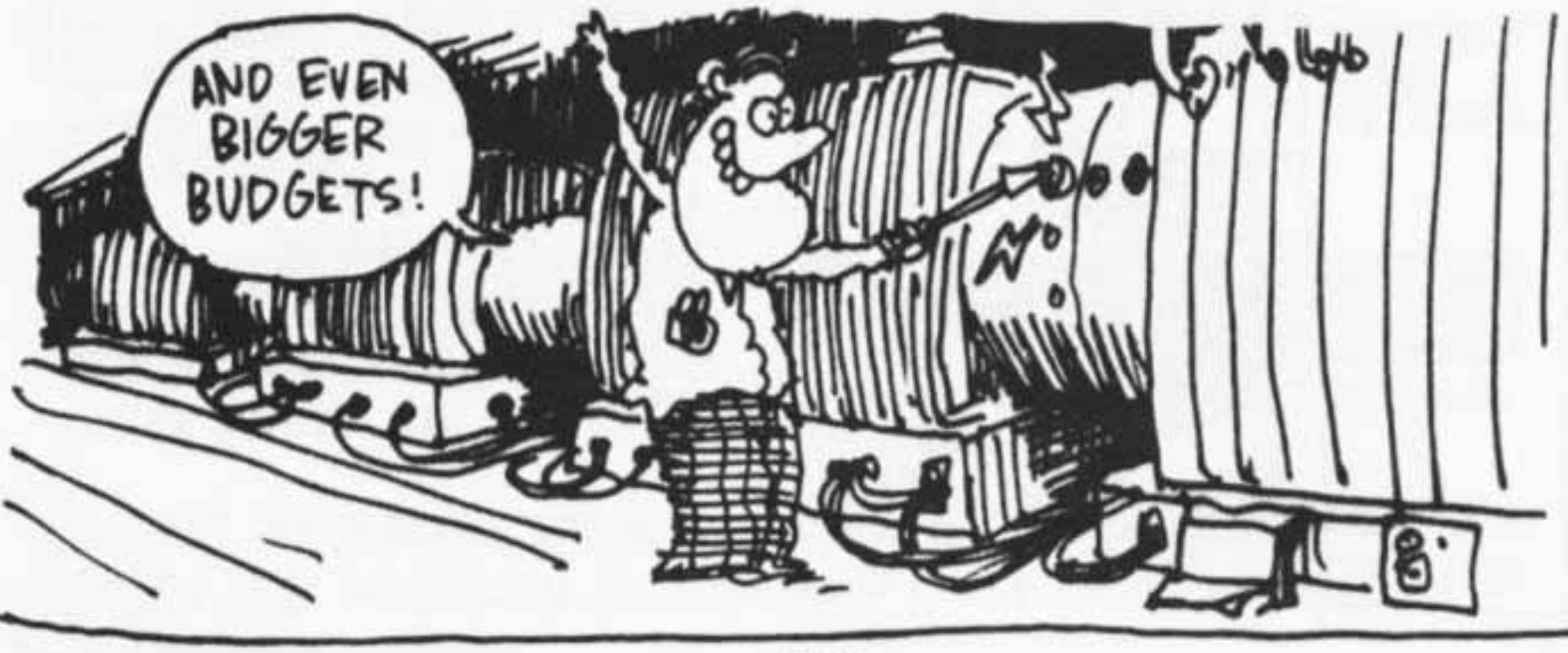
ZERO

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



superconductors.

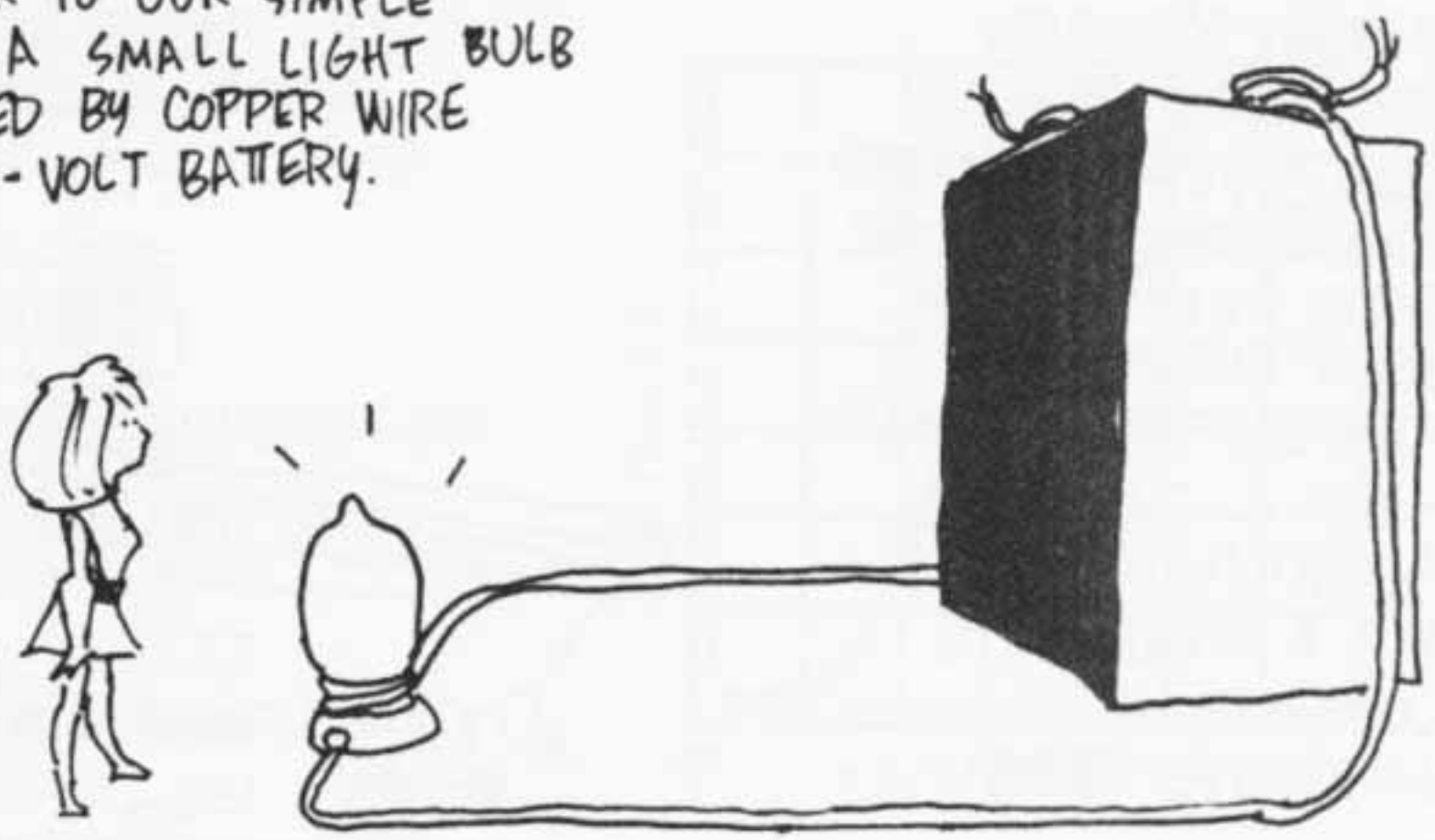
THE WONDERFUL THING ABOUT SUPERCONDUCTORS IS THAT THEY CAN CARRY HUGE CURRENTS WITHOUT ANY LOSS TO HEAT. THESE CURRENTS CAN EVEN PERSIST FOR YEARS WITHOUT LOSS OF ENERGY. SUPERCONDUCTORS, THOUGH EXPENSIVE, ARE USED IN PARTICLE ACCELERATORS, WHERE SUPERSTRONG ELECTROMAGNETS REQUIRE GIANT ELECTRIC CURRENTS.



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

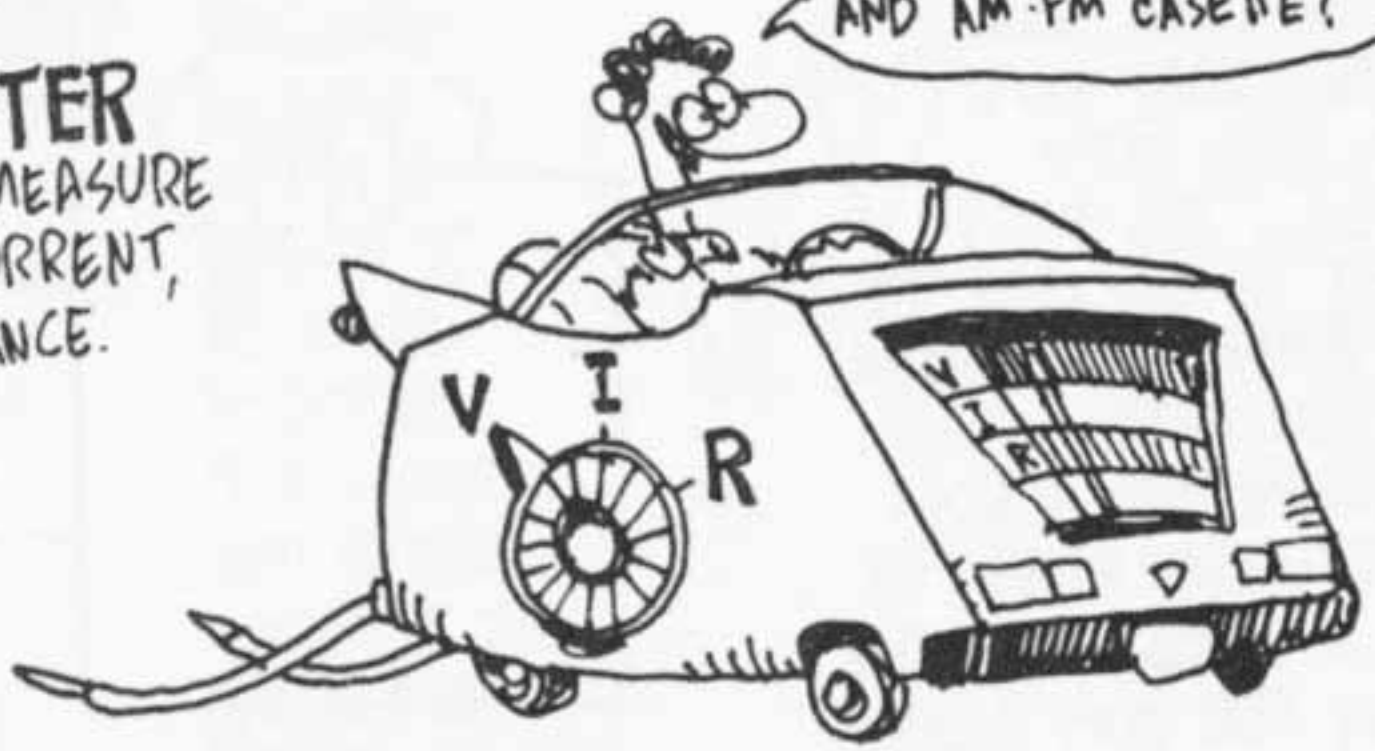
$$i = V/R = \frac{6 \text{ VOLTS}}{6 \text{ OHMS}} = 1 \text{ AMPERE}$$

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

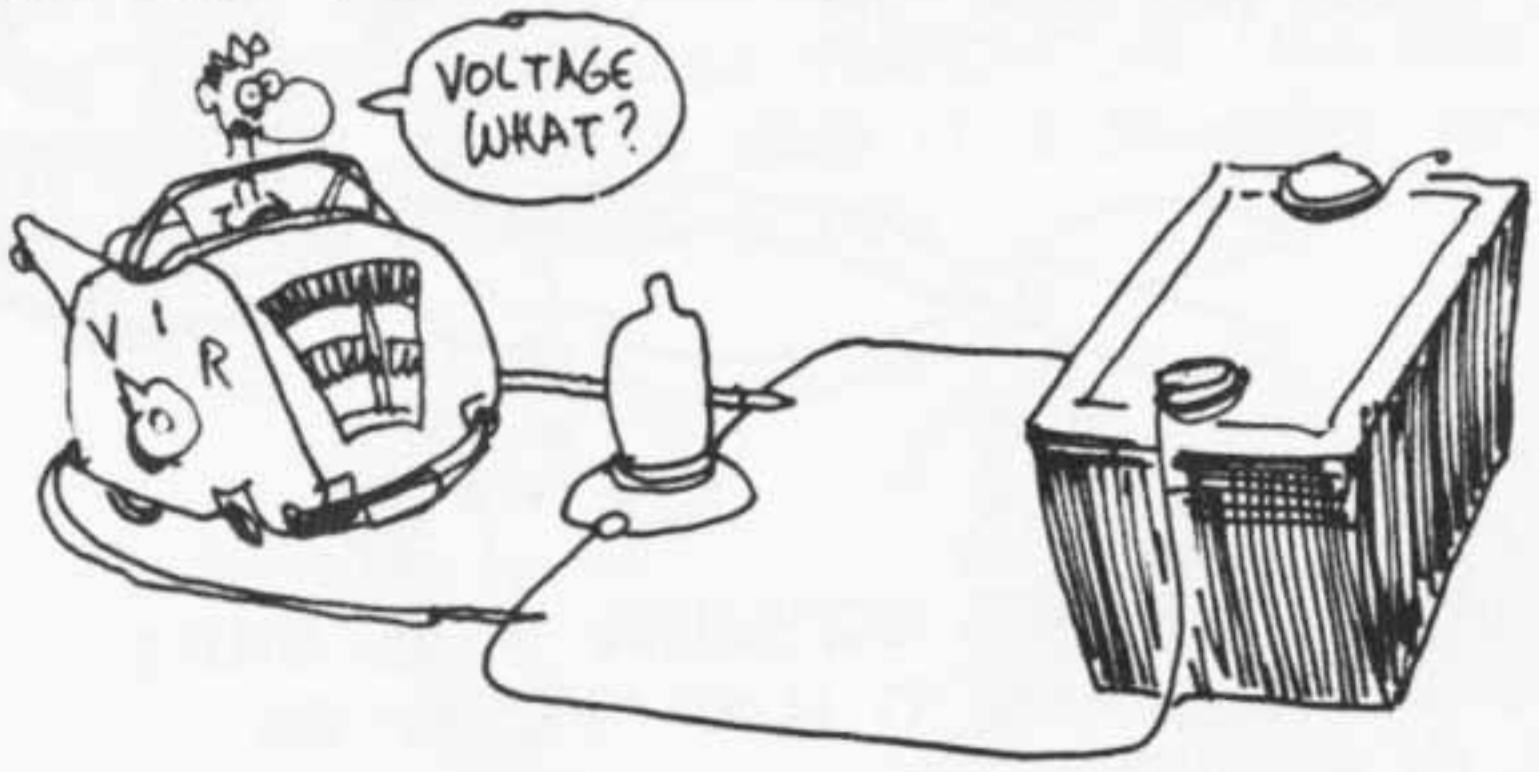
THE QUESTION IS, HOW WOULD YOU MEASURE THESE QUANTITIES IN THE CIRCUIT?

*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.

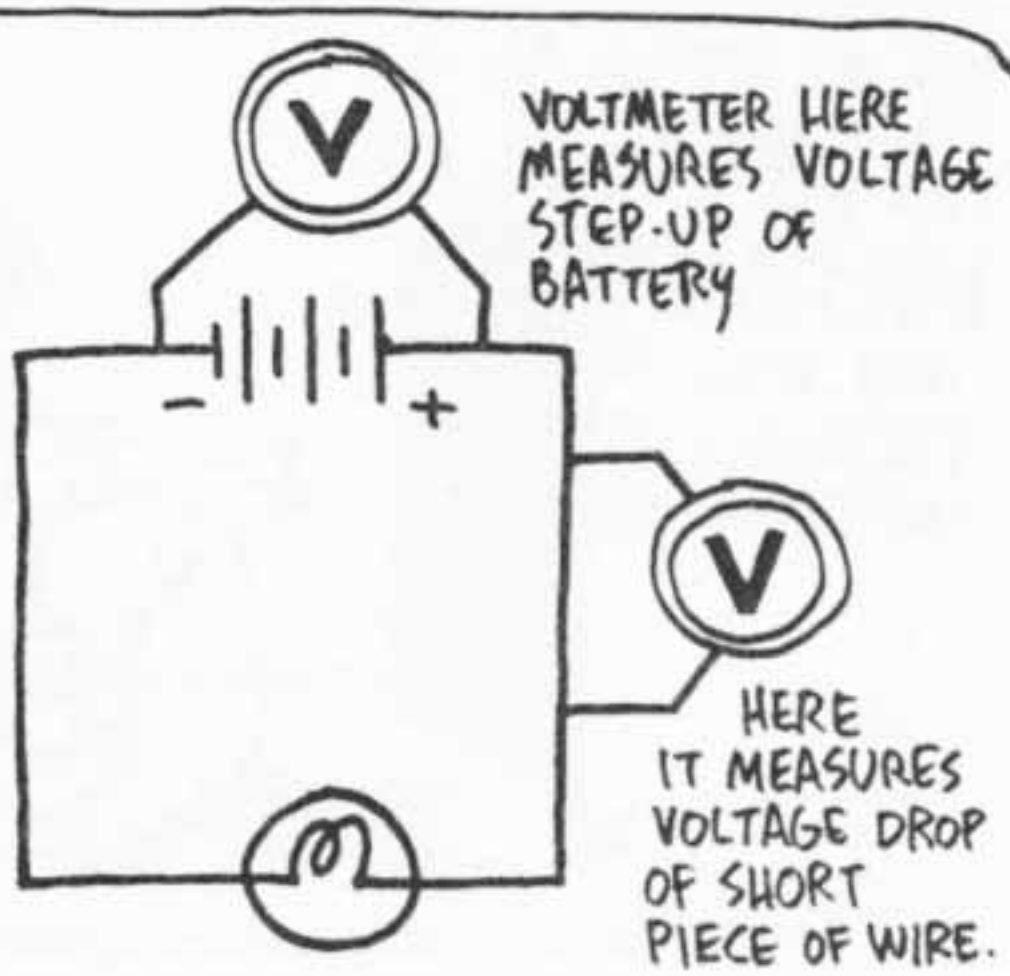


TO MEASURE VOLTAGE, TOUCH THE METER'S LEADS **ACROSS** THE LAMP OR BATTERY. TOUCHING IT ACROSS THE LAMP MEASURES THE **VOLTAGE DROP** OF THE LAMP.



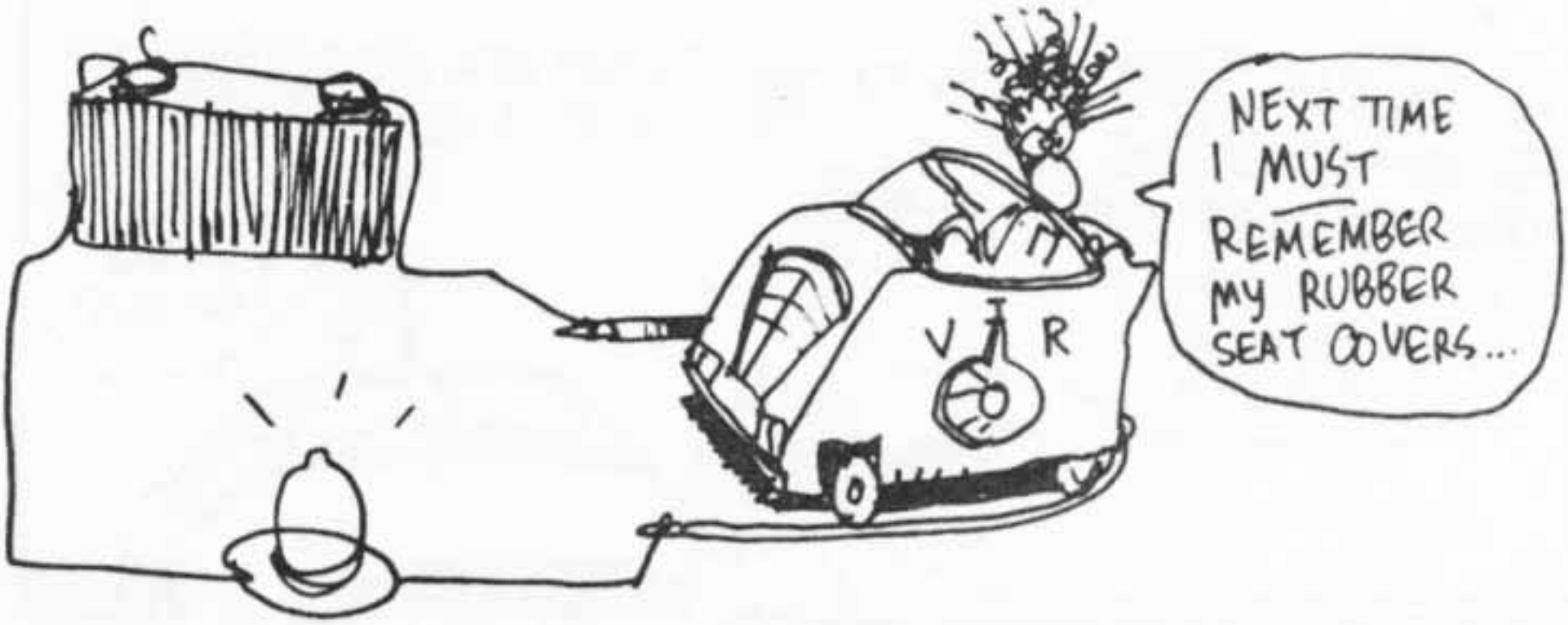
THE VOLTAGE "DROP" REFERS TO THE ENERGY PER CHARGE THAT IS GOING INTO HEAT AND LIGHT.

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.

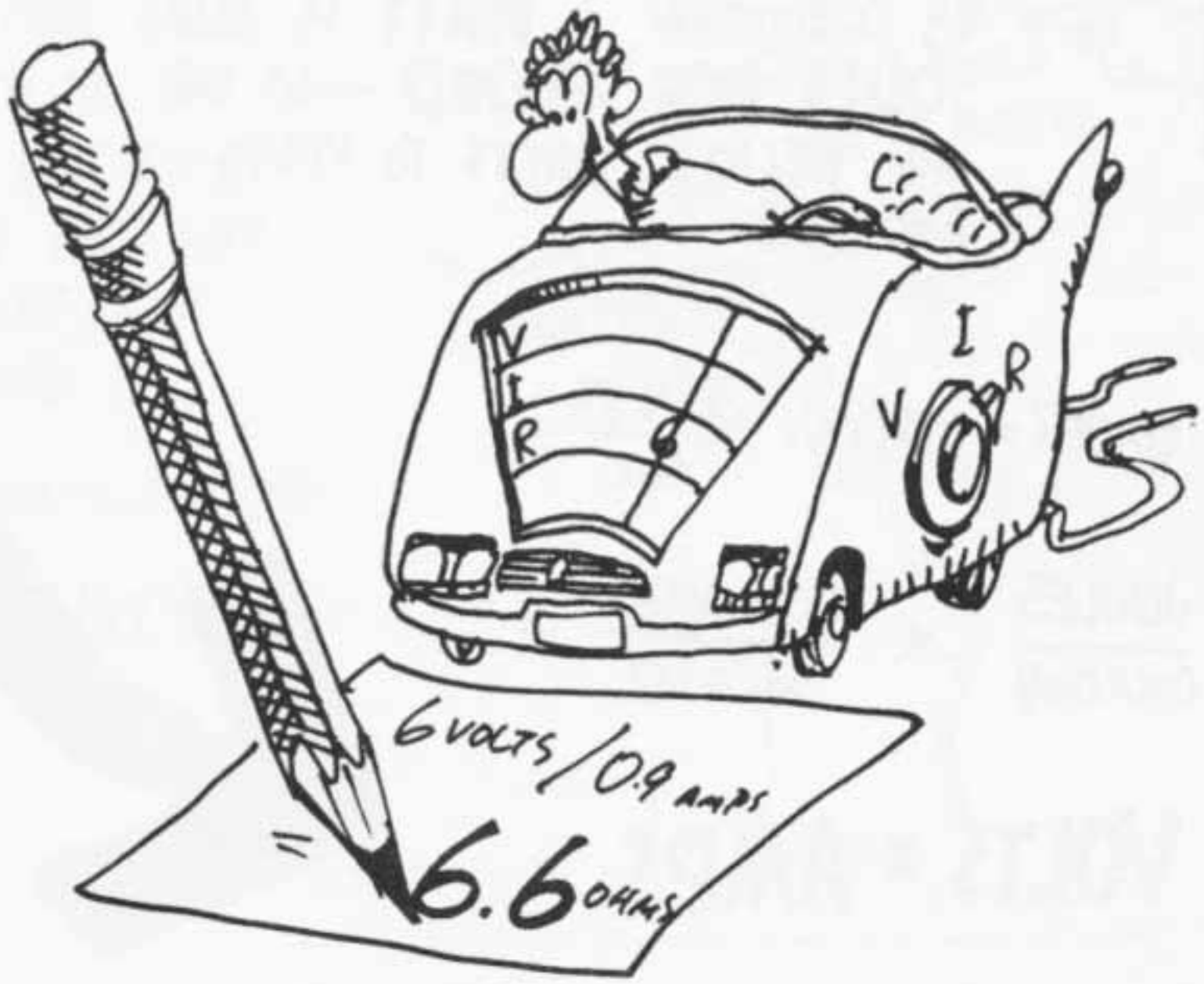
THE SAME CURRENT IS FLOWING EVERYWHERE IN THIS SIMPLE CIRCUIT, AND WE MUST MAKE IT FLOW THROUGH THE AMMETER TO BE MEASURED.



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.

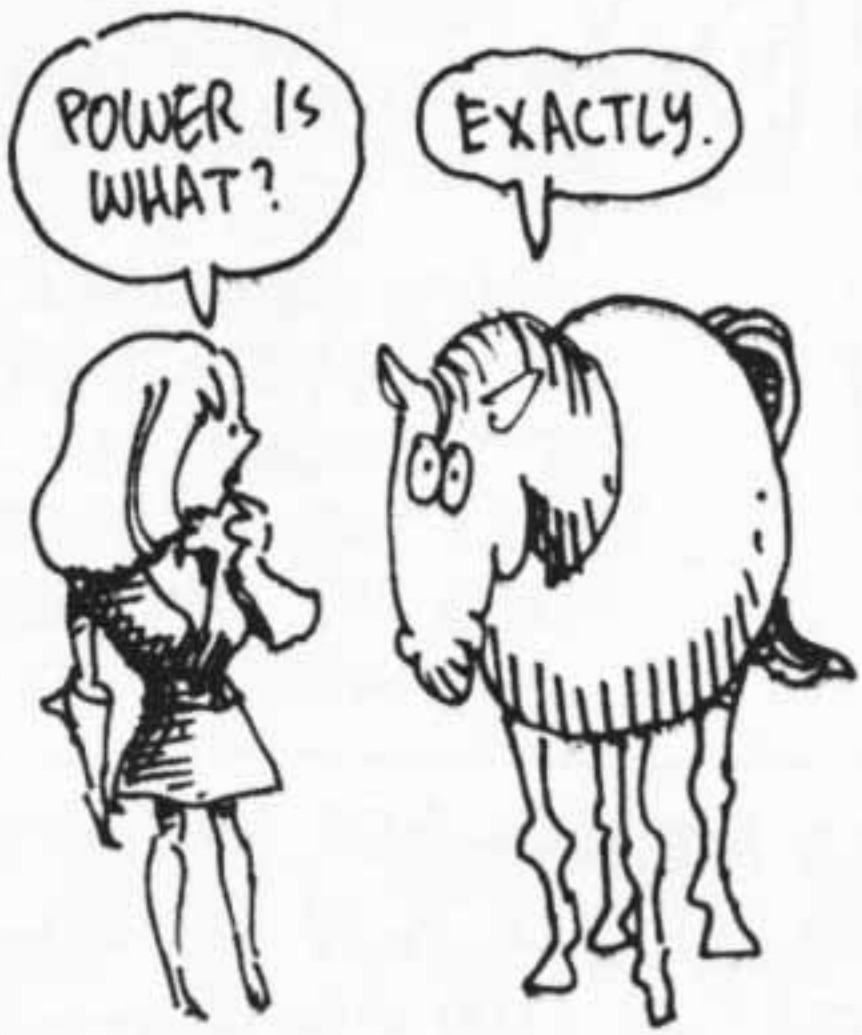
OR YOU COULD USE THE PREVIOUS VOLTAGE AND CURRENT READINGS TO CALCULATE THE RESISTANCE WITH OHM'S LAW.

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.

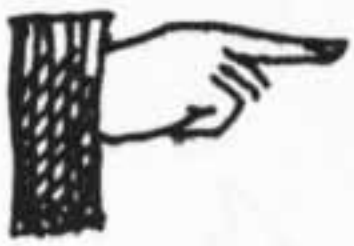


ANOTHER FAMILIAR ELECTRICAL UNIT IS THE

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.

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

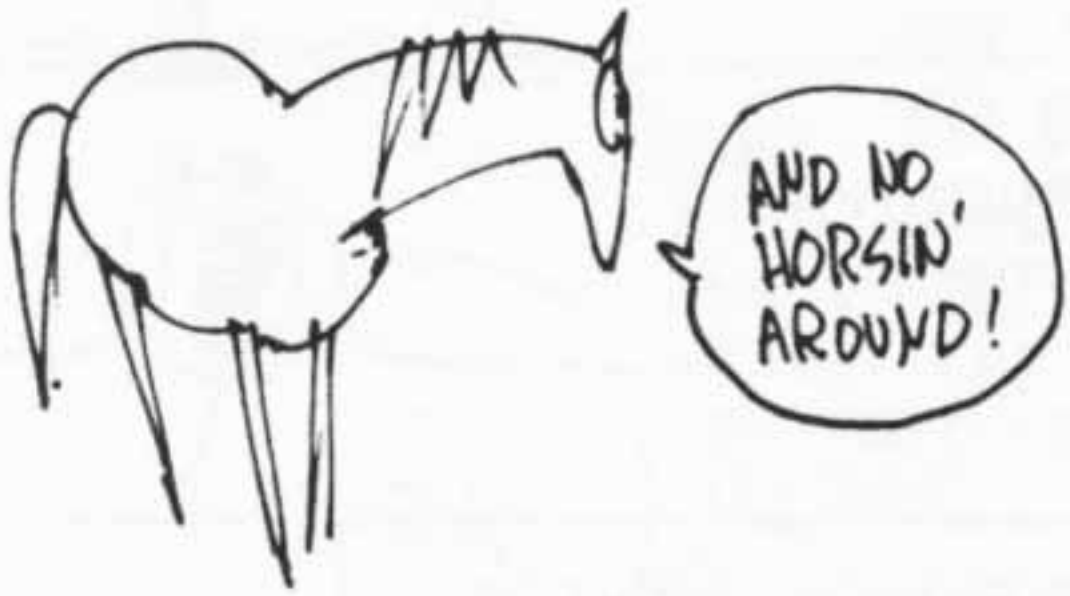
$$\frac{\text{JOULES}}{\text{COULOMB}} \times \frac{\text{COULOMBS}}{\text{SECOND}} =$$

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

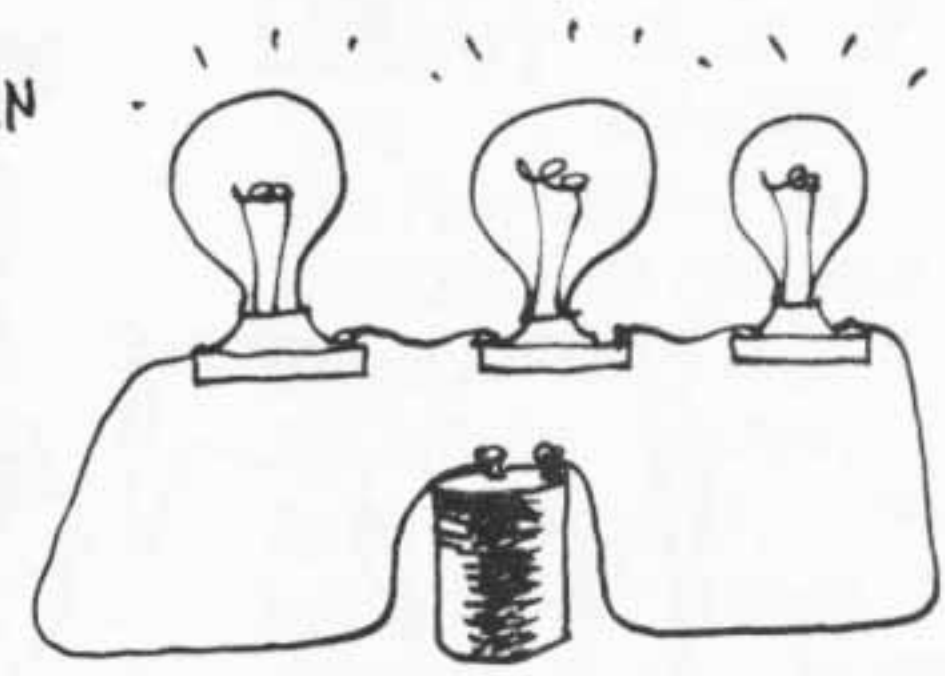
P = 6 VOLTS x 1 AMP

= 6 WATTS.

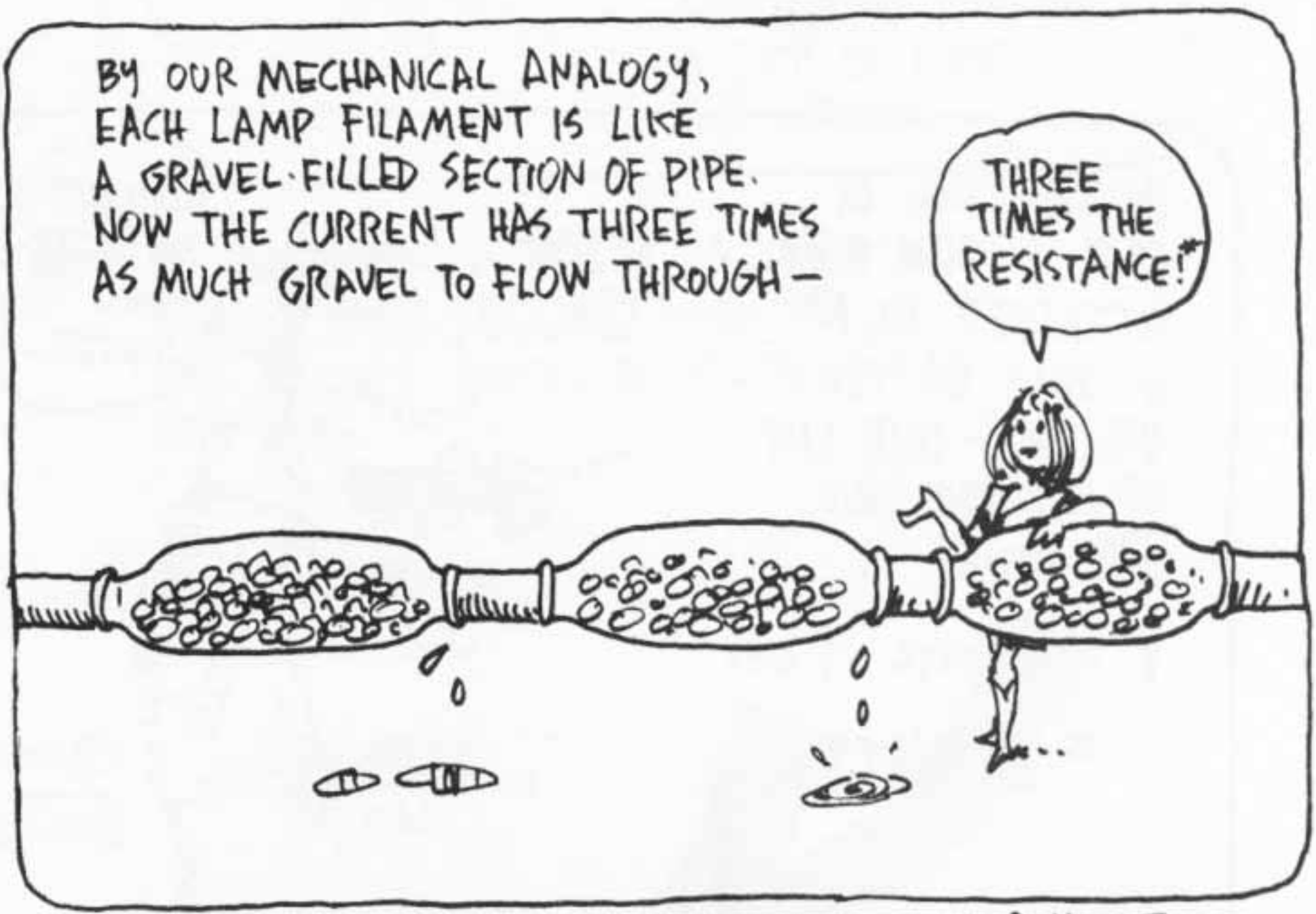
CHAPTER 16:

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.



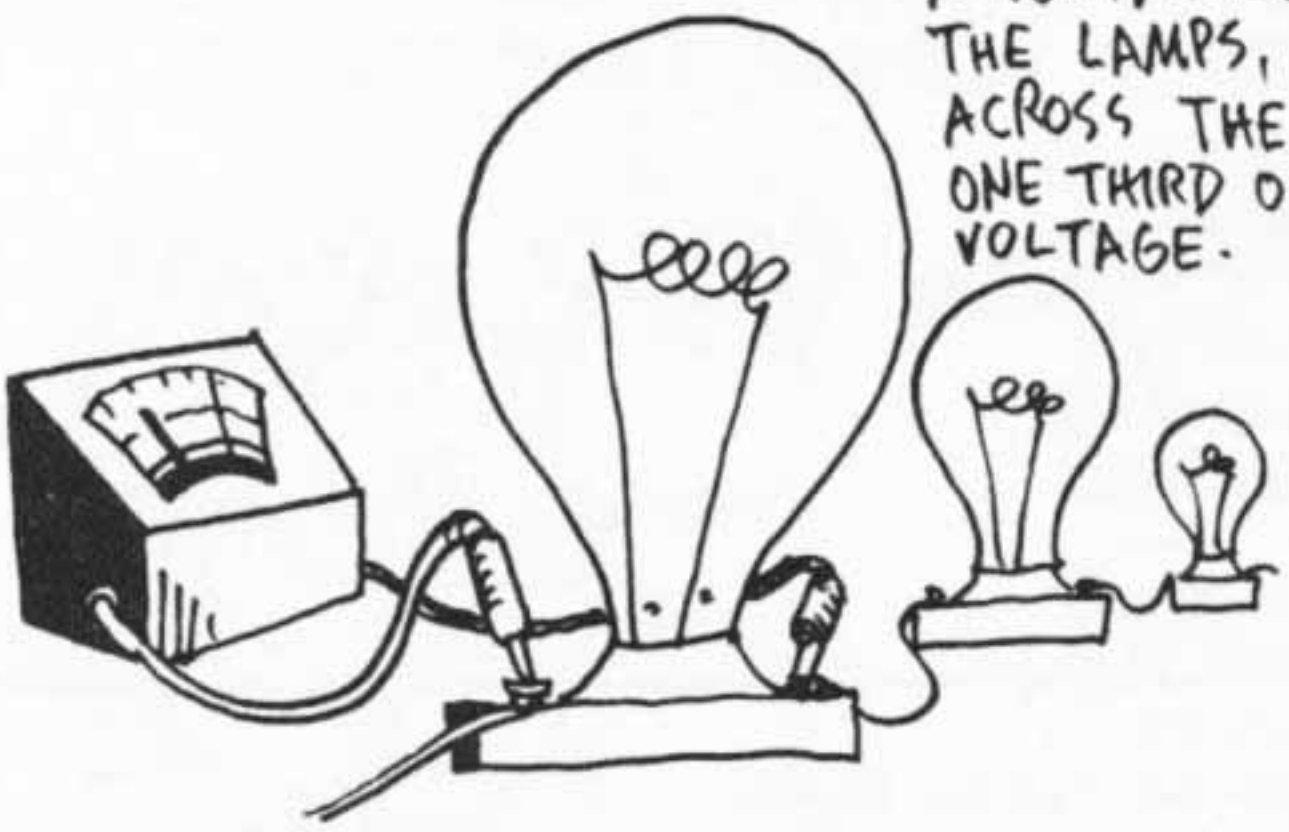
BY OUR MECHANICAL ANALOGY, EACH LAMP FILAMENT IS LIKE A GRAVEL-FILLED SECTION OF PIPE. NOW THE CURRENT HAS THREE TIMES AS MUCH GRAVEL TO FLOW THROUGH—



*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.

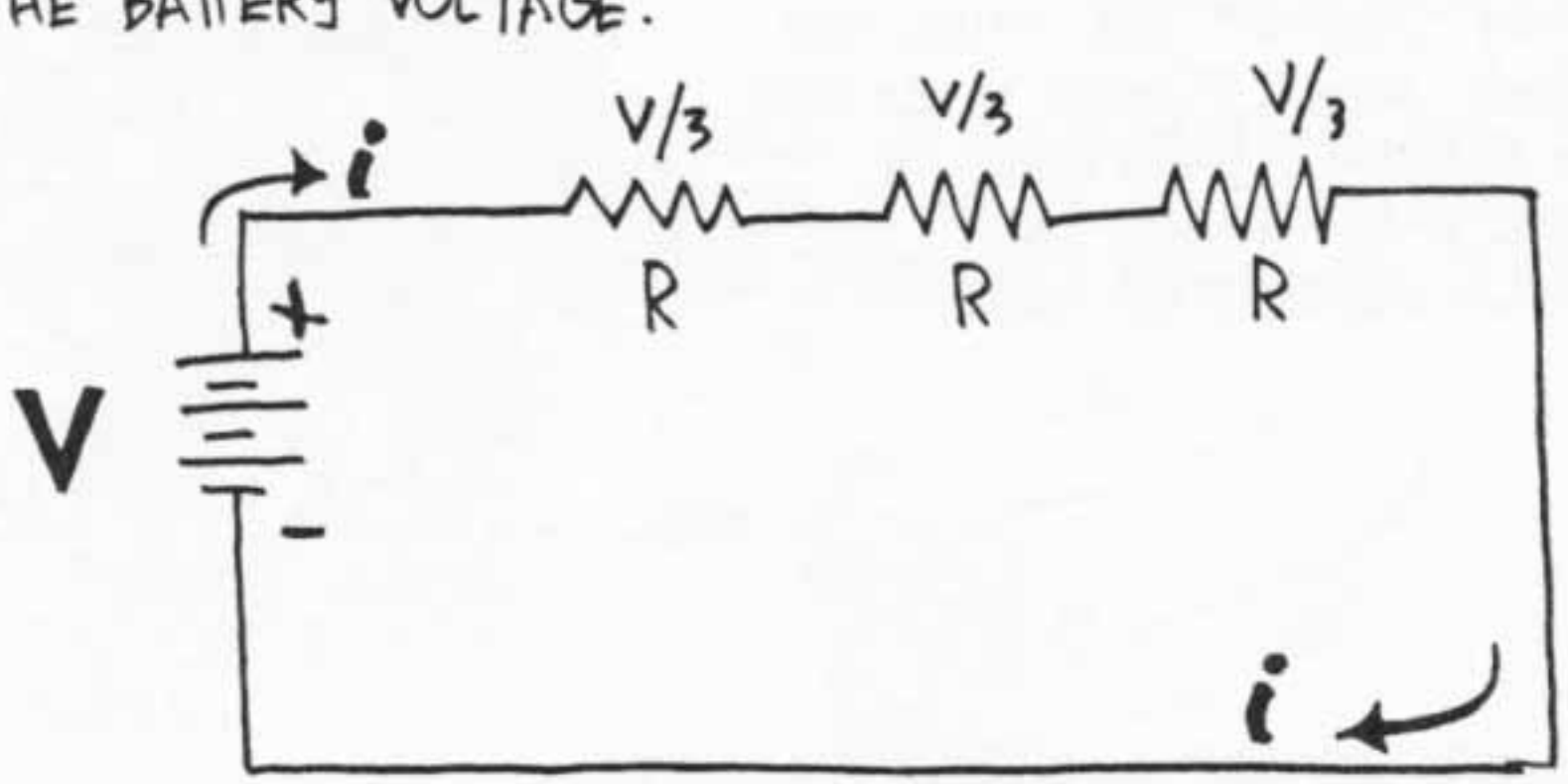
$$i = \frac{V}{R}$$

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.

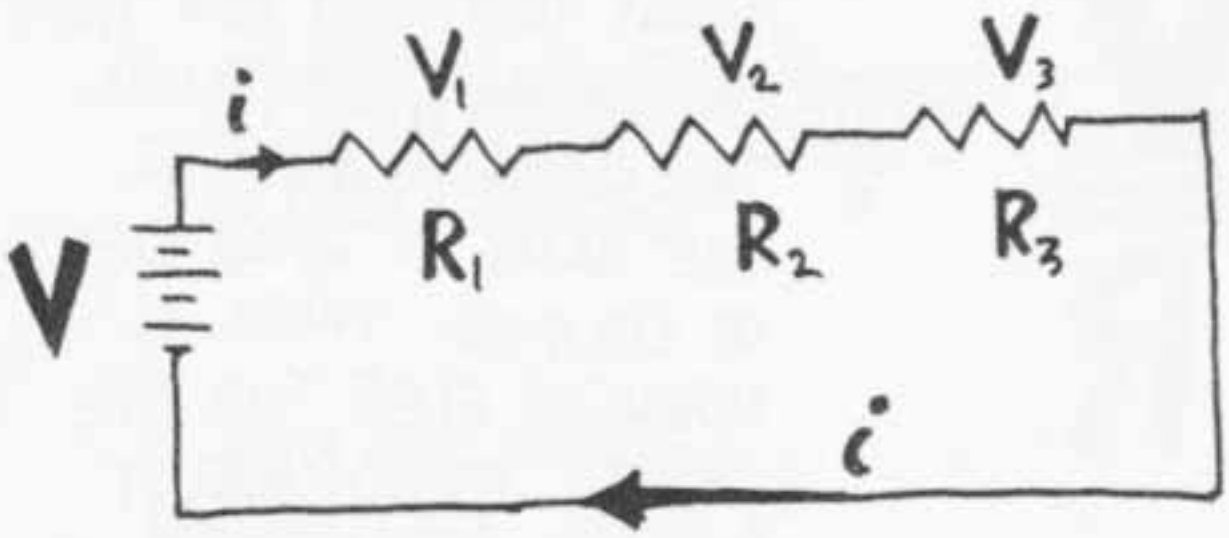


WHEN I TOUCH THE LEADS OF A VOLTMETER ACROSS ONE THE LAMPS, THE VOLTAGE DROP ACROSS THE LAMP IS ONE THIRD OF THE BATTERY VOLTAGE.

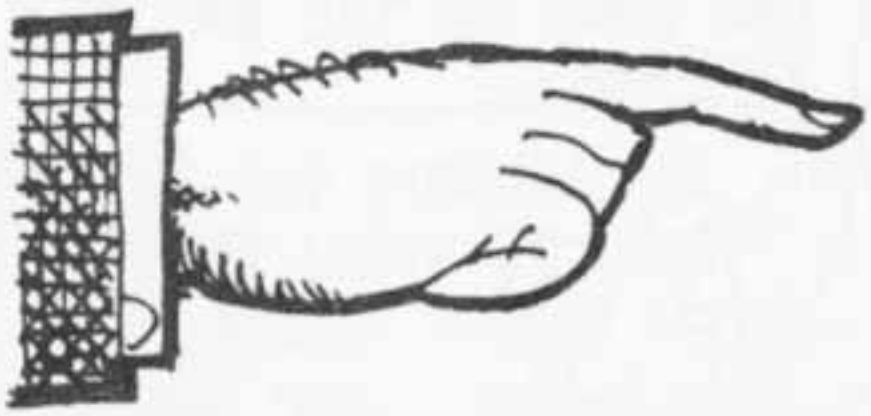
THE LAMPS DIVIDE UP THE VOLTAGE, AND THE SUM OF THE VOLTAGE DROPS ACROSS THE SERIES COMPONENTS MUST EQUAL THE BATTERY VOLTAGE.



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.



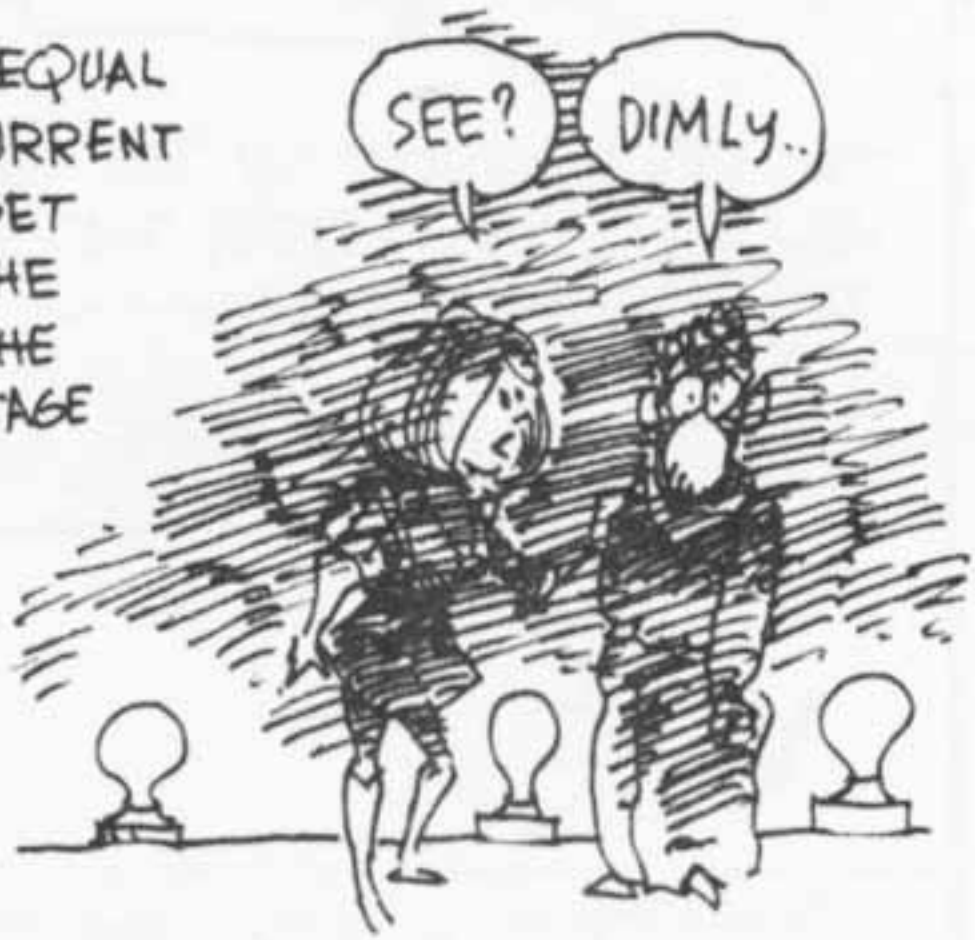
THE TOTAL ENERGY CONSUMED BY THE LAMPS MUST EQUAL THE ENERGY PRODUCED BY THE BATTERY, SO THESE VOLTAGE DROPS MUST ADD TO THE BATTERY VOLTAGE. THIS IS CALLED THE LOOP THEOREM, OR KIRKHHOFF'S FIRST LAW:



$$V = V_1 + V_2 + V_3$$

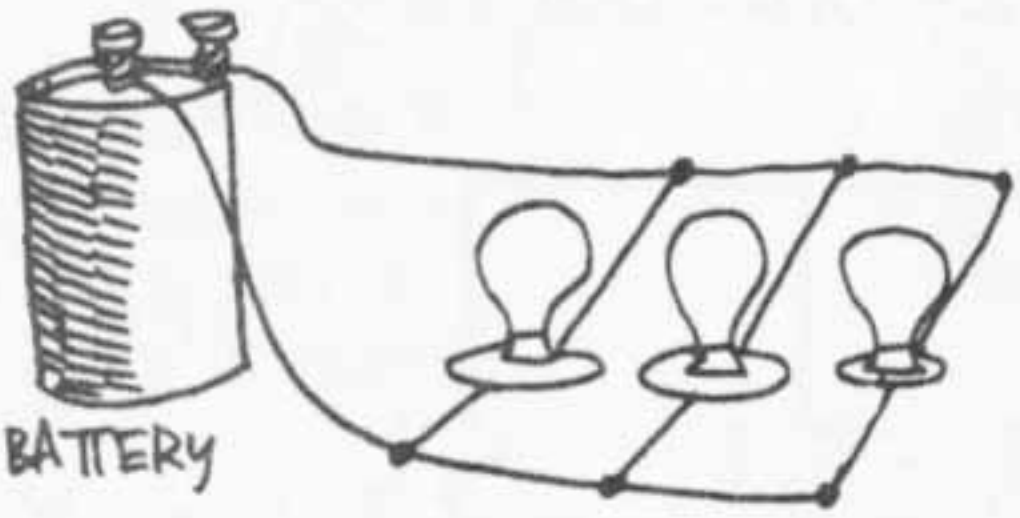
(AND $V_1 = iR_1$, ETC.)

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!!



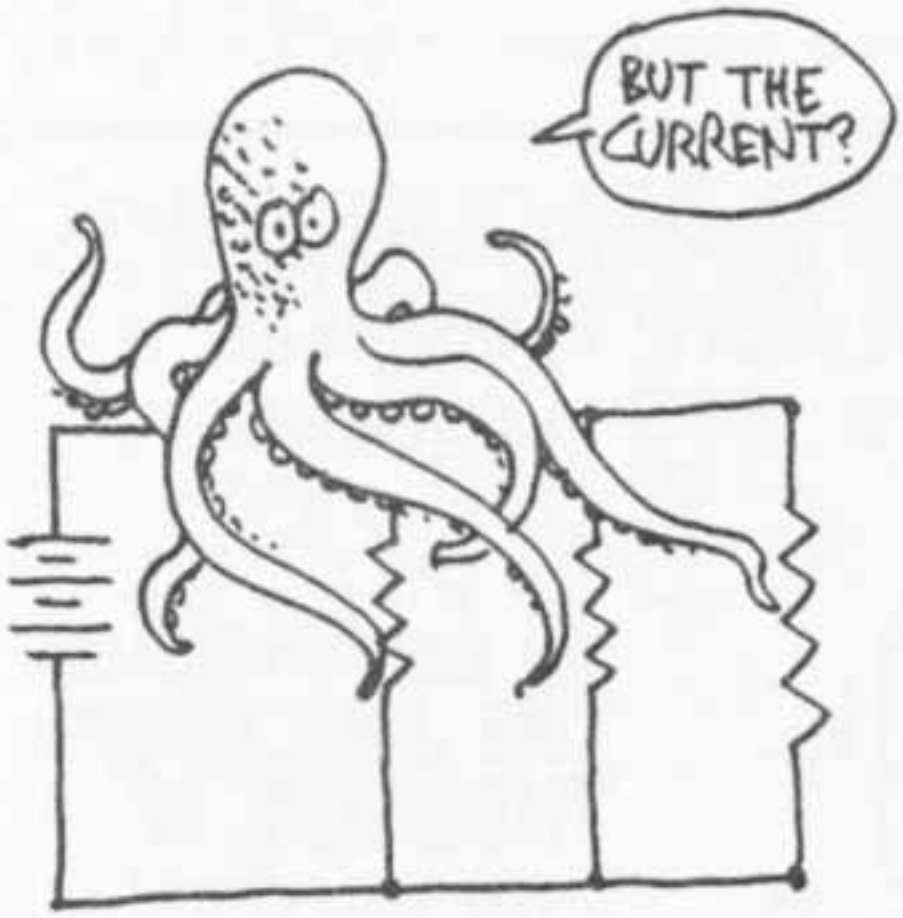
* REMEMBER, VOLTAGE IS ENERGY PER CHARGE.

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



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

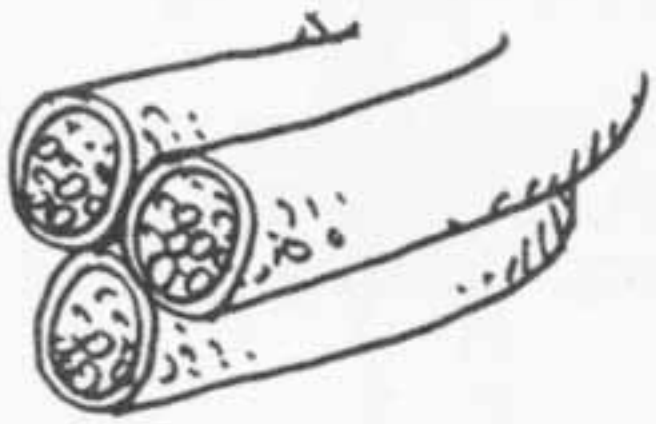
THIS WAY EVERY BULB GETS A FULL DOSE OF VOLTAGE, AND SHINES WITH ITS NORMAL BRIGHTNESS. THIS IS THE WAY A HOUSE WOULD NORMALLY BE WIRED SO THAT EVERY ELECTRIC FIXTURE GETS FULL HOUSE VOLTAGE.



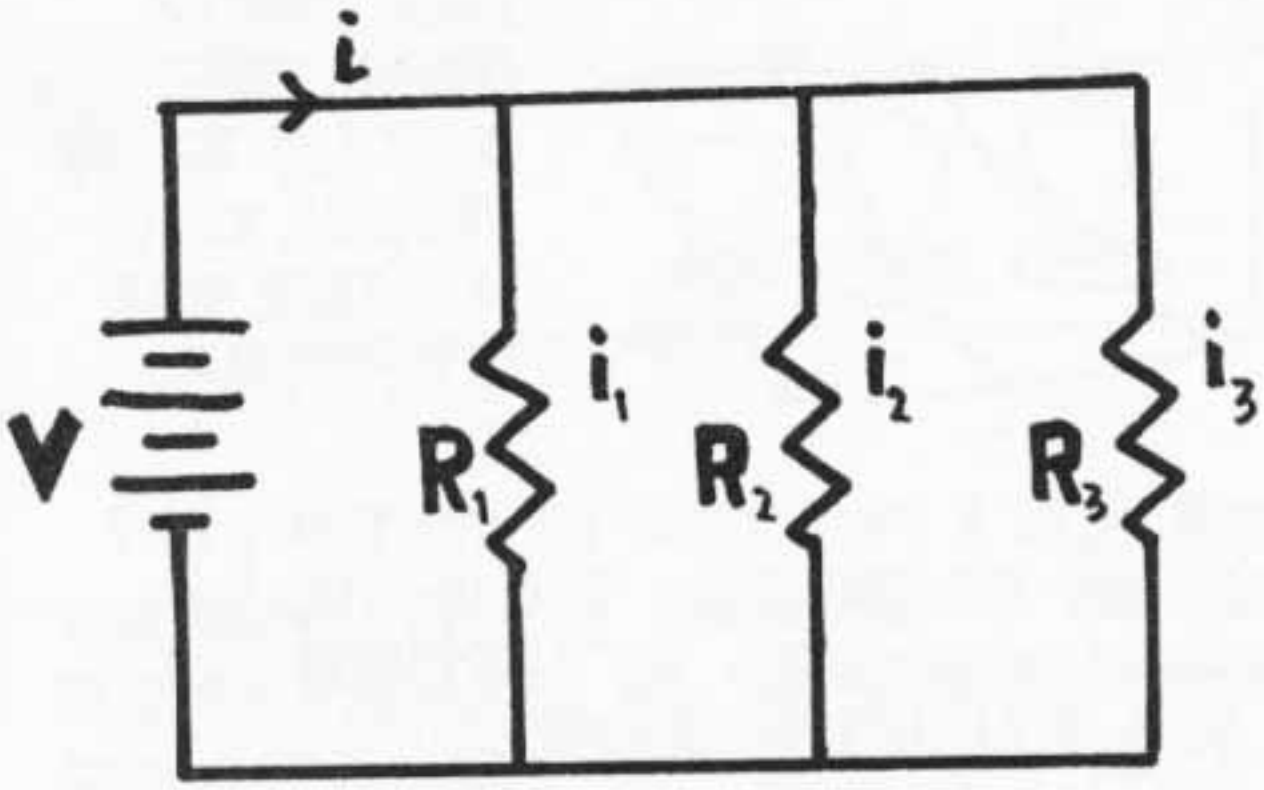
IN THE PARALLEL CIRCUIT, THE **CURRENT** HAS TO DIVIDE AND FLOW THROUGH THE THREE BRANCHES.

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 $i = V/R$.



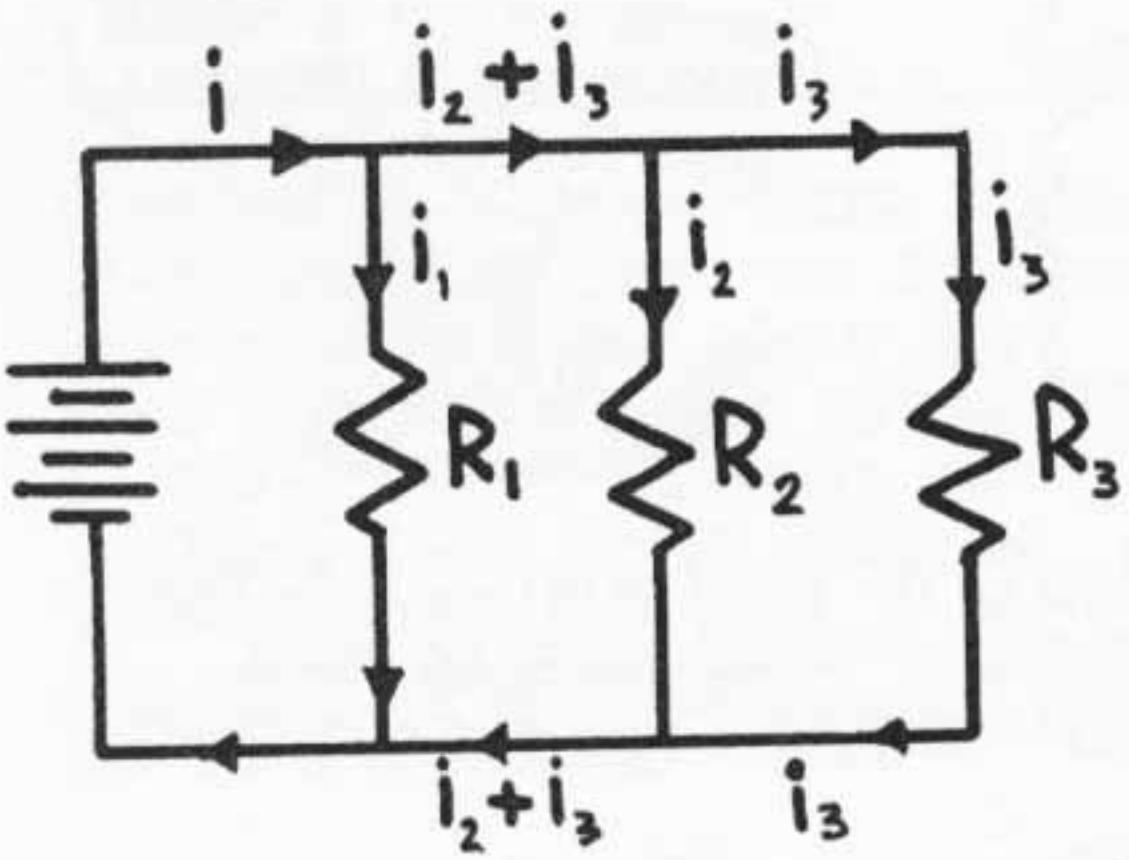
$$i_1 = \frac{V}{R_1}$$

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

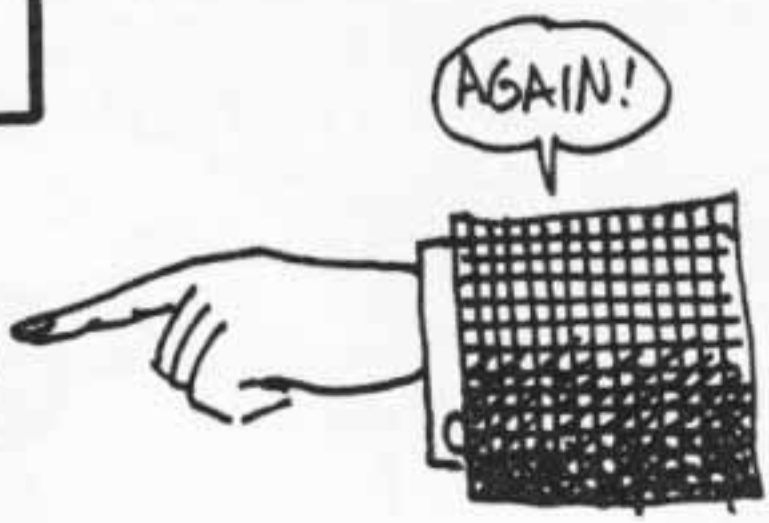
$$i_3 = \frac{V}{R_3}$$

$$i = i_1 + i_2 + i_3$$

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:**

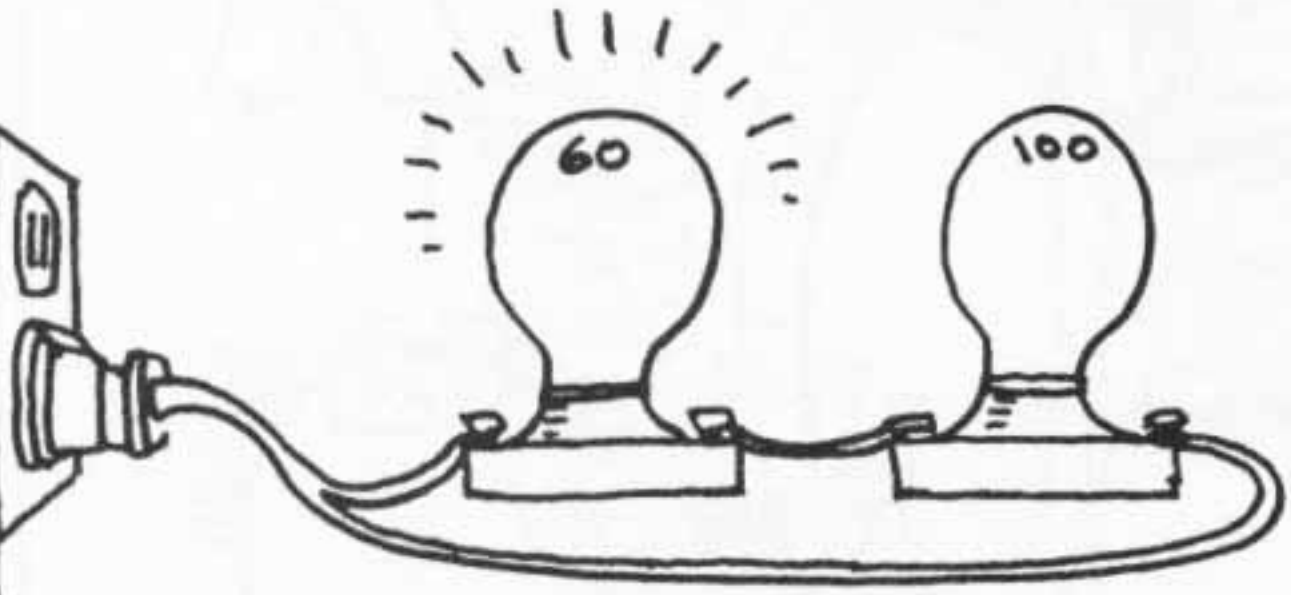


THE CURRENT FLOWING INTO ANY JUNCTION EQUALS THE SUM OF THE CURRENTS FLOWING OUT.

HERE IS AN INTERESTING

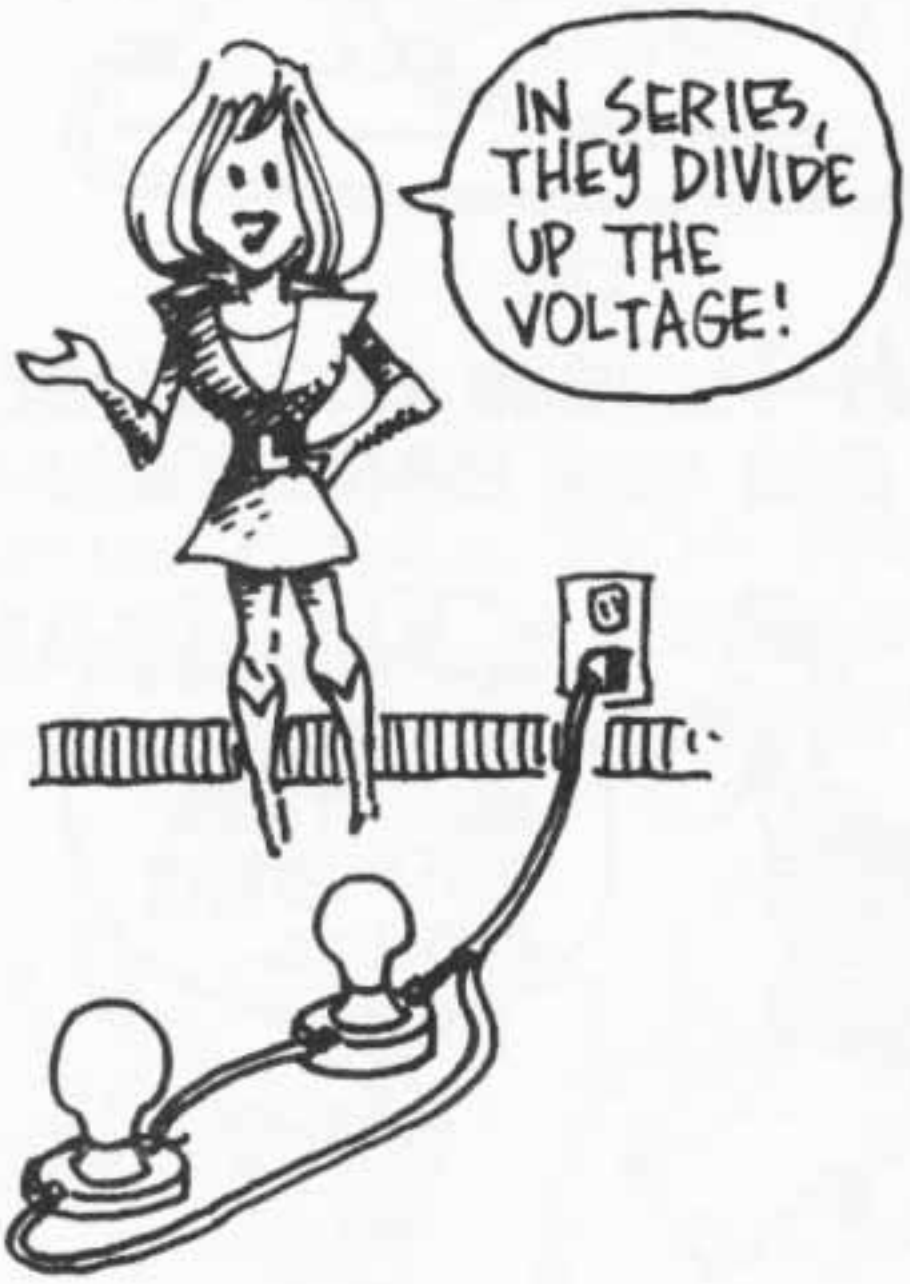
PARADOX

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.



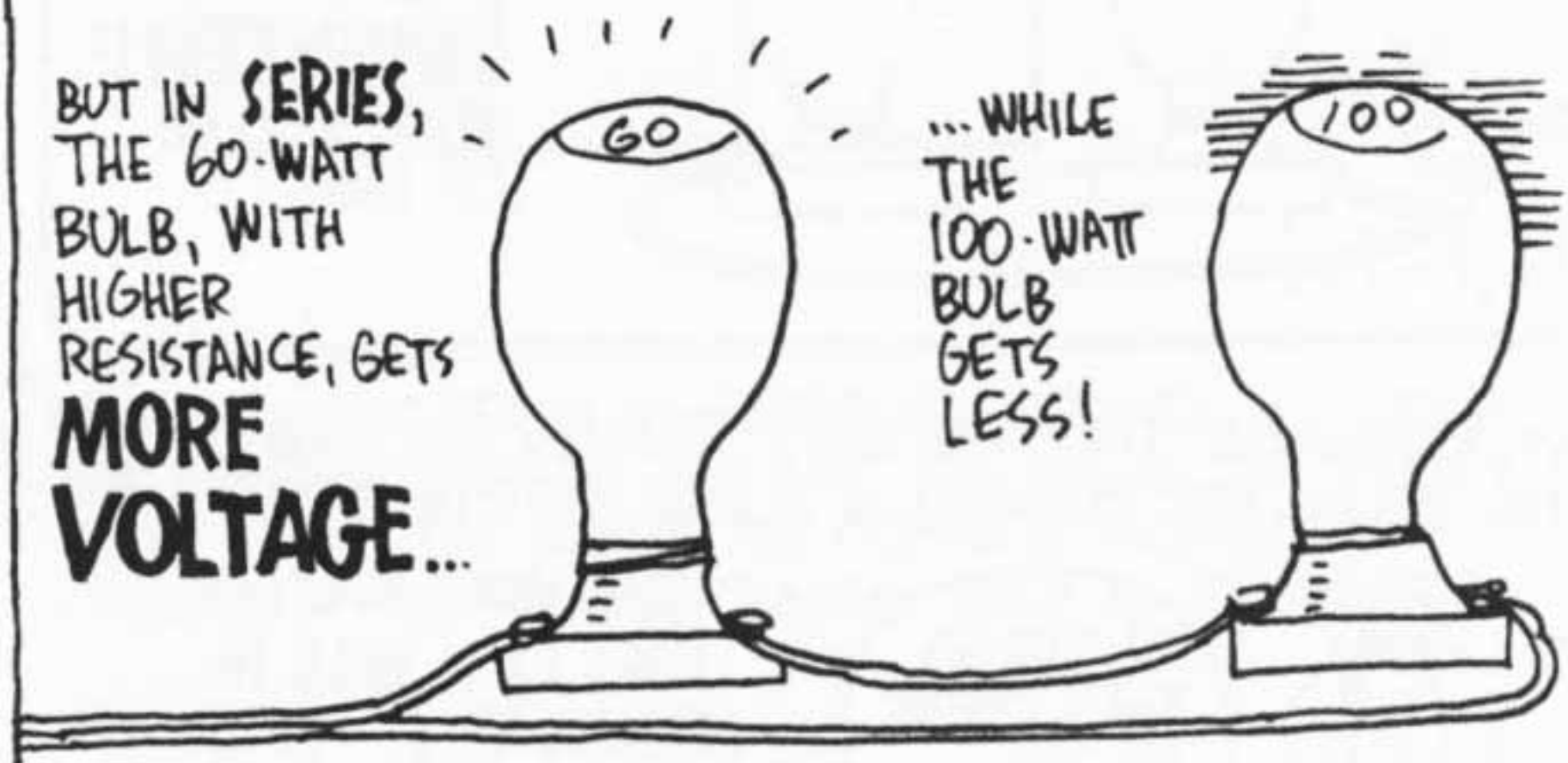
HOW MUCH VOLTAGE DOES EACH BULB IN SERIES GET? BOTH BULBS GET THE SAME CURRENT i, SO OHM'S LAW

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.

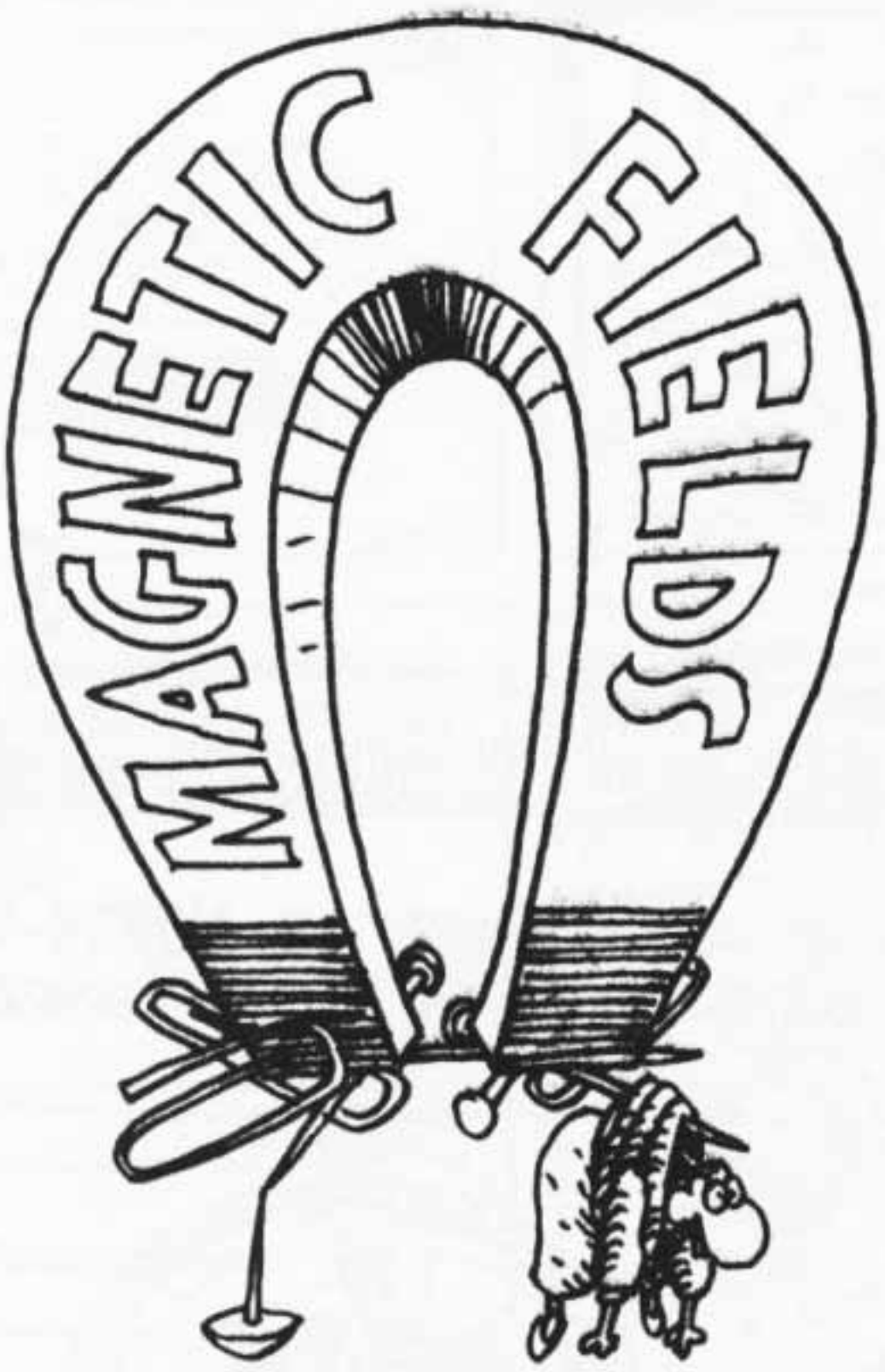
BUT IN **SERIES**, THE 60-WATT BULB, WITH HIGHER RESISTANCE, GETS **MORE VOLTAGE**...



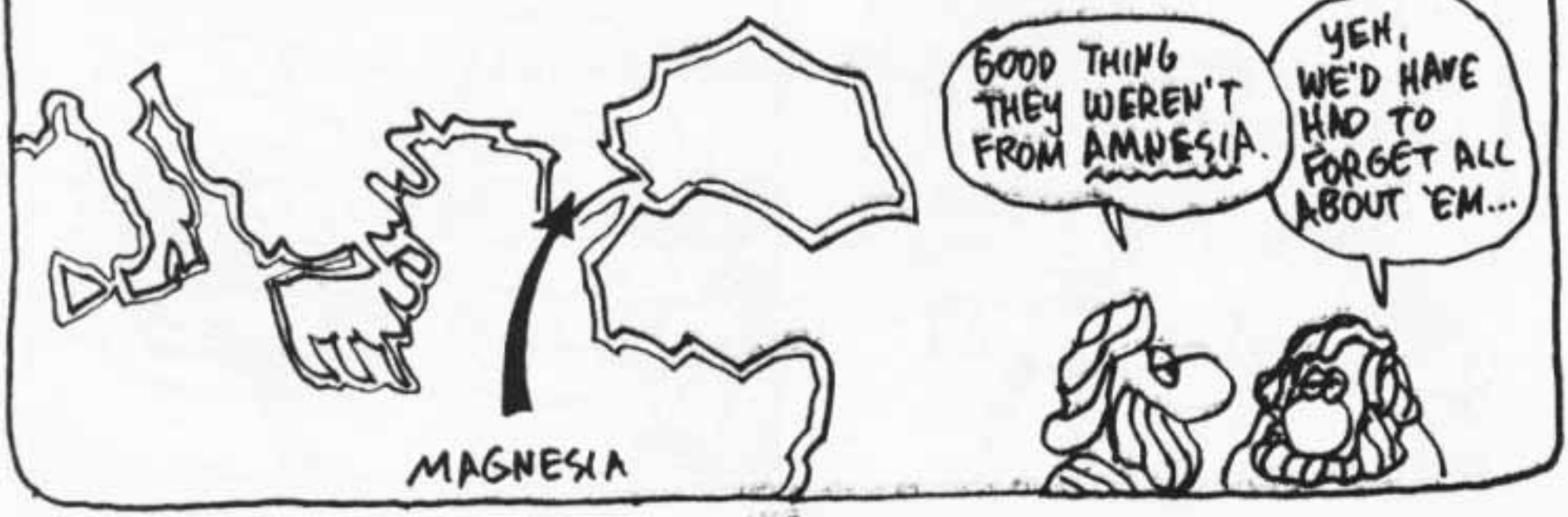
...WHILE THE 100-WATT BULB GETS LESS!

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

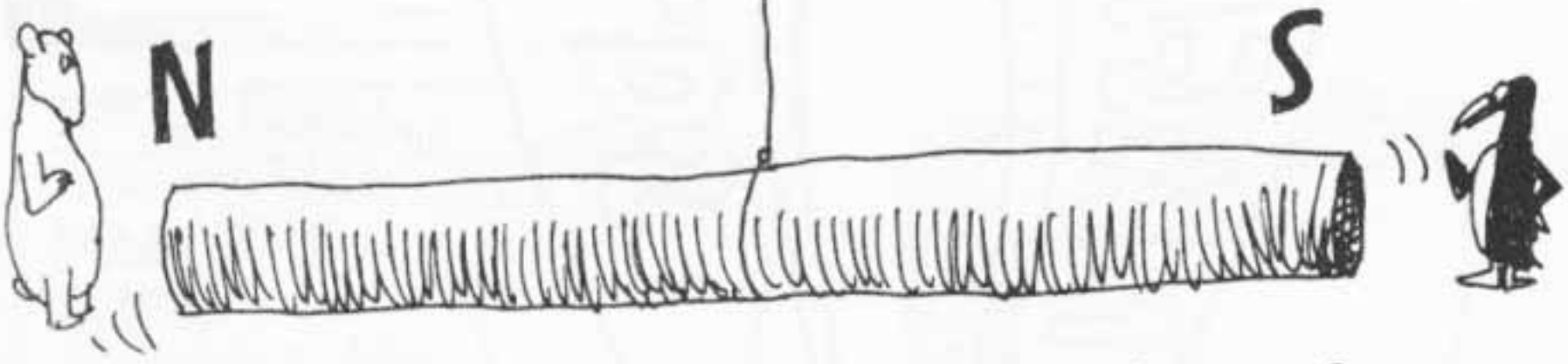
◊CHAPTER 17◊



SEVERAL THOUSAND YEARS AGO, THE GREEKS DISCOVERED THAT CERTAIN METALLIC ROCKS FROM THE DISTRICT OF **MAGNESIA** IN ASIA MINOR WOULD ATTRACT IRON, AND ATTRACT OR REPEL SIMILAR ROCKS. HENCE THE NAME "MAGNET..."



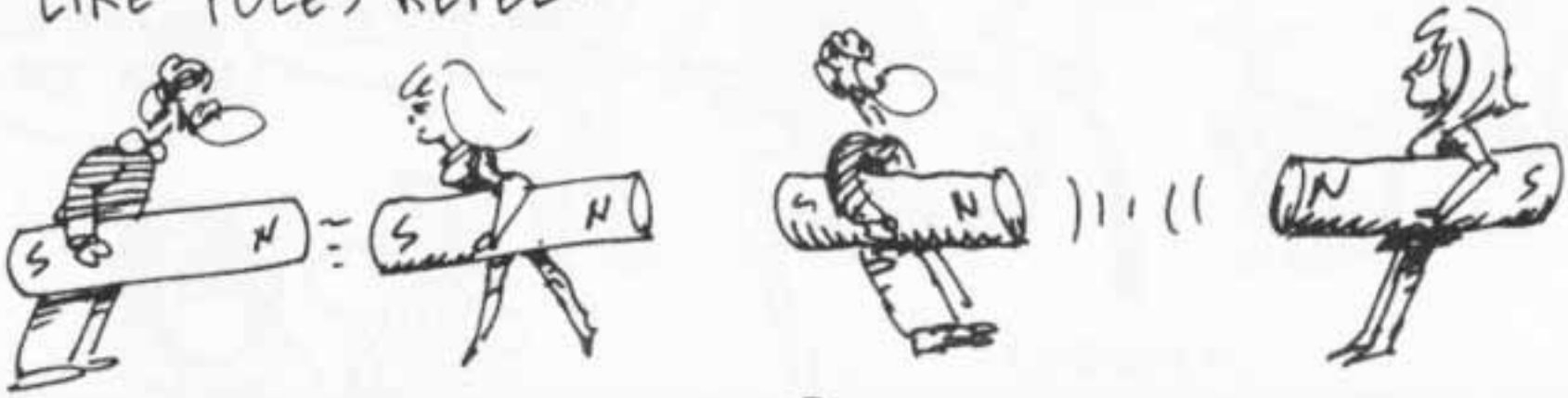
FURTHER STUDY ESTABLISHED THAT MAGNETS ALWAYS HAVE TWO **POLES,** CALLED **NORTH** AND **SOUTH.**



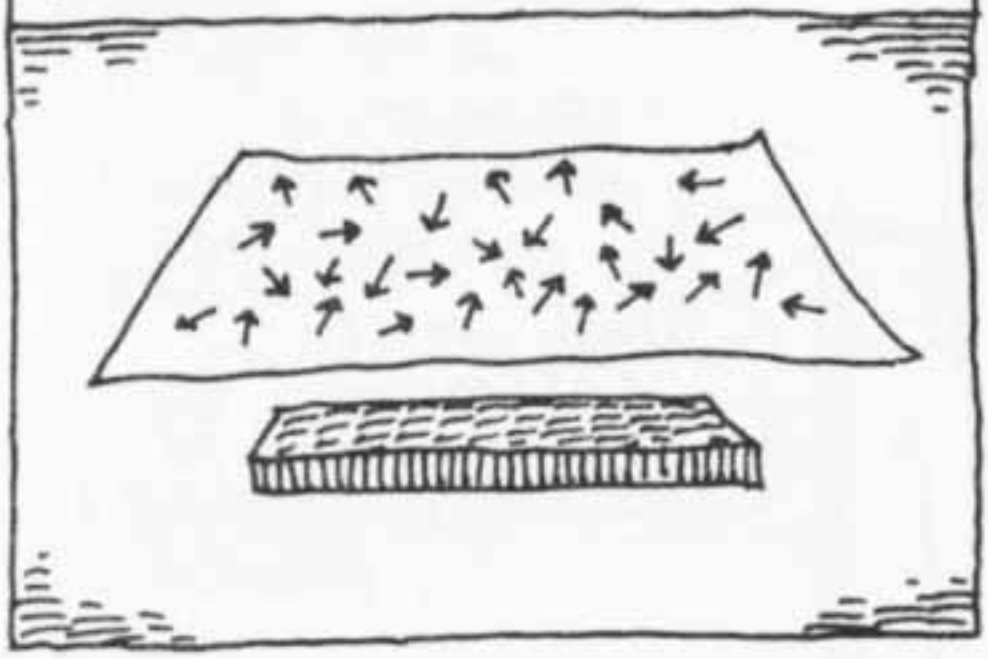
IF YOU ALLOW A MAGNET TO PIVOT, ITS **NORTH** POLE IS THE ONE THAT POINTS TOWARD THE EARTH'S (GEOGRAPHIC) NORTH.

A **COMPASS** IS JUST A MAGNETIC NEEDLE ON A PIVOT.

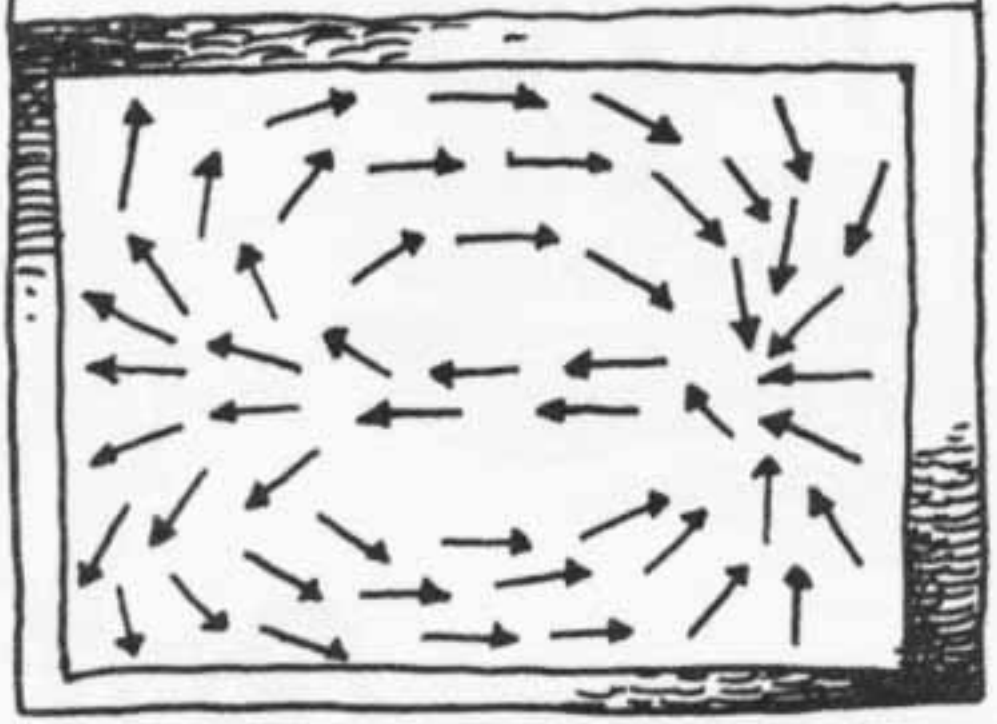
WE ALSO NOTE THAT UNLIKE POLES ATTRACT, WHILE LIKE POLES REPEL.



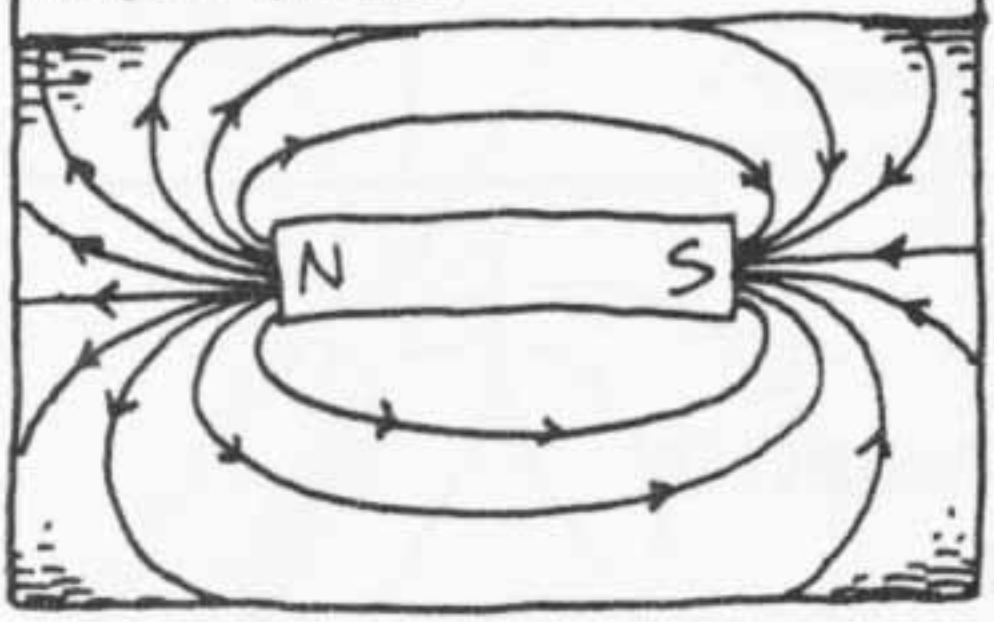
NOW IMAGINE THAT WE HAD SCATTERED TINY COMPASS NEEDLES ON A SHEET OF PAPER AND BROUGHT A BAR MAGNET UNDERNEATH THEM:



THE NEEDLES WILL LINE UP, REVEALING THE BAR MAGNET'S **MAGNETIC FIELD.**



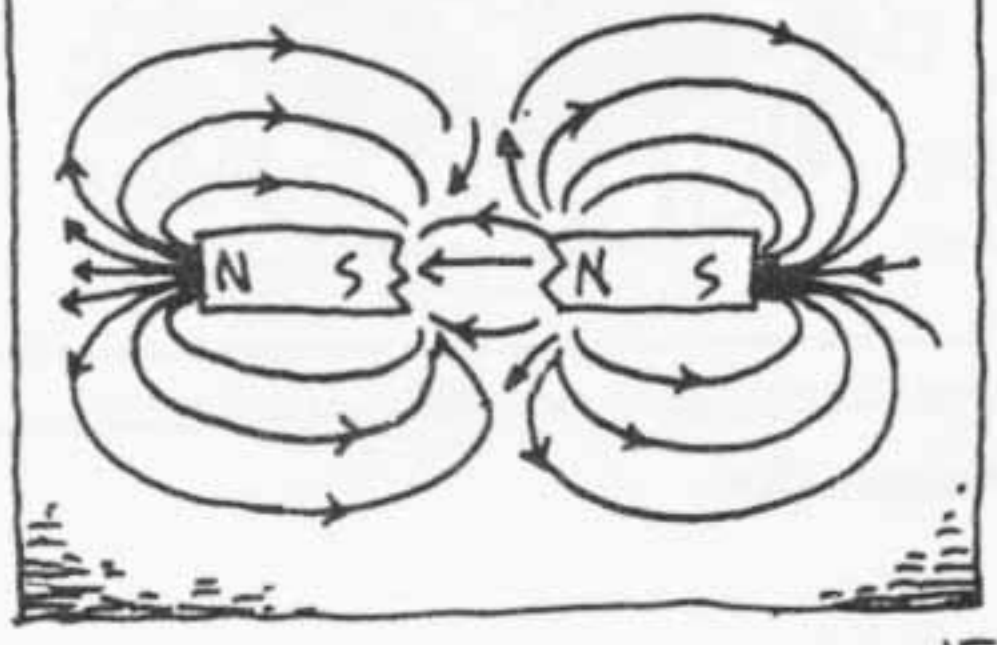
AS WITH THE ELECTRIC FIELD, WE CONNECT THE LINES ALONG THE DIRECTION OF THE ARROWS AND SEE THE RESULTING MAGNETIC **FIELD LINES.**



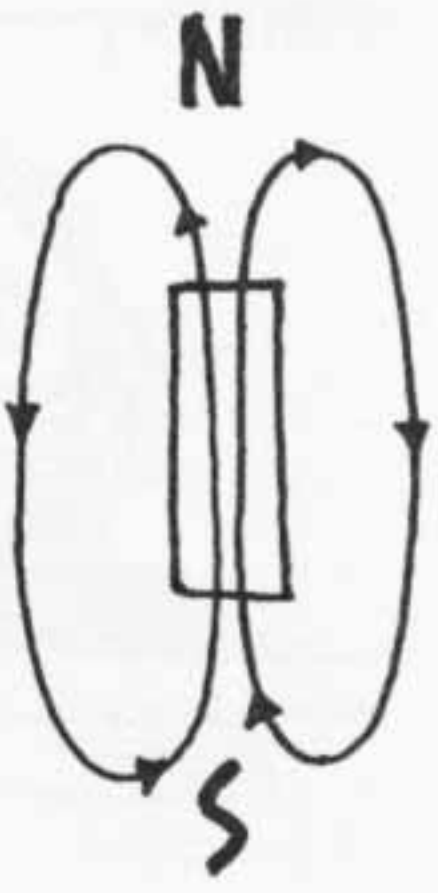
BY CONVENTION, WE AGREE THAT THE FIELD LINES EMERGE FROM THE **NORTH** MAGNETIC POLE AND POINT TOWARD THE **SOUTH** MAGNETIC POLE.

(NOTE THAT THIS MAKES THE EARTH'S SOUTH MAGNETIC POLE BE THE ONE IN THE GEOGRAPHIC NORTH!)

YOU WOULD FIND THAT BREAKING THE MAGNET GENERATES TWO NEW POLES! YOU CAN NEVER ISOLATE A POLE FROM ITS OPPOSITE.



ALSO, THE FIELD LINES DON'T STOP OR END, BUT PASS THROUGH THE MAGNET FROM SOUTH TO NORTH, FORMING CLOSED CURVES.



UP UNTIL THE YEAR

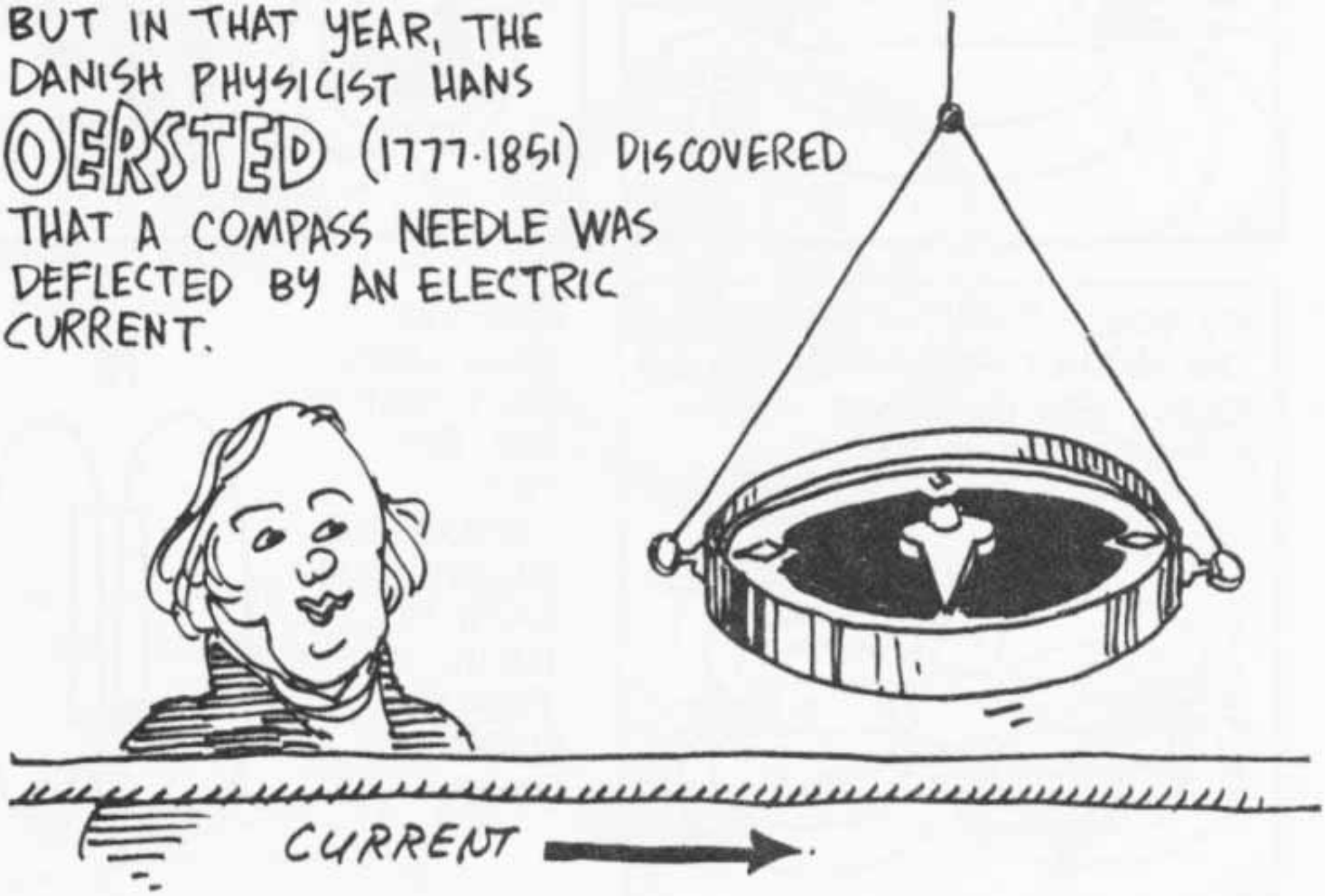
1820

EVERYONE THOUGHT MAGNETISM AND ELECTRICITY WERE COMPLETELY SEPARATE.

ELECTRICITY? MAGNETISM? TO DO? WITH EACH OTHER? SOMETHING? HA HA HA HA

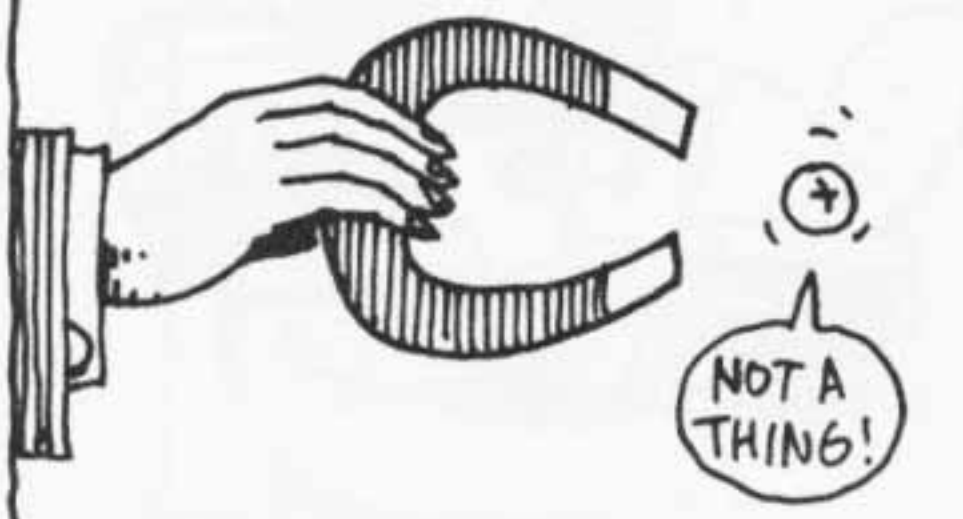
BUT IN THAT YEAR, THE DANISH PHYSICIST HANS

OERSTED (1777-1851) DISCOVERED THAT A COMPASS NEEDLE WAS DEFLECTED BY AN ELECTRIC CURRENT.

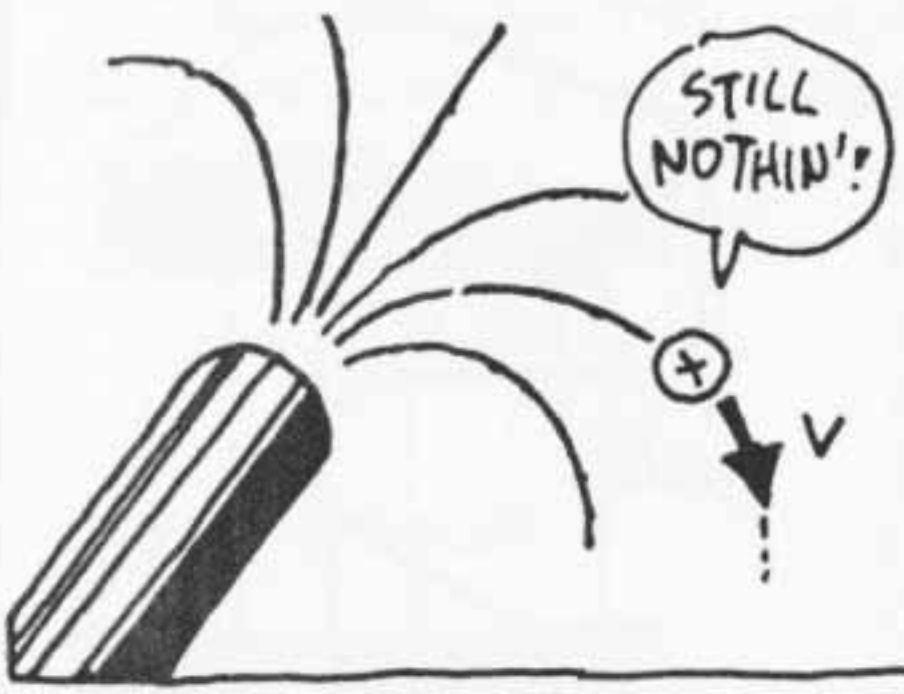


Q: WHAT DOES A CHARGE FEEL IN A MAGNETIC FIELD?

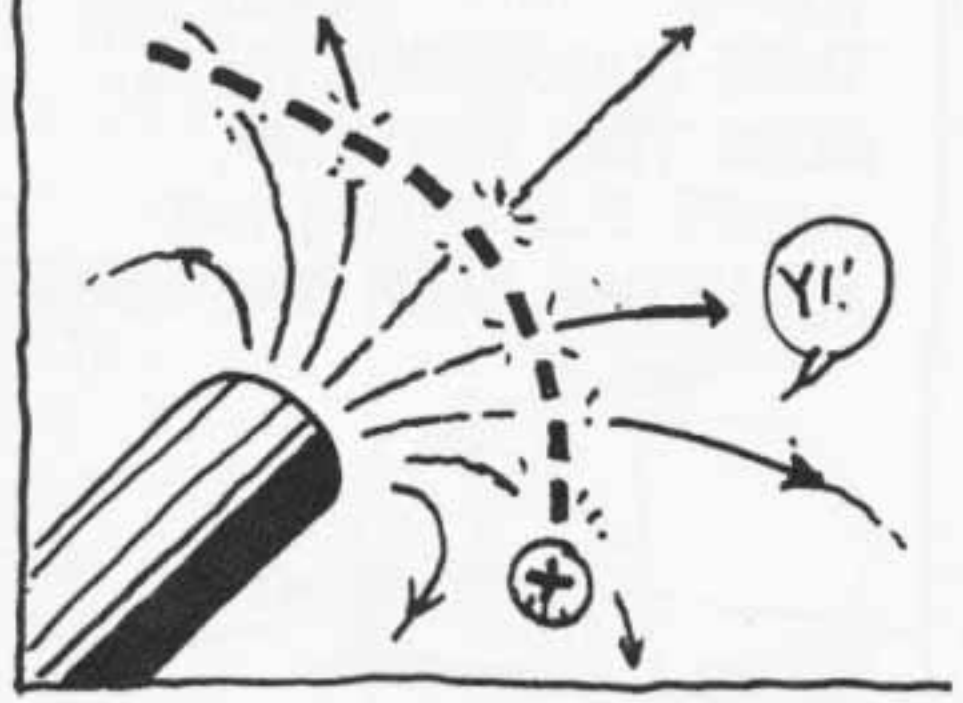
FIRST, IF THE CHARGE IS NOT MOVING, THERE IS NO FORCE.



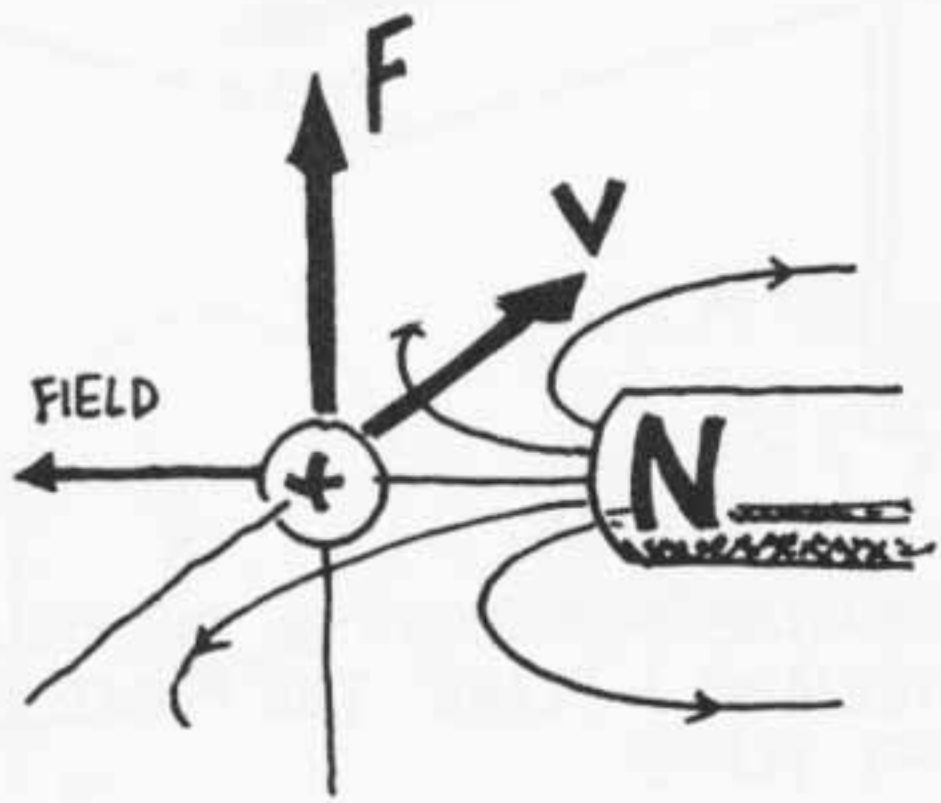
...AND THERE IS NO FORCE IF THE CHARGE IS MOVING ALONG A FIELD LINE...

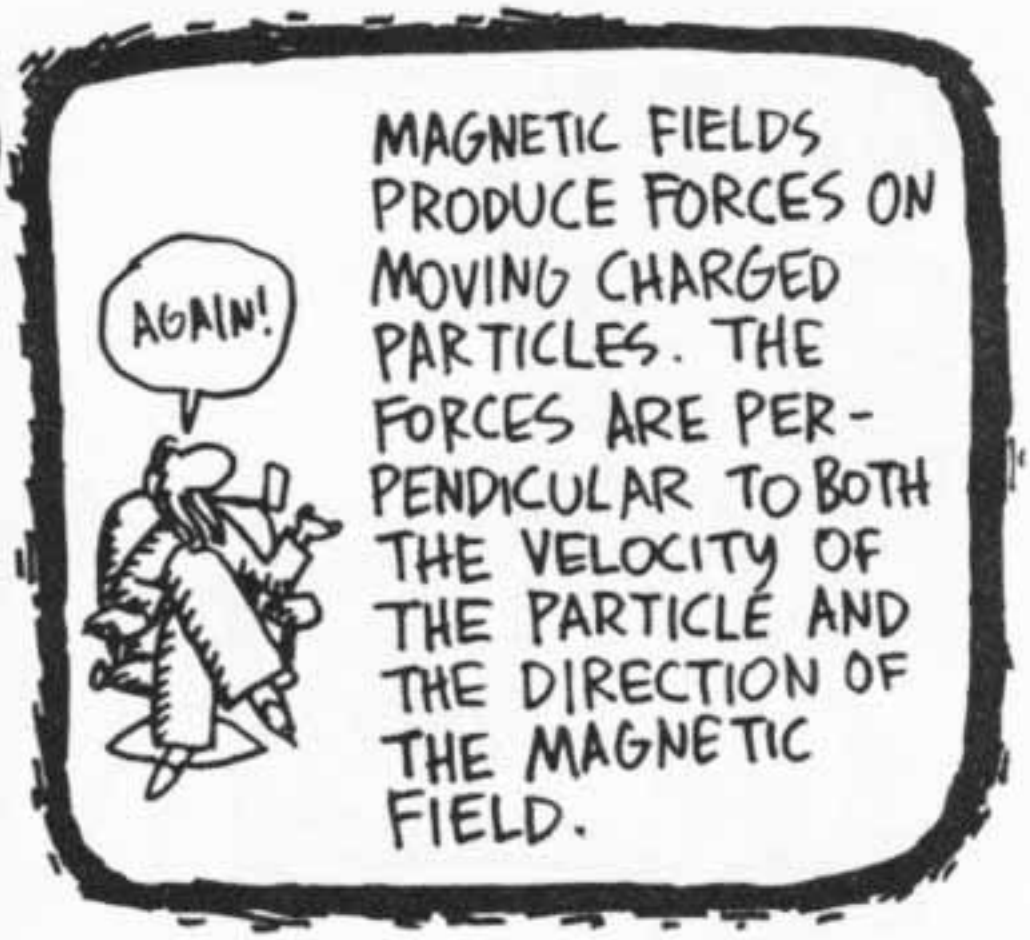


...BUT IF THE CHARGE IS MOVING ACROSS THE FIELD LINES, IT FEELS SOMETHING!

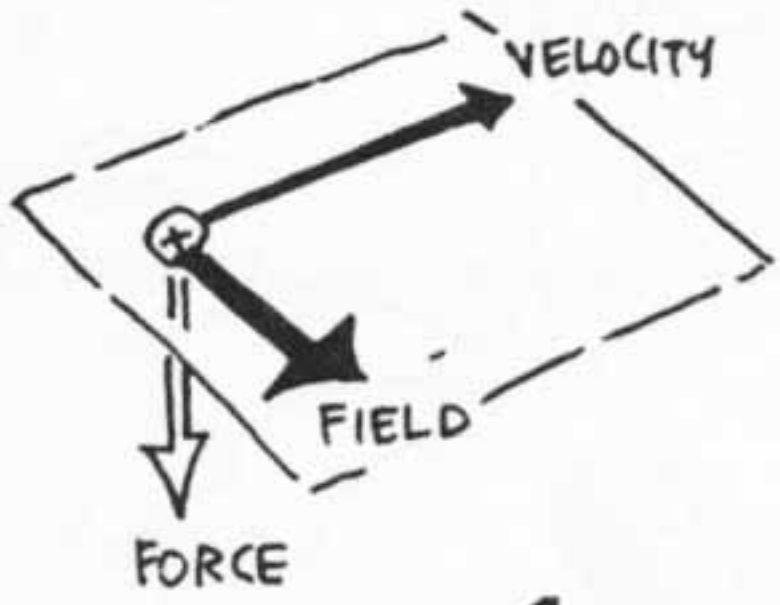


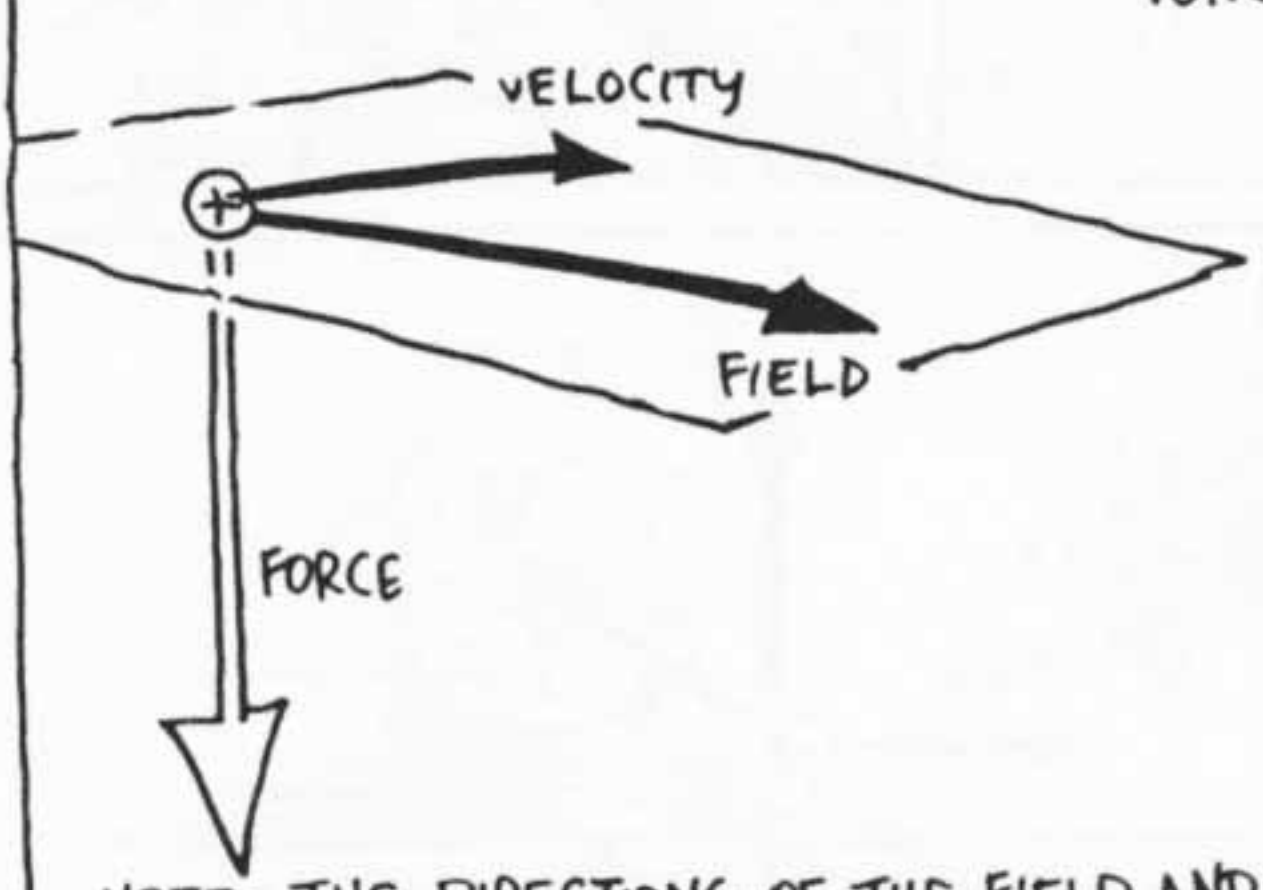
THE FORCE ON THE CHARGE IS A "SIDEWAYS" FORCE — PERPENDICULAR TO BOTH THE FIELD LINE AND THE CHARGE'S VELOCITY:

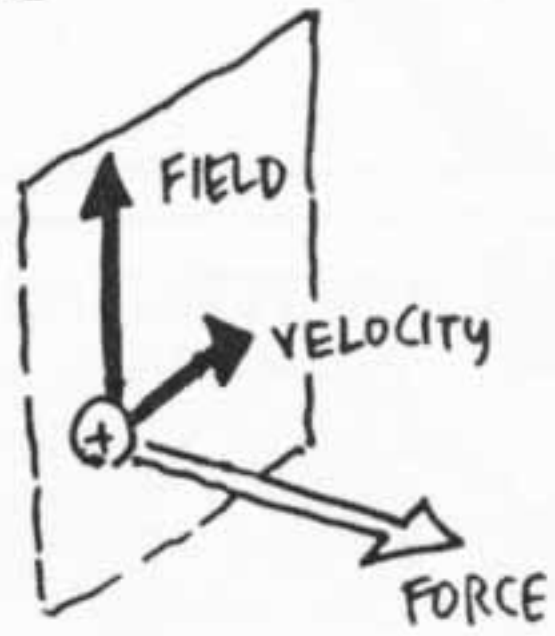




THE SIZE OF THE FORCE IS PROPORTIONAL TO THE INTENSITY OF THE FIELD AND THE SPEED WITH WHICH THE PARTICLE IS CUTTING ACROSS IT. HERE ARE SOME EXAMPLES TO PONDER. THIS "SIDEWAYS", THREE-DIMENSIONAL FORCE, MORE THAN ANYTHING, MAKES ELECTRICITY AND MAGNETISM SEEM COMPLICATED.

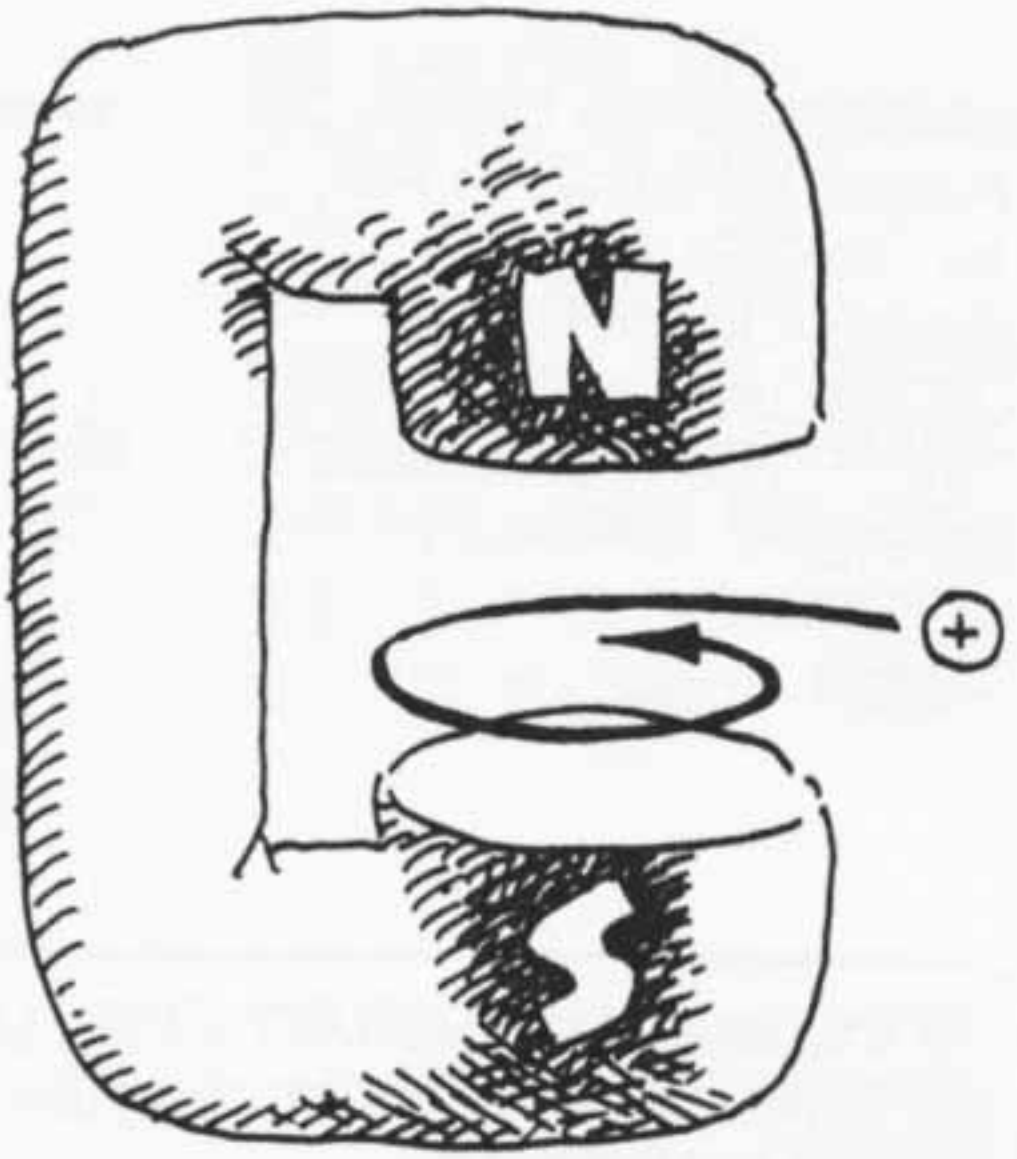




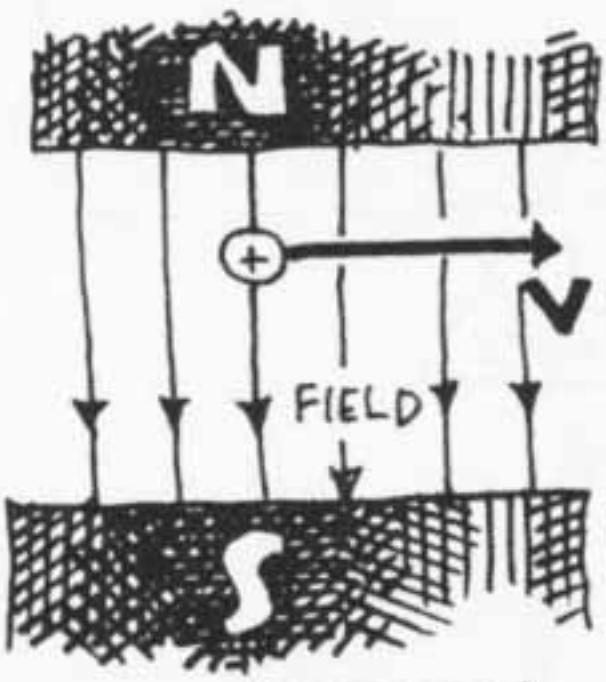


NOTE: THE DIRECTIONS OF THE FIELD AND THE VELOCITY DETERMINE A PLANE. THE FORCE IS PERPENDICULAR TO THAT PLANE.

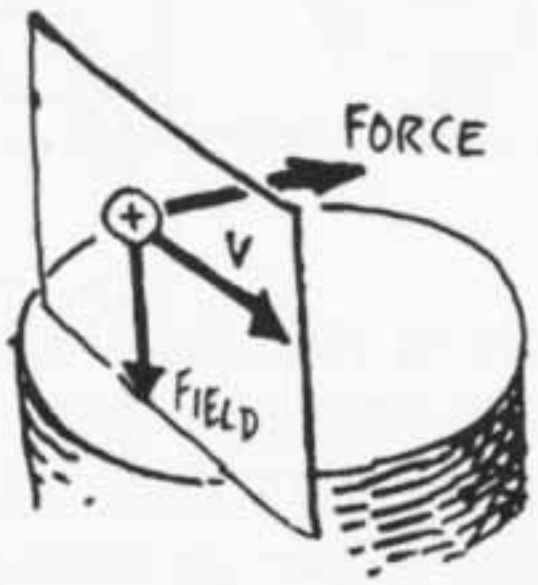
HERE IS A MAGNETIC FIELD THAT WILL MAKE CHARGED PARTICLES CIRCLE INDEFINITELY BETWEEN TWO NEARBY OPPOSITE POLE FACES:



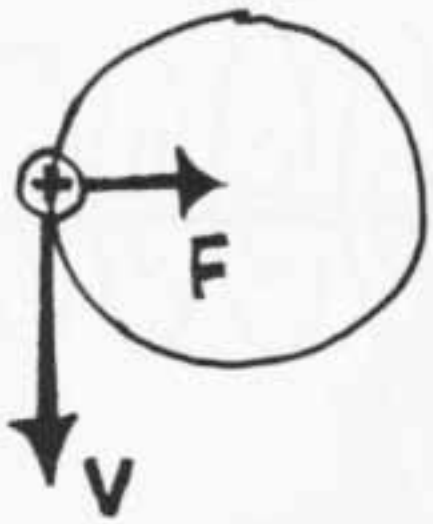
THE MAGNETIC FIELD BETWEEN THE FACES IS ALWAYS PERPENDICULAR TO THE PARTICLE'S VELOCITY: SO THE FORCE, PERPENDICULAR TO BOTH, POINTS TO THE CENTER OF THE CIRCLE!



SIDE VIEW



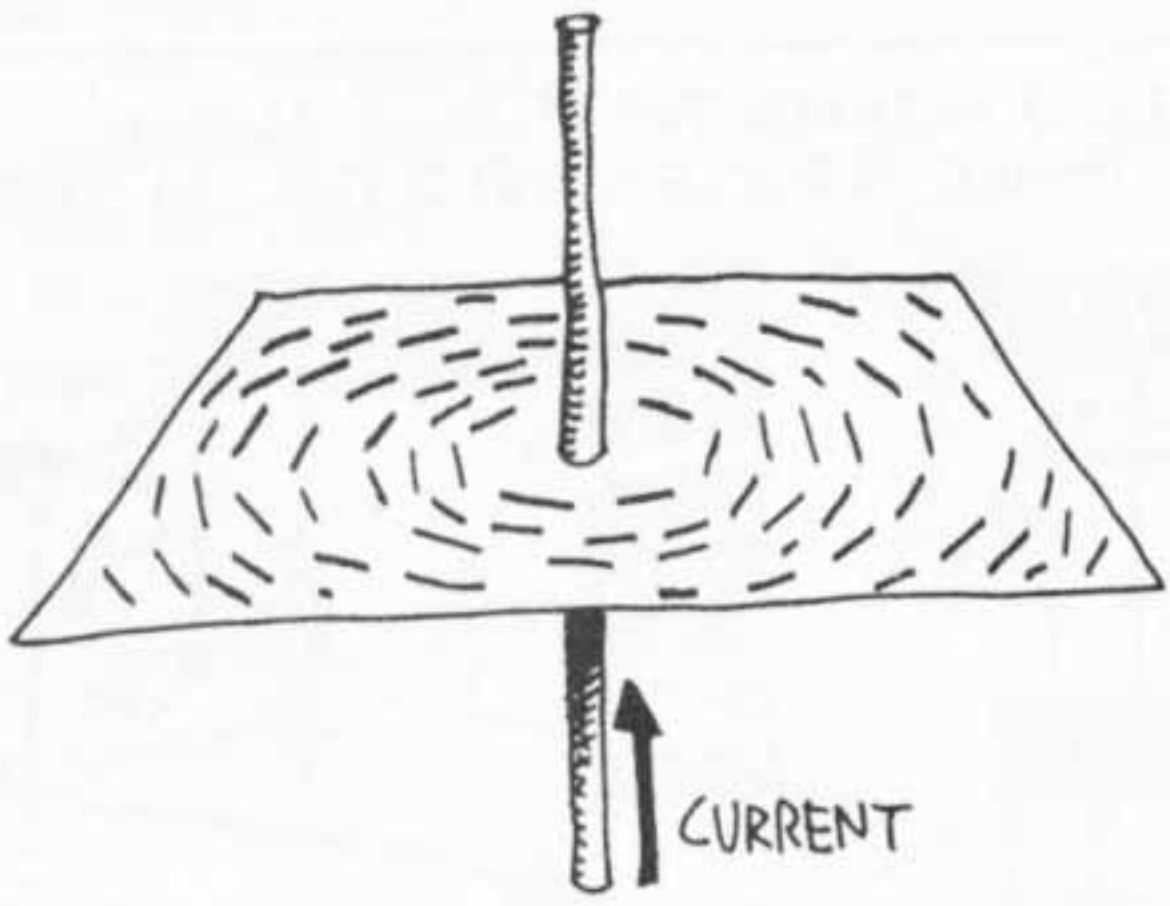
THIS PROVIDES JUST THE CENTRIPETAL FORCE NEEDED TO KEEP THE PARTICLE IN CIRCULAR MOTION! SEEN FROM ABOVE, IT LOOKS LIKE THIS FAMILIAR PICTURE:



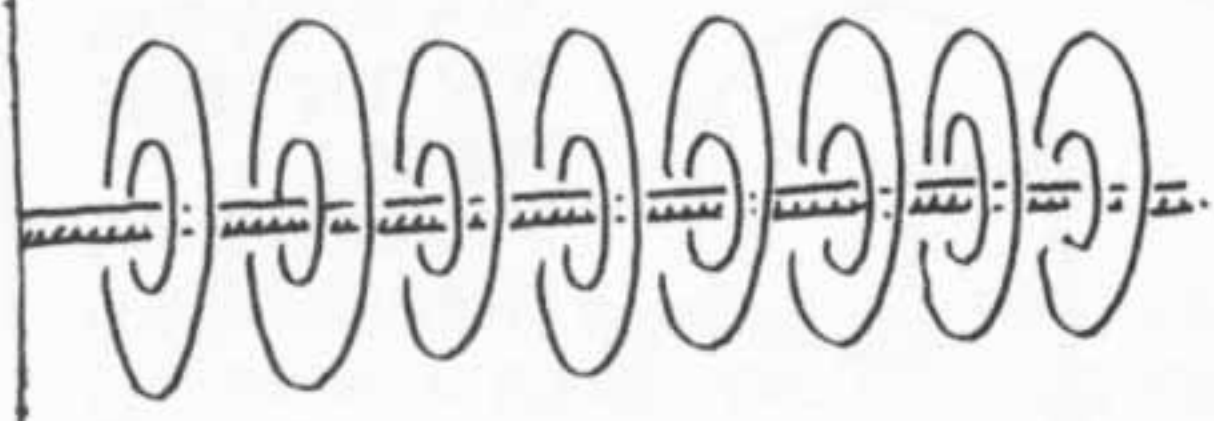
THIS IS THE BASIS FOR THE LARGE PARTICLE ACCELERATORS AND STORAGE RINGS.

MAGNETS EXERT FORCES ON MOVING PARTICLES — AND, AS OERSTED SHOWED, MOVING CHARGES ALSO CREATE MAGNETIC FIELDS. THAT'S WHAT DEFLECTED OERSTED'S COMPASS...

TO EXAMINE THE SIMPLEST CASE, LET US PASS A CURRENT-CARRYING WIRE STRAIGHT THROUGH A PLANE COVERED WITH COMPASS NEEDLES:



THE NEEDLES LINE UP IN CIRCLES AROUND THE WIRE.

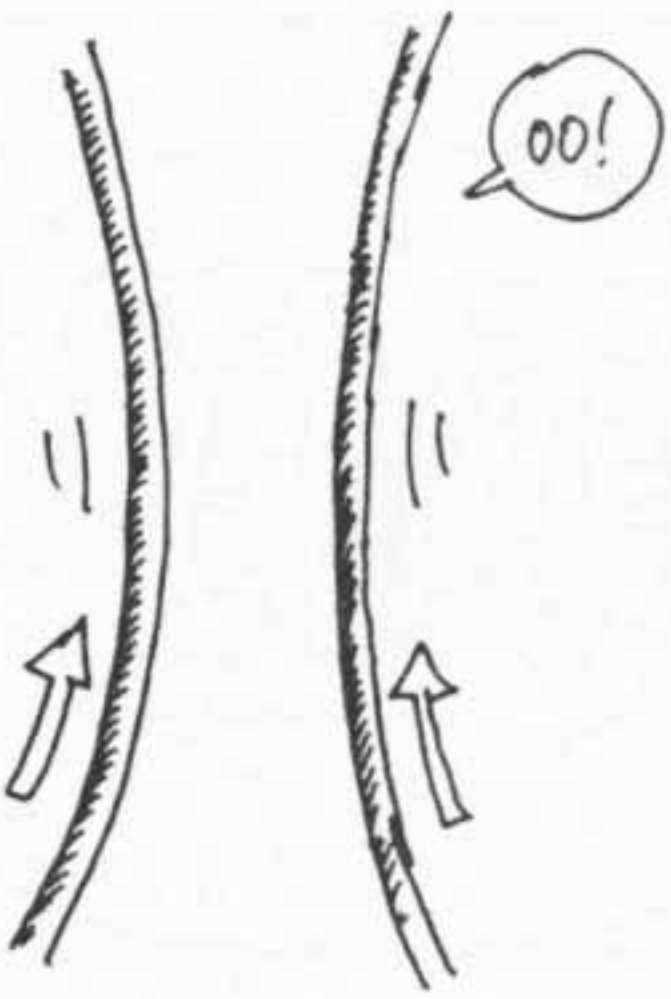


THE MAGNETIC FIELD OF A CURRENT IS CIRCLES CENTERED ON THE WIRE AND LYING IN THE PLANE PERPENDICULAR TO THE CURRENT.

YOU CAN FIND THE DIRECTION OF THE MAGNETIC FIELD BY POINTING THE THUMB OF YOUR RIGHT HAND ALONG THE DIRECTION OF THE FLOW OF POSITIVE CHARGES. YOUR FINGERS CURL IN THE DIRECTION OF THE MAGNETIC FIELD.

THIS IS KNOWN AS THE

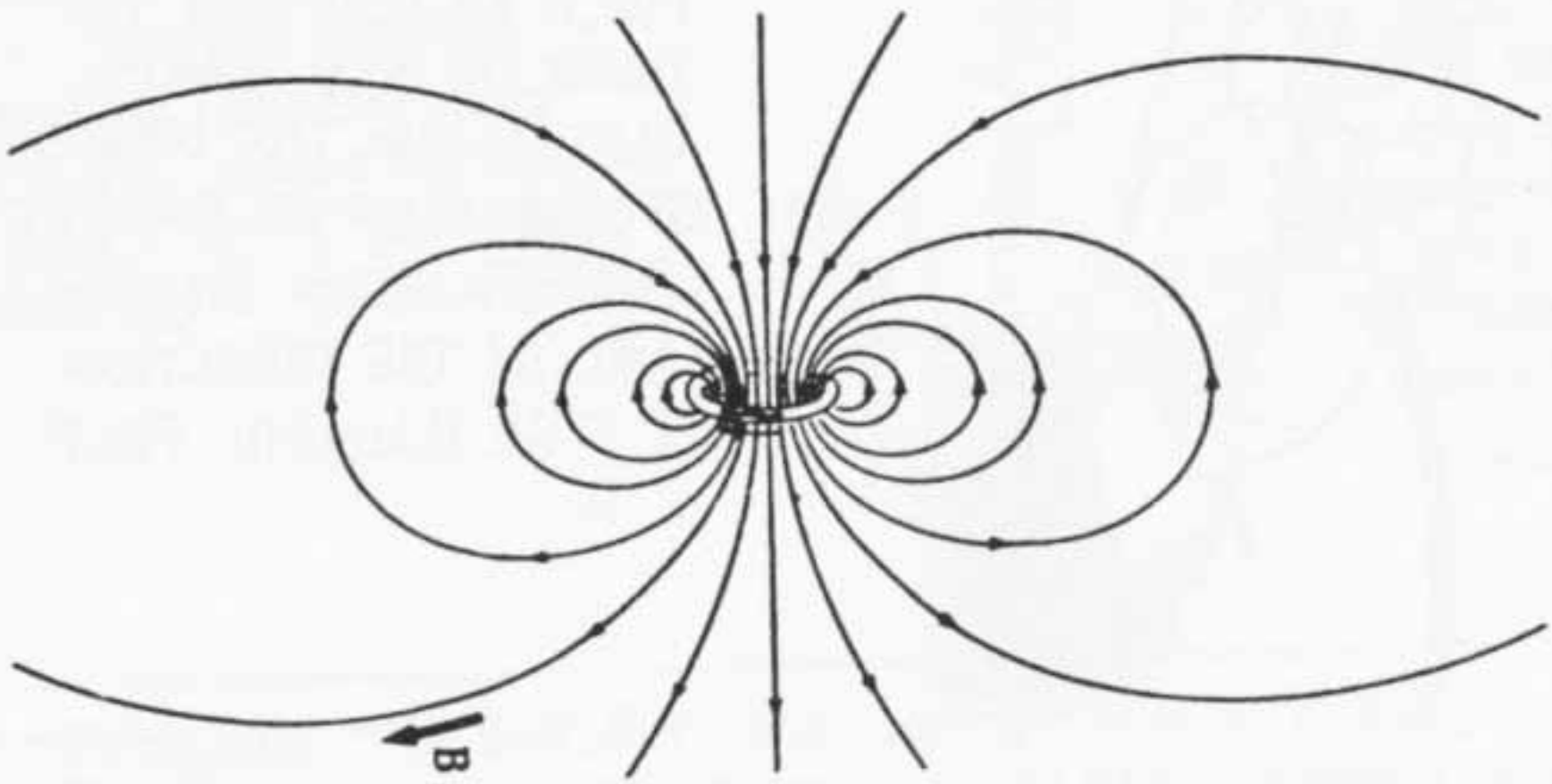
right-hand rule.



TWO PARALLEL CURRENTS ATTRACT EACH OTHER. THE MAGNETIC FIELD CIRCLING EACH WIRE CAUSE FORCES ON THE CURRENT IN THE OTHER WIRE, PULLING IT CLOSER. SEE IF YOU CAN CONVINCE YOURSELF THAT THIS IS THE RIGHT DIRECTION, USING THE RIGHT-HAND RULE!

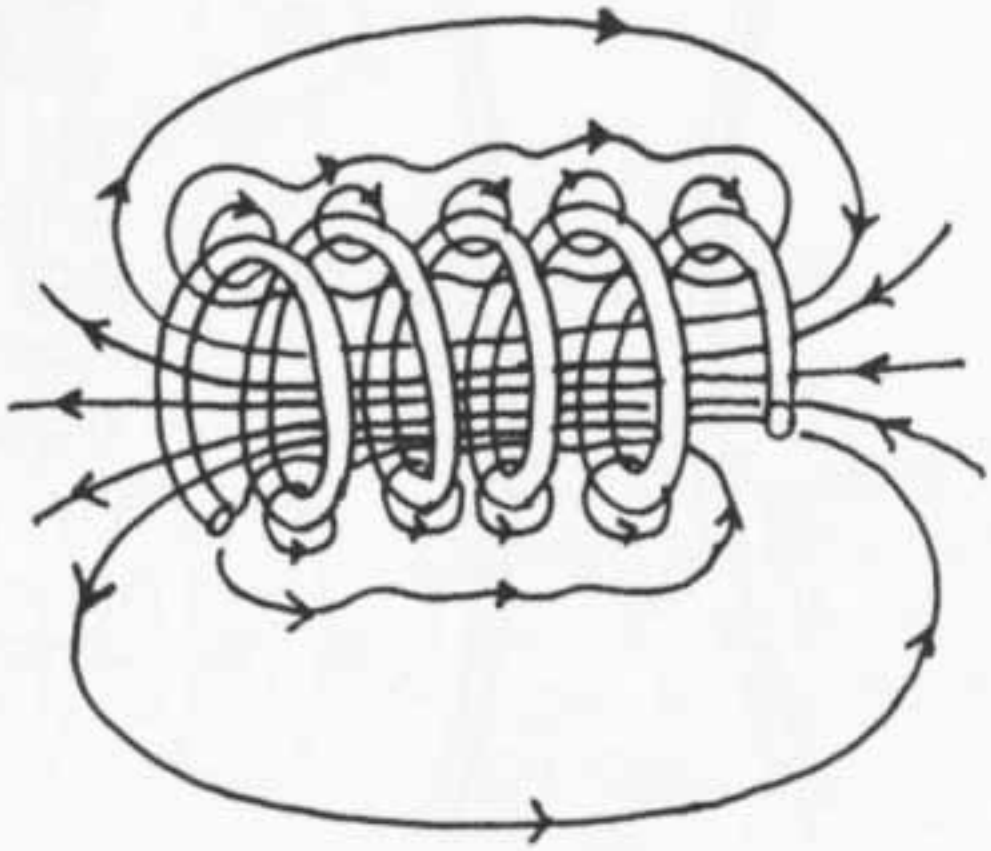
AMPERE, DISCOVERER OF THE FORCE BETWEEN PARALLEL WIRES

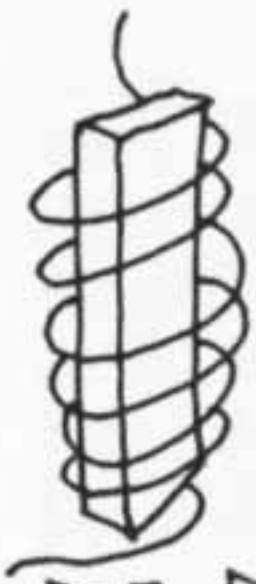
IF WE BEND A CURRENT-CARRYING WIRE INTO A CIRCLE, WE GET THIS MAGNETIC FIELD:



NOTICE THAT ONE SIDE LOOKS JUST LIKE A **NORTH** POLE — THE FIELD LINES ARE COMING OUT — AND THE OTHER SIDE LOOKS LIKE A **SOUTH** POLE, WITH FIELD LINES GOING IN...

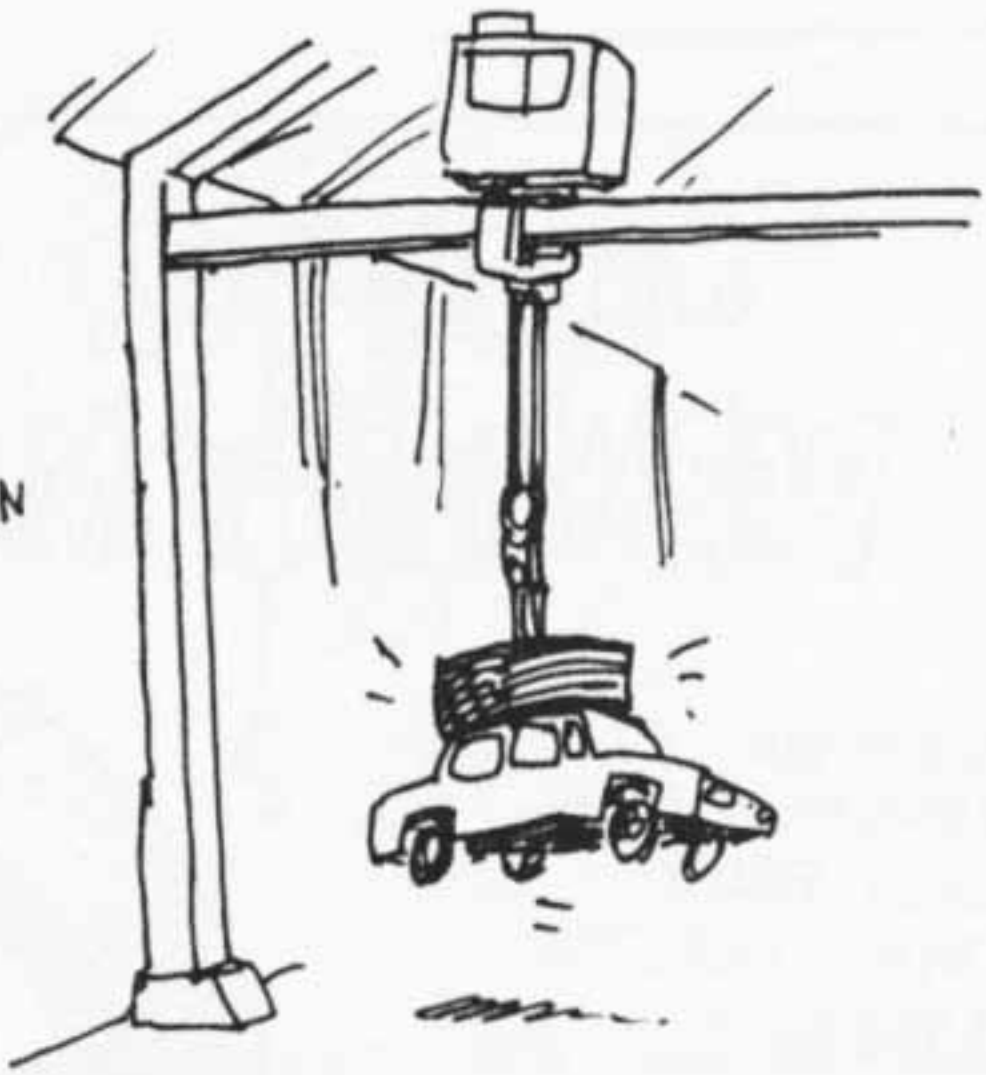
BY WINDING MANY TURNS, THE MAGNETIC FIELD IS MADE PROPORTIONALLY LARGER. BY WINDING TURNS ALONG A CYLINDER, WE GET A **SOLENOID COIL**, WITH A MAGNETIC FIELD JUST LIKE A BAR MAGNET!





INSERTING AN IRON BAR INTO THE COIL CONCENTRATES AND STRENGTHENS THE MAGNETIC FIELD, AND THE RESULT IS AN

ELECTRO-MAGNET.



MAYBE YOU'RE GETTING CONFUSED WITH ALL THESE MAGNETIC AND ELECTRIC FIELDS. SUPPOSE THE ROOM WERE FILLED WITH THEM — HOW WOULD YOU KNOW, AND HOW WOULD YOU KNOW WHICH WAS WHICH?

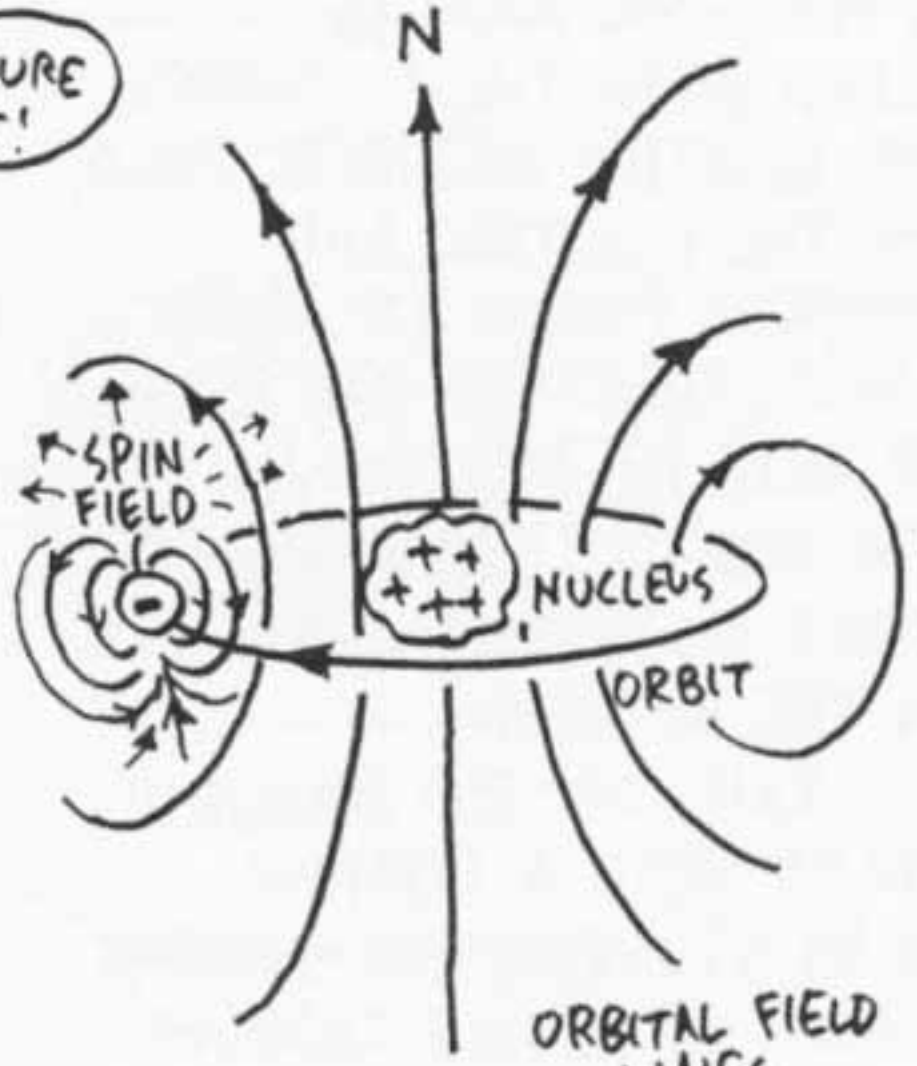
IN FACT, THE ROOM **IS** FILLED WITH THEM. THERE'S THE EARTH'S MAGNETIC FIELD, AND THE ELECTRIC AND MAGNETIC FIELDS OF RADIO WAVES THAT YOU CAN PICK UP WITH AN ANTENNA. (THE ELECTRIC FIELD OF RADIO WAVES MOVES THE CHARGES IN THE ANTENNA.) YOU CAN TEST FOR MAGNETIC FIELDS WITH A COMPASS, OR BY STUDYING THE SIDEWAYS FORCES ON MOVING CHARGES.

◊CHAPTER 18◊
PERMANENT MAGNETS

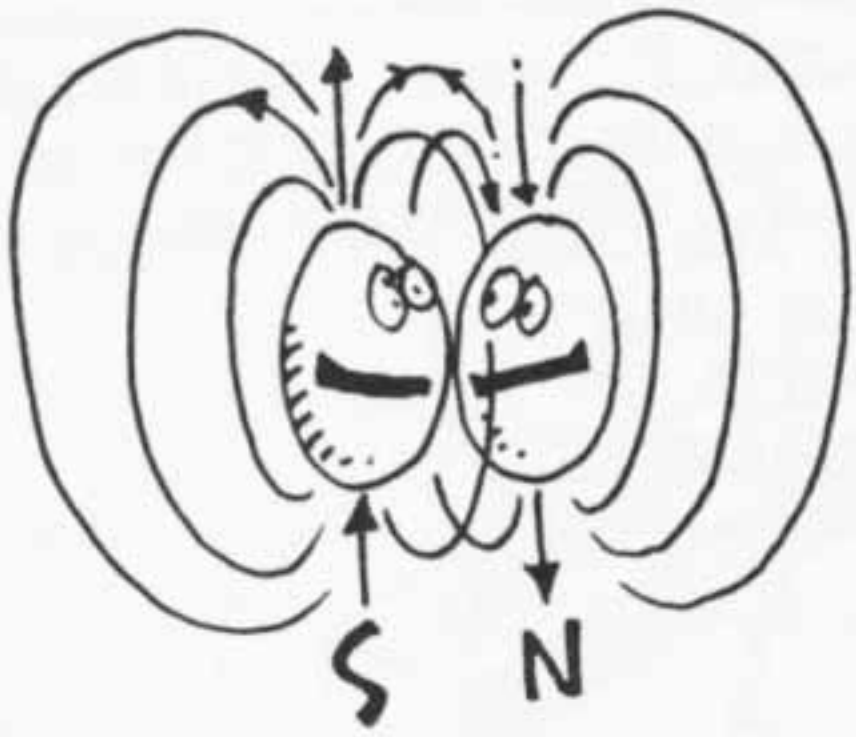
ALL KNOWN MAGNETIC FIELDS RESULT FROM MOVING ELECTRIC CHARGES.

WHERE ARE THE CHARGES THAT CREATE THE MAGNETIC FIELD OF AN IRON MAGNET? THEY ARE THE ELECTRONS IN THE IRON ATOMS THEMSELVES!

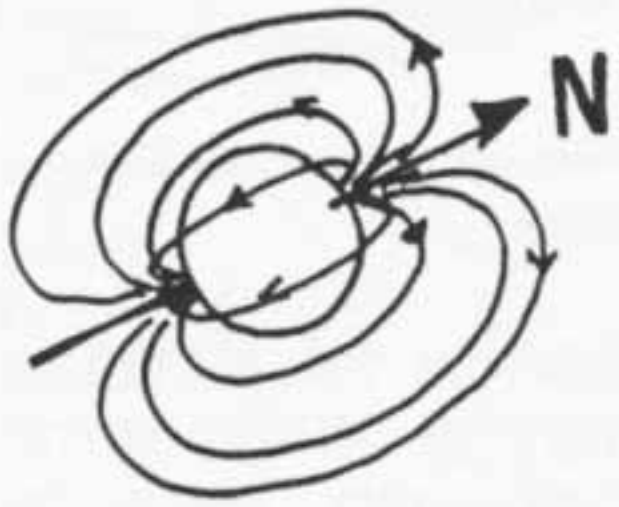
AN ELECTRON ORBITING THE ATOMIC NUCLEUS IS LIKE A SMALL CIRCULAR CURRENT, SO IT PRODUCES AN **ORBITAL MAGNETIC FIELD.** ALSO, THE ELECTRON SPINS ON ITS OWN AXIS, GENERATING A **SPIN MAGNETIC FIELD.**



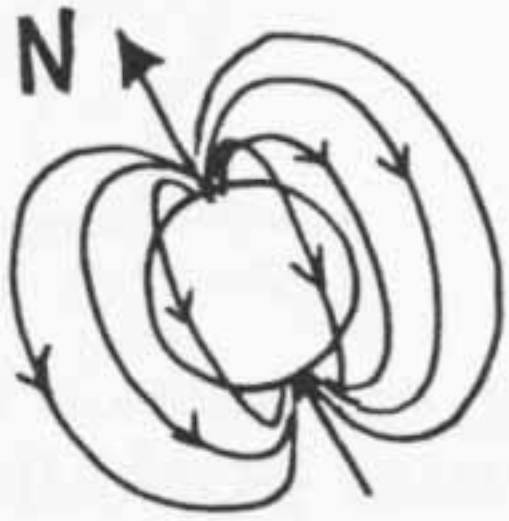
MOST ELECTRONS IN ATOMS HAVE THEIR MAGNETIC FIELDS CANCELLED OUT BY THE MAGNETIC FIELDS OF OTHER ELECTRONS...



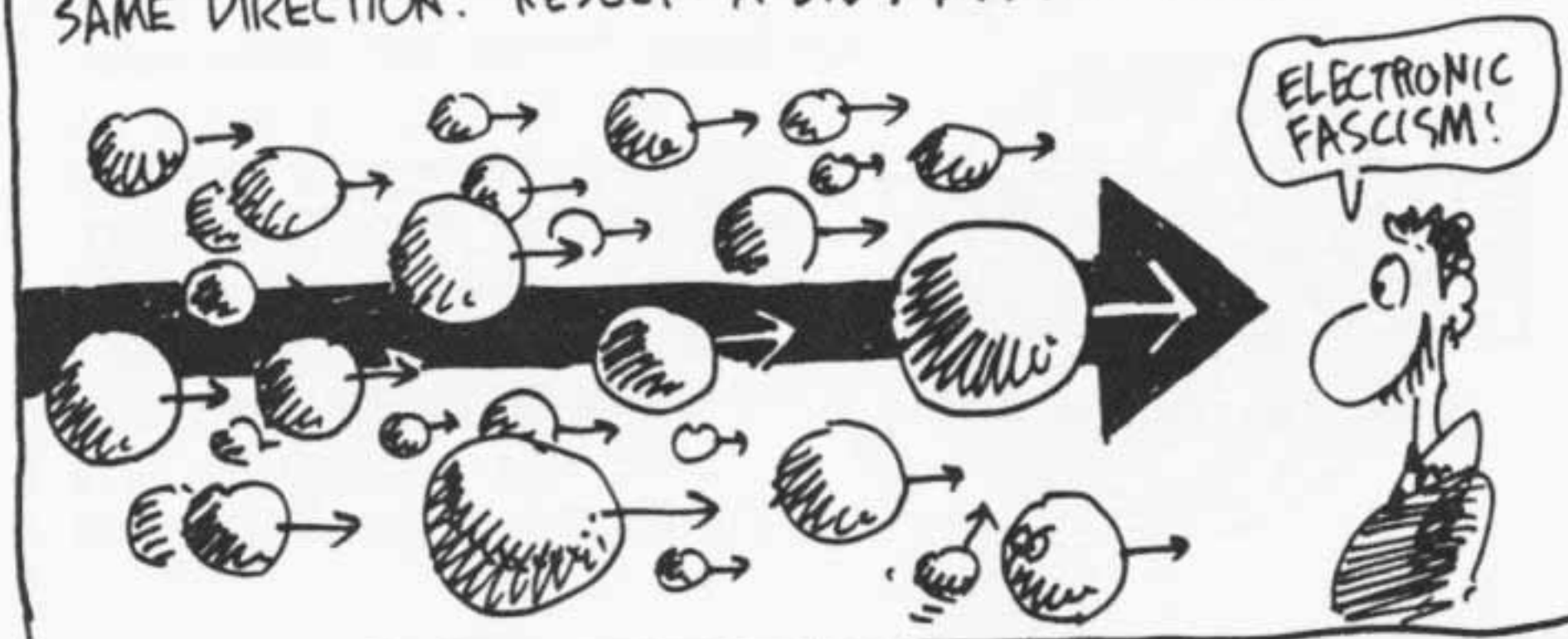
BUT IN **MAGNETIC** MATERIALS — LIKE THE METALS **IRON**, **NICKEL**, AND **COBALT** — THERE ARE LONE ELECTRONS THAT CONTRIBUTE A NET MAGNETIC FIELD TO EACH ATOM.



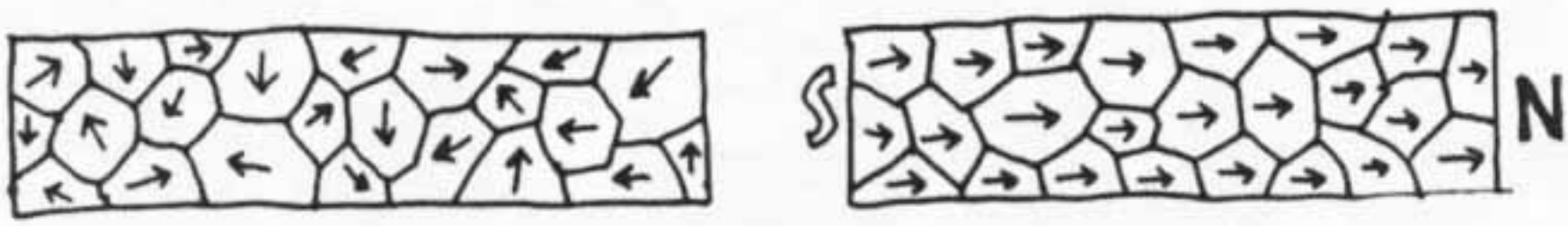
...AND FURTHERMORE,



IN THESE "FERROMAGNETIC" ELEMENTS, THE ATOMS THEMSELVES LINE UP SO THAT THEIR MAGNETIC FIELDS ALL POINT IN THE SAME DIRECTION. RESULT: A BIG MAGNETIC FIELD!



ALL THE ATOMS IN MICROSCOPIC REGIONS OF THE MATERIAL, CALLED **DOMAINS**, DO LINE UP. BUT IN UNMAGNETIZED IRON, THE DOMAINS ARE RANDOMLY ORIENTED. WHEN THE IRON IS PLACED IN A MAGNETIC FIELD, THE DOMAINS TEND TO LINE UP WITH THE FIELD, AND THE IRON BECOMES MAGNETIZED.



UNMAGNETIZED

MAGNETIZED

SOME METAL ALLOYS ARE MAGNETICALLY "HARD." IT TAKES A STRONG EXTERNAL MAGNETIC FIELD TO ORIENT THEIR DOMAINS— BUT ONCE ORIENTED, THE DOMAINS TEND TO STAY LINED UP.

ALNICO V

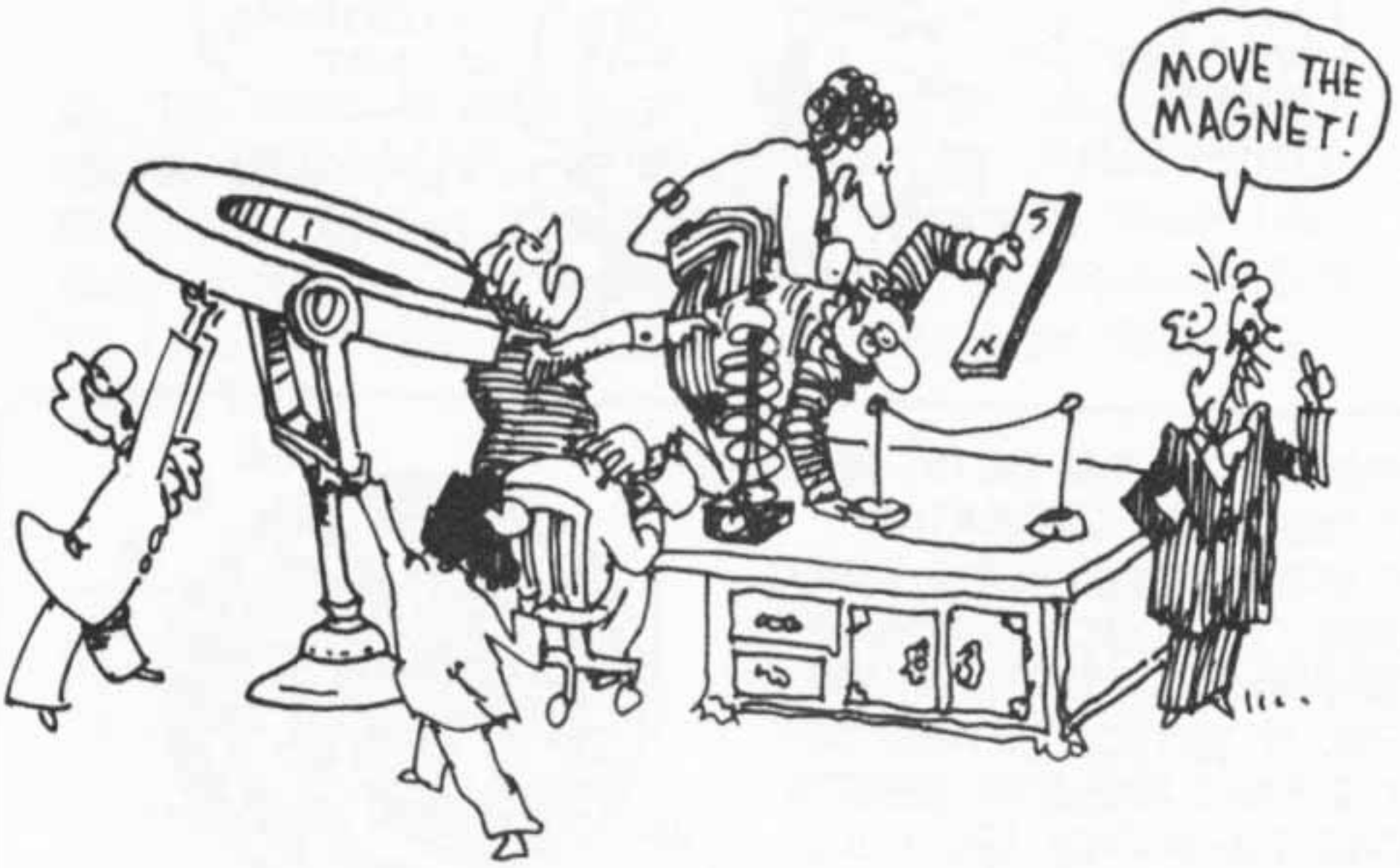
AN ALLOY OF ALUMINUM, NICKEL, COBALT, IRON, AND COPPER, IS VERY MAGNETICALLY HARD. PURE IRON, ON THE OTHER HAND IS MAGNETICALLY "SOFT": EASILY MAGNETIZED, BUT EASILY DEMAGNETIZED BY REMOVING THE EXTERNAL FIELD.

THE FERROMAGNETIC EFFECT OPERATES ONLY BELOW A CRITICAL TEMPERATURE, 770° C FOR IRON. HEATING DISRUPTS MAGNETISM.

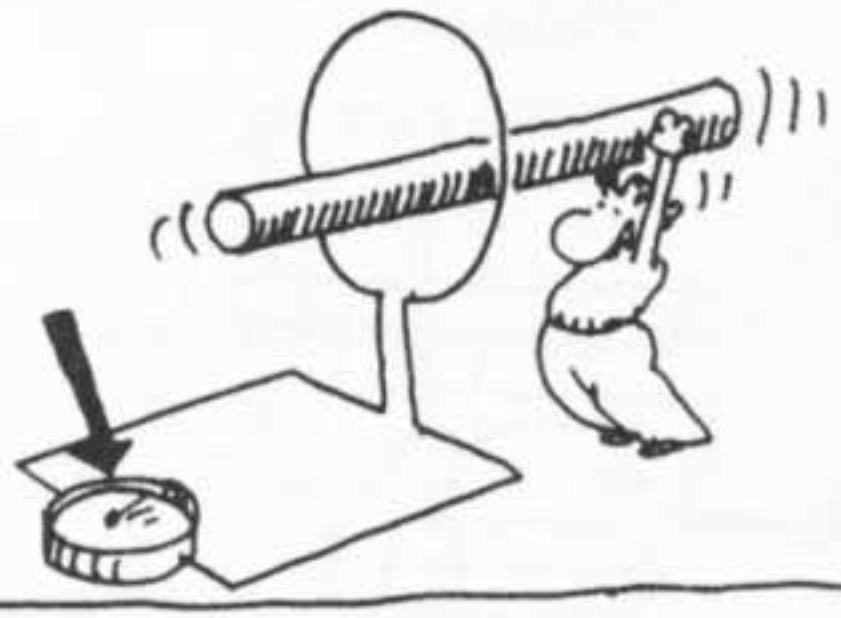
PRESUMABLY, THE EARTH'S MAGNETISM IS CAUSED BY CIRCULATING ELECTRIK FIELDS IN THE EARTH'S CORE. THE EXACT MECHANISM REMAINS A MYSTERY. DO YOU FIND IT RATHER AMUSING THAT THE FIRST MAGNETIC EFFECTS EVER DISCOVERED ARE STILL NOT SATISFACTORILY EXPLAINED?

·CHAPTER 19·
FARADAY INDUCTION

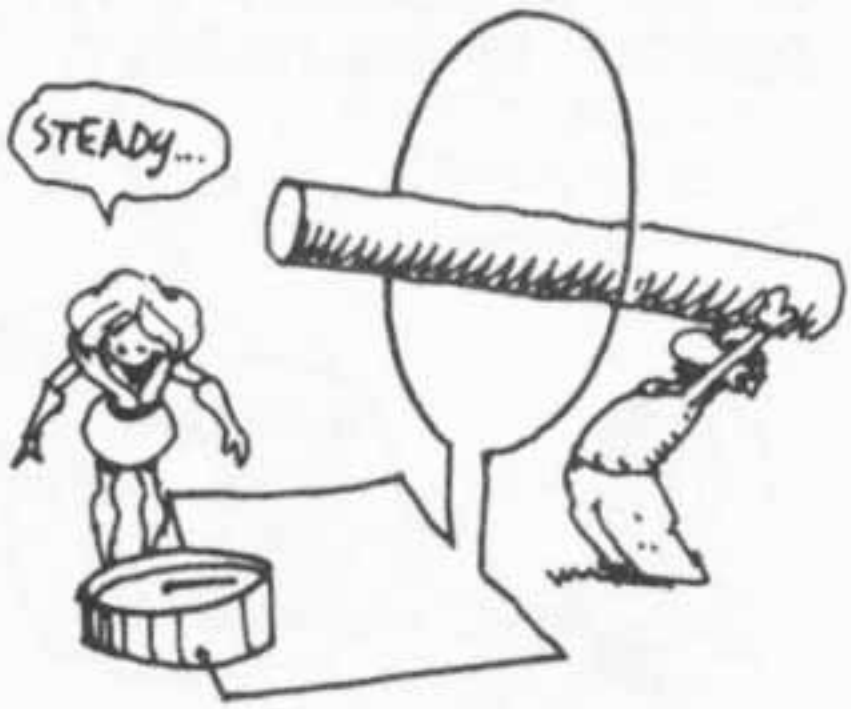
FOR TWELVE YEARS AFTER OERSTED'S DISCOVERY, "ELECTRICIANS" LOOKED FOR THE COMPLEMENTARY EFFECT: HOW TO MAKE A MAGNETIC FIELD PRODUCE A CURRENT? AT LAST, IN 1832, MICHAEL FARADAY MADE A SUGGESTION—



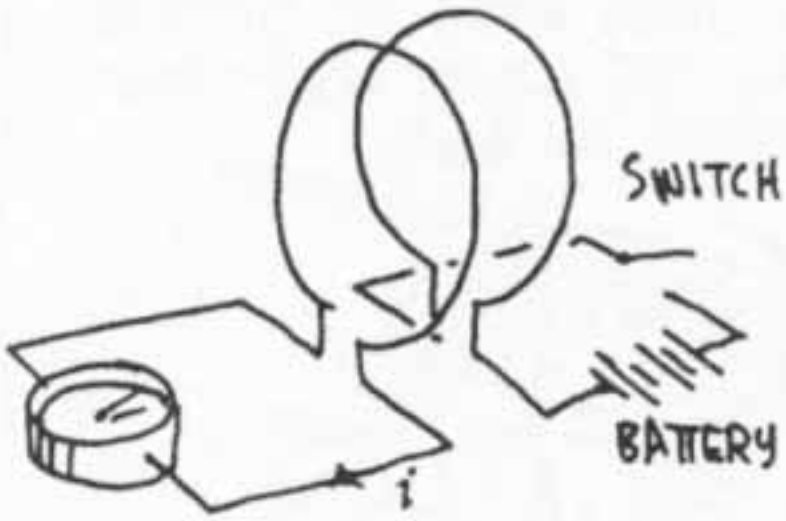
HERE RINGO THRUSTS A MAGNET INTO A LOOP OF WIRE CONNECTED TO A SENSITIVE CURRENT METER, A GALVANOMETER. THE GALVANOMETER NEEDLE DEFLECTS!



WHEN THE MAGNET IS HELD STILL, THE METER REGISTERS NO CURRENT.



ANOTHER WAY TO INDUCE CURRENT IS TO PLACE A SECOND LOOP NEARBY AND ENERGIZE IT WITH A BATTERY. WHEN CURRENT IN THE SECOND LOOP IS SWITCHED ON OR OFF, A CURRENT PULSE IS INDUCED IN THE FIRST!



BUT WHEN THE CURRENT IN THE SECOND LOOP IS STEADY, NO CURRENT IS INDUCED IN THE FIRST LOOP.

CURRENT FLOWS IN 2. BUT NOT IN 1.

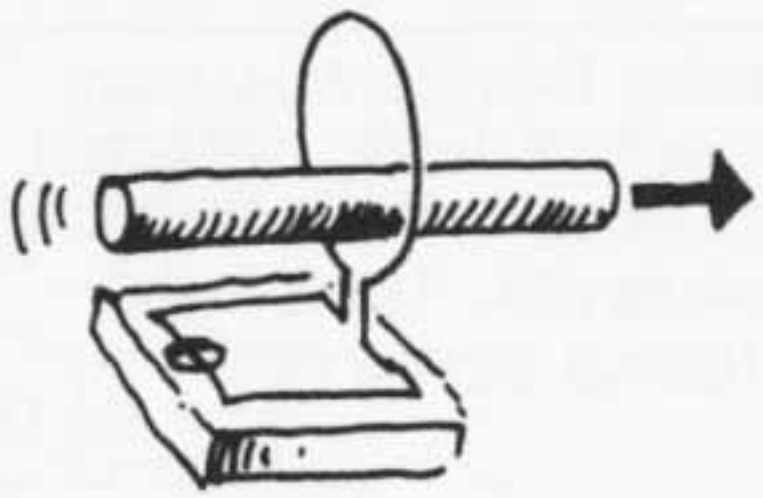
ISN'T IT MIRACULOUS, ENERGY INVISIBLY GETTING ACROSS SPACE ??

FARADAY DESCRIBED THIS BY SAYING THAT

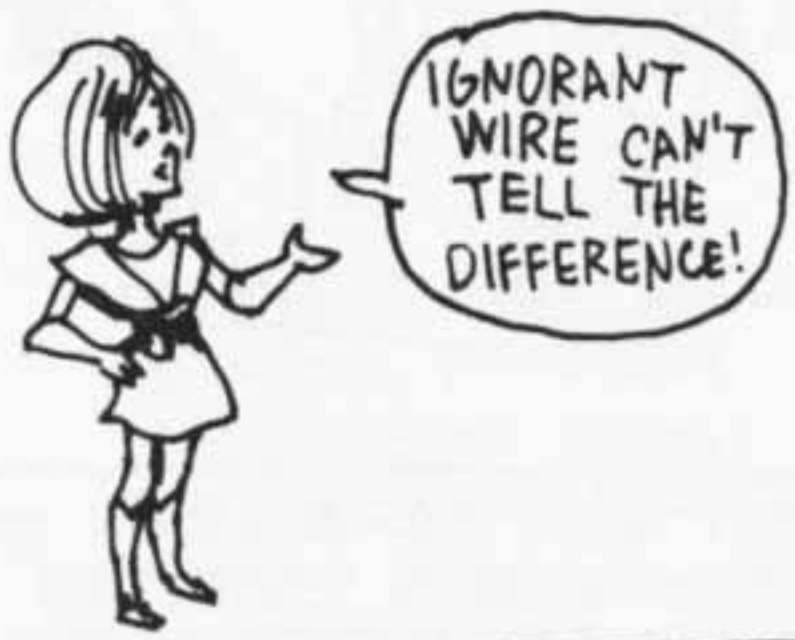
ELECTRO-MOTIVE FORCES

ARE GENERATED IN THE WIRE WHENEVER MAGNETIC FIELD LINES CUT ACROSS THE WIRE.

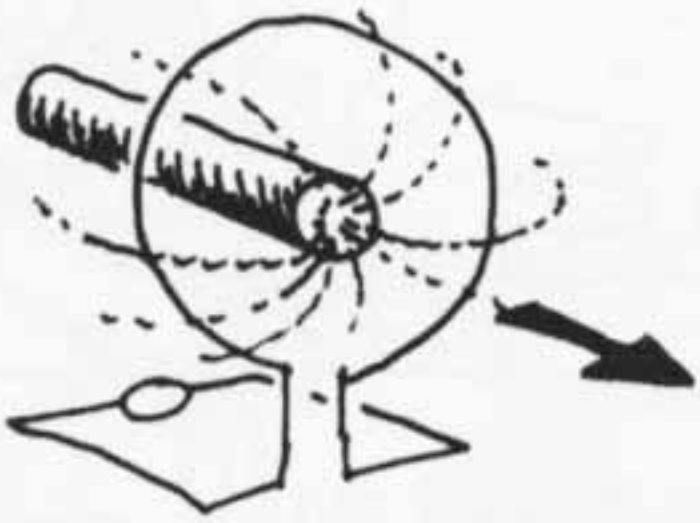
IT DOESN'T MATTER WHETHER THE MAGNETIC FIELD MOVES OR THE WIRE MOVES WITH RESPECT TO THE MAGNET.



IS EQUIVALENT TO

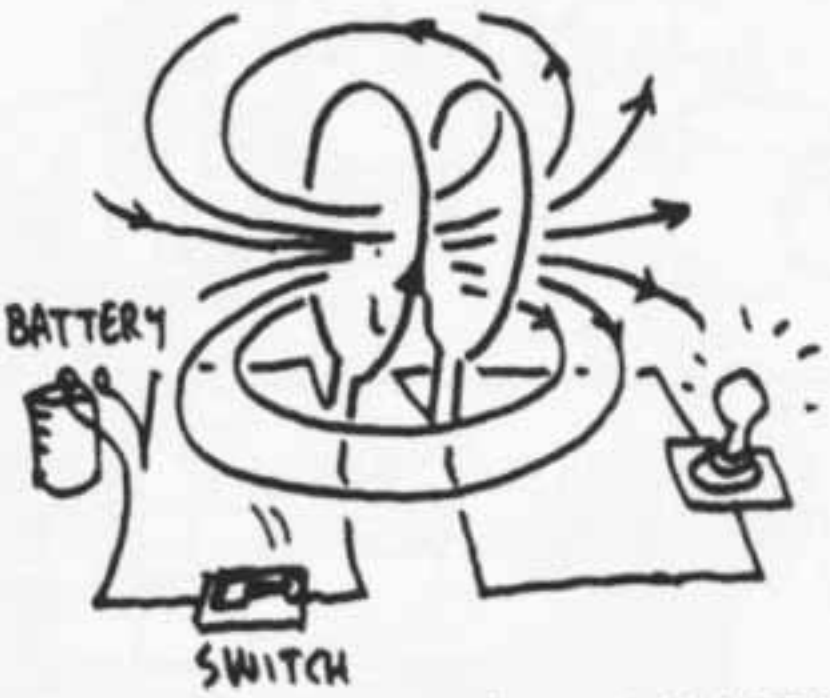


WHEN THE MAGNET IS THRUST INTO THE LOOP, ITS FIELD LINES CUT ACROSS THE WIRE, GENERATING AN **EMF** THAT PRODUCES A CURRENT.

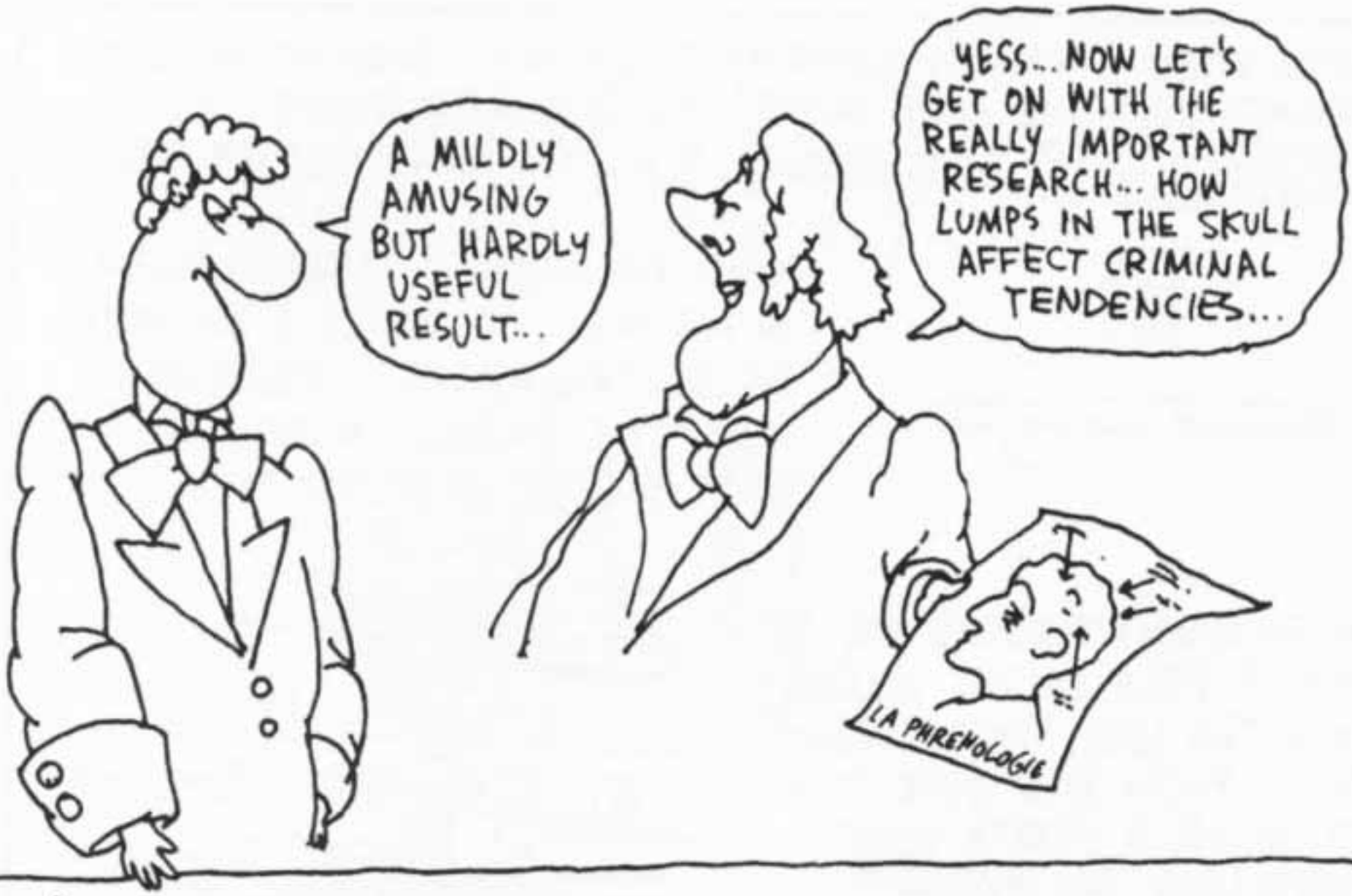


DITTO WHEN THE LOOP IS MOVED OVER THE MAGNET.

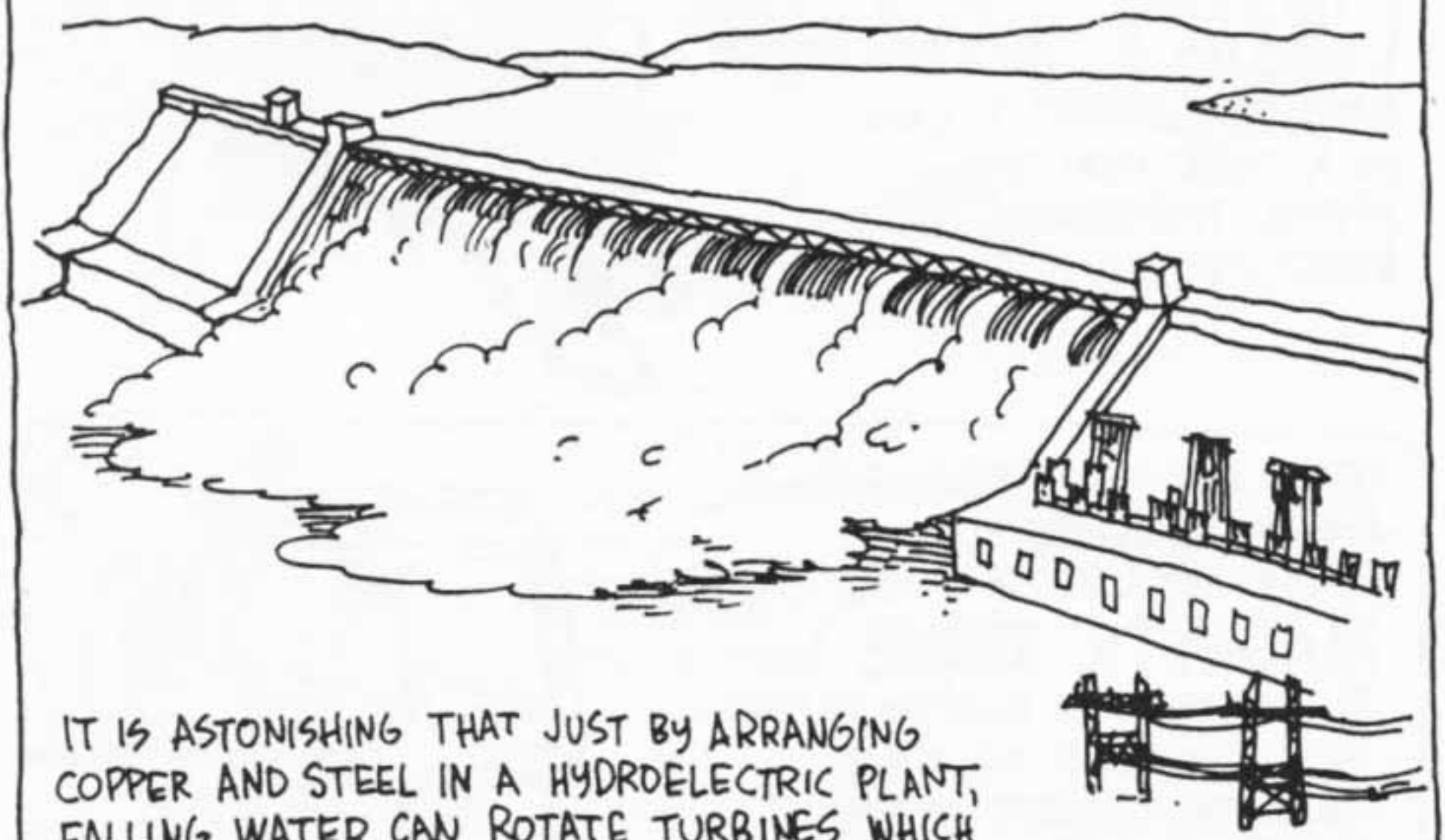
IN THE CASE OF TWO WIRE LOOPS, WHEN CURRENT IS FIRST TURNED ON IN ONE LOOP, MAGNETIC FIELD LINES BUILD UP, CUTTING ACROSS THE OTHER LOOP AND PRODUCING AN EMF.



WHEN THE CURRENT IS SWITCHED OFF, THE FIELD LINES COLLAPSE, AGAIN CUTTING ACROSS THE LOOP.

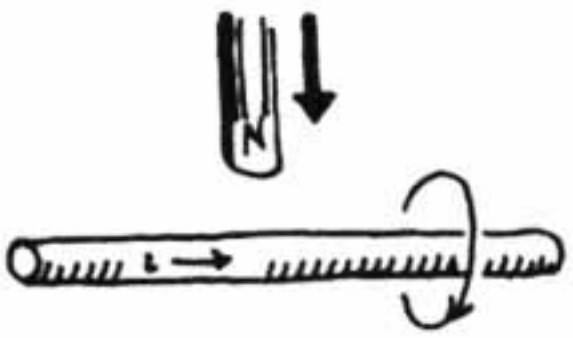


ALTHOUGH FARADAY'S DISCOVERY WAS AT FIRST RECEIVED WITH INDIFFERENCE, TODAY ALL OUR ELECTRIC POWER IS GENERATED BY MOVING GIANT COILS OF WIRE NEAR MAGNETS!



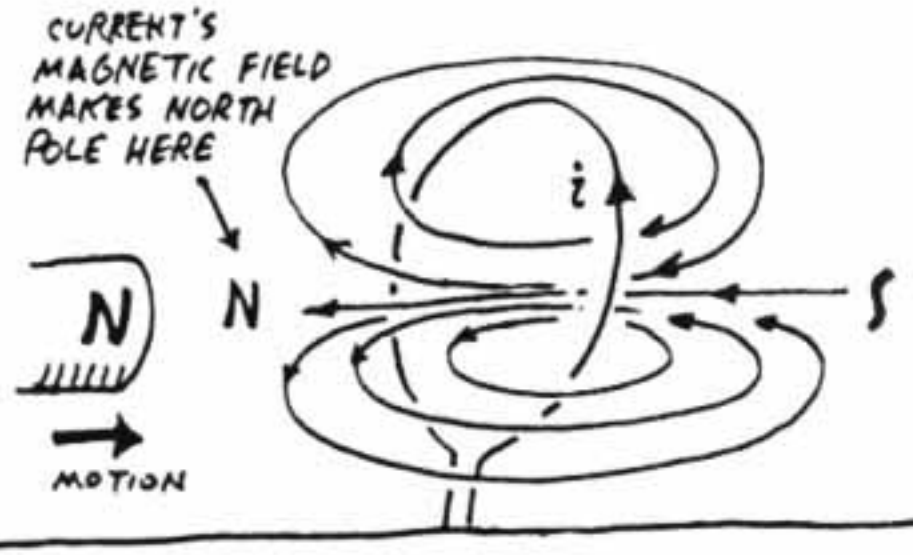
IT IS ASTONISHING THAT JUST BY ARRANGING COPPER AND STEEL IN A HYDROELECTRIC PLANT, FALLING WATER CAN ROTATE TURBINES WHICH GENERATE ENOUGH ELECTRICITY TO POWER CITIES HUNDREDS OF MILES AWAY!!

LET'S STUDY FARADAY'S EXPERIMENT FURTHER. WHEN WE MOVE THE MAGNET NEAR THE LOOP, GENERATING CURRENT. WHERE DOES THE **ENERGY** COME FROM TO MOVE THE GALVANOMETER NEEDLE?



WHEN THE INDUCED CURRENT FLOWS IN THE WIRE, IT MAKES A MAGNETIC FIELD. THIS MAGNETIC FIELD MUST RESIST THE MAGNET'S MOTION, SO WORK IS DONE IN MOVING IT.

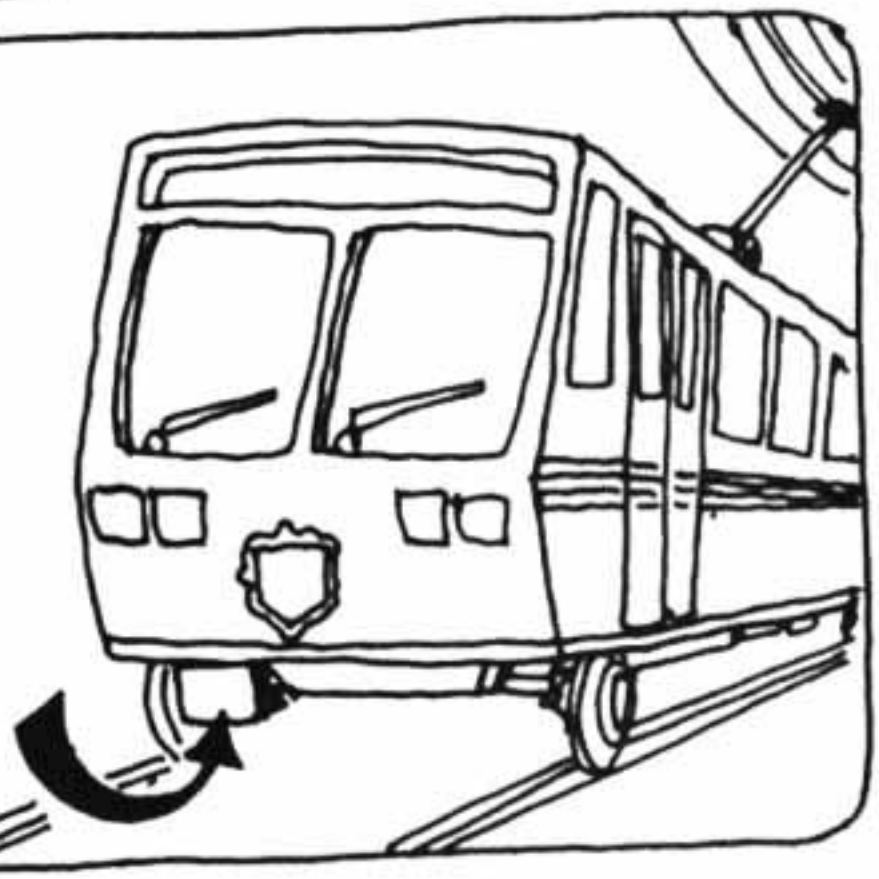
WHEN RINGO THRUSTS THE NORTH POLE OF THE MAGNET INTO THE LOOP, THE CURRENT MUST FLOW IN A DIRECTION TO MAKE A NORTH POLE REPELLING THE MAGNET.



THIS IS KNOWN AS **LENZ'S LAW:**

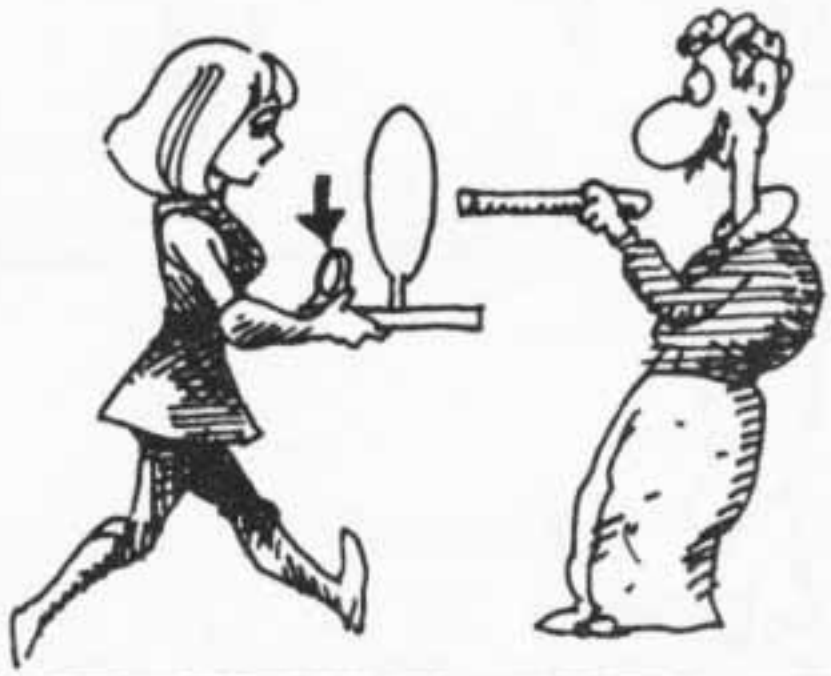
INDUCED CURRENT FLOWS IN A DIRECTION TO OPPOSE THE CHANGE THAT PRODUCED IT.

LENZ'S LAW IS A CONSEQUENCE OF ENERGY CONSERVATION. A USEFUL APPLICATION IS THE **MAGNETIC BRAKE** USED IN TROLLEYS. AN ELECTROMAGNET IS PLACED NEAR THE TRACK. THEN THE CURRENT IN THE ELECTROMAGNET INDUCES AN OPPOSING CURRENT IN THE TRACK, SLOWING THE TROLLEY.

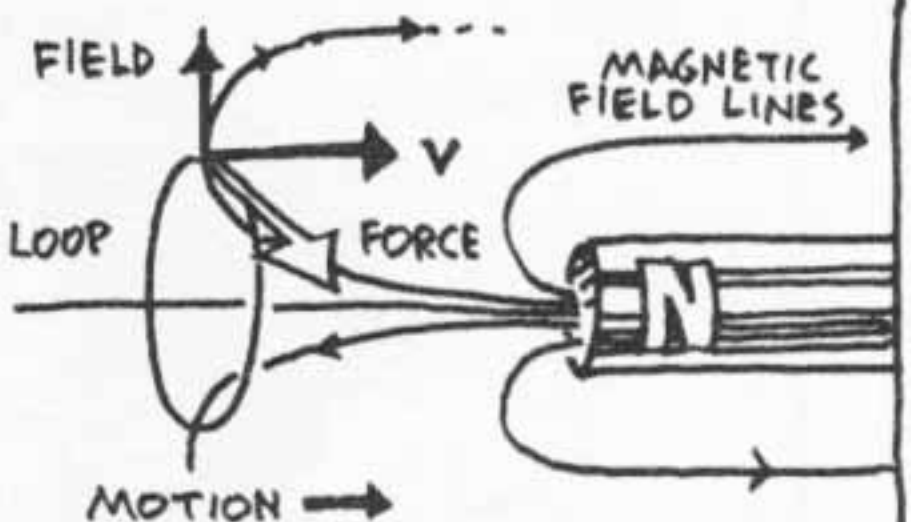


◊CHAPTER 20◊
RELATIVITY

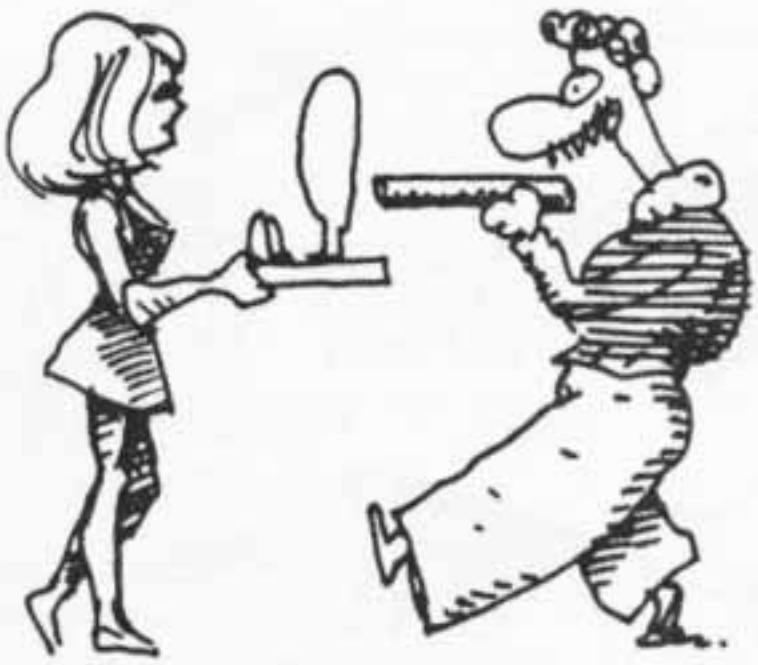
LET'S THINK THROUGH THE FARADAY EXPERIMENT AGAIN. I HOLD THE LOOP, RINGO THE MAGNET. WHEN I MOVE, SO DOES THE GALVANOMETER NEEDLE.



THIS IS EASILY UNDERSTOOD. THE WIRE HAS CHARGES. WHEN THEY MOVE, THEY FEEL THE SIDEWAYS MAGNETIC FORCE WHICH DRIVES THEM AROUND THE LOOP.



BUT WHAT ABOUT WHEN RINGO MOVES AND I STAND STILL?



WE KNOW THAT A CURRENT IS INDUCED, BUT BY WHAT? THE CHARGES ARE NOT INITIALLY MOVING, SO HOW CAN THE MAGNET AFFECT THEM?

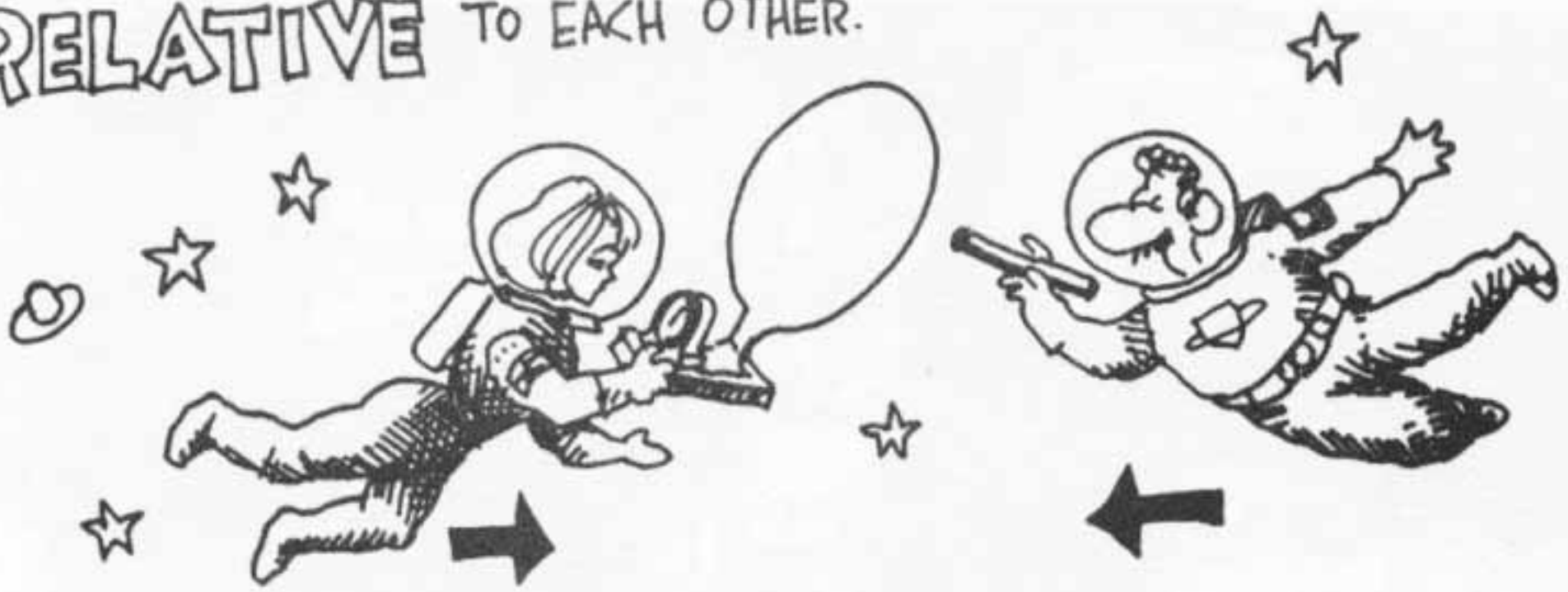
IF ONLY MAGNETIC AND ELECTRIC FIELDS CAN MOVE CHARGES, THERE MUST HAVE BEEN AN ELECTRIC FIELD, TOO?

BRAVO!

RINGO HAS DEDUCED WHAT IT TOOK EINSTEIN TO REALIZE. EINSTEIN SAW THAT, DEPENDING ON WHO WAS MOVING, THE CURRENT IS SOMETIMES DUE TO A MAGNETIC FIELD AND SOMETIMES TO AN ELECTRIC FIELD.

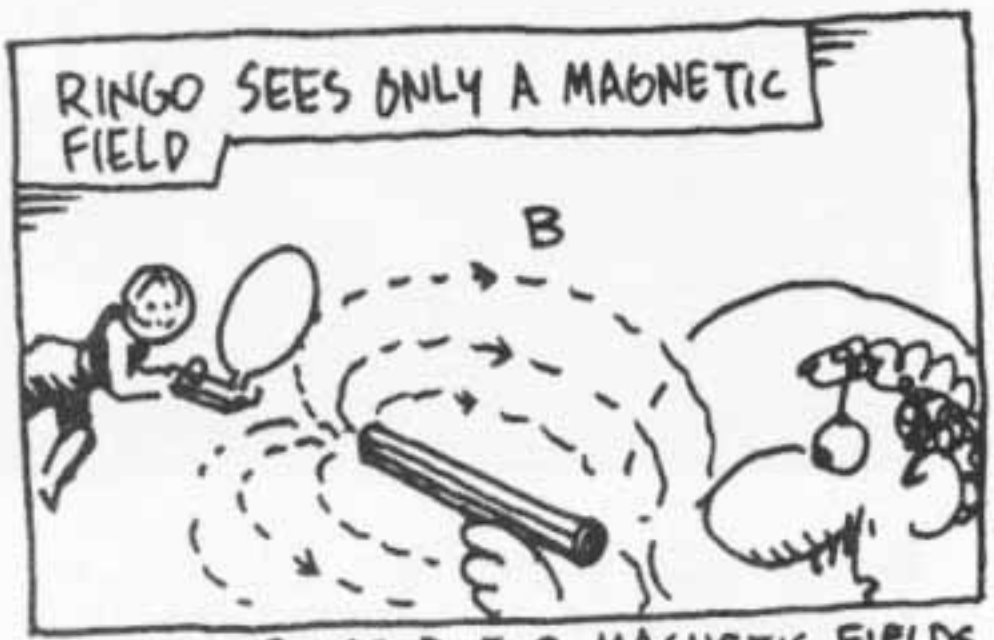
CHANGING MAGNETIC FIELDS CAUSE ELECTRIC FIELDS!!

NOW AGAIN... ONE MORE TIME... WE'LL DO THE FARADAY EXPERIMENT... BUT THIS TIME IN OUTER SPACE, SO WE CAN'T TELL WHO IS "REALLY" MOVING. WE KNOW ONLY THAT WE ARE MOVING RELATIVE TO EACH OTHER.



I THINK I AM STATIONARY, AND RINGO IS MOVING. I DETECT A MAGNETIC FIELD, BUT IT CAN'T MOVE THE CHARGES, SO THERE MUST BE AN ELECTRIC FIELD ALSO, CAUSED BY THE CHANGING MAGNETIC FIELD.

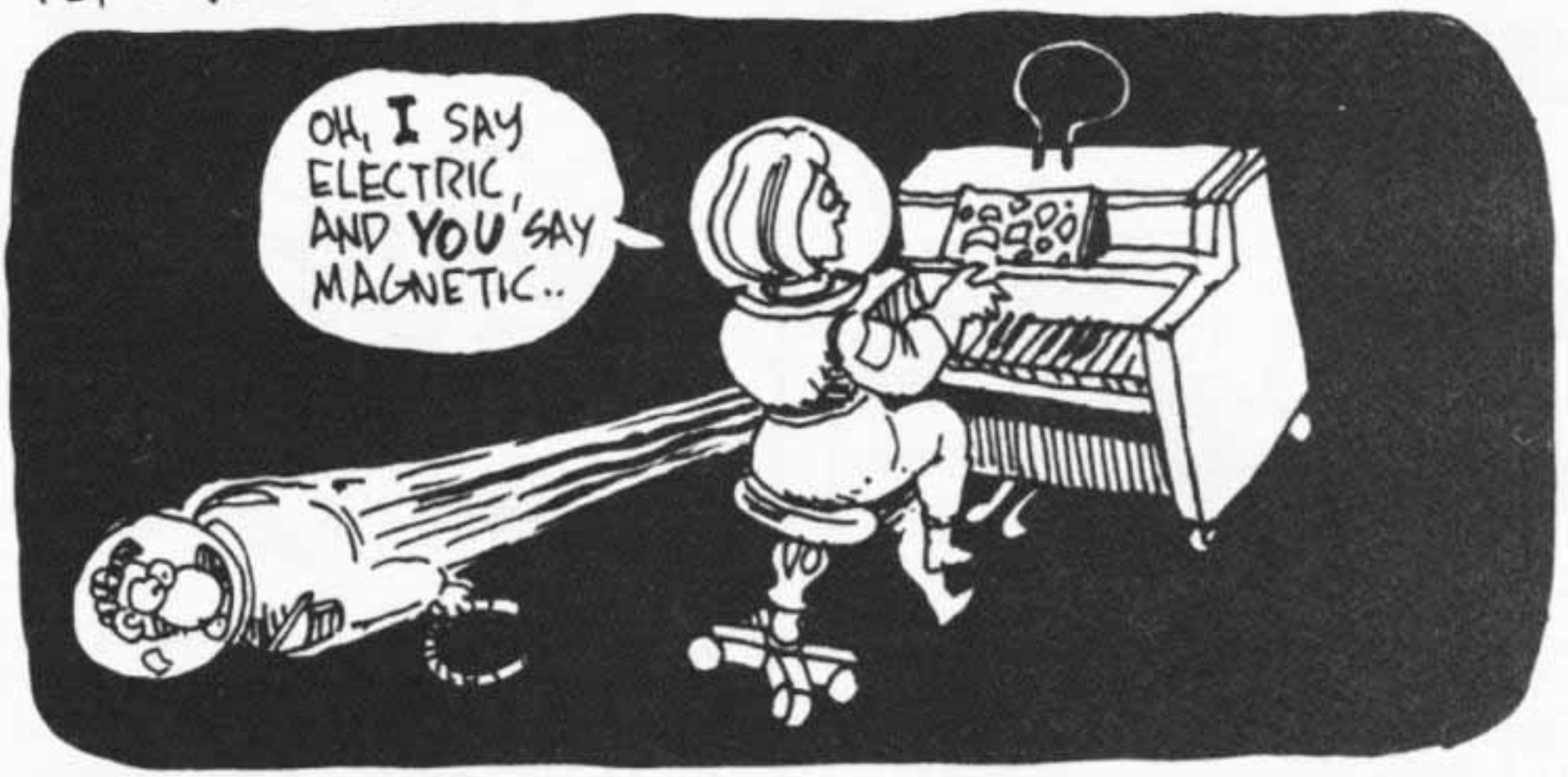
RINGO THINKS HE IS STATIONARY AND I AM MOVING. HE DETECTS ONLY A MAGNETIC FIELD AND MOVING CHARGES, WHICH ACCOUNT FOR THE INDUCED CURRENT.



PHYSICISTS USE B FOR MAGNETIC FIELDS.

RINGO AND I DISAGREE ON WHAT FIELDS ARE PRESENT!

THIS IS THE HALLMARK OF RELATIVITY THEORY: TWO OBSERVERS LIKE RINGO AND ME, IF THEY ARE MOVING WITH RESPECT TO EACH OTHER, WILL DISAGREE ON THEIR MEASUREMENTS OF KEY PHYSICAL QUANTITIES OF THE UNIVERSE!

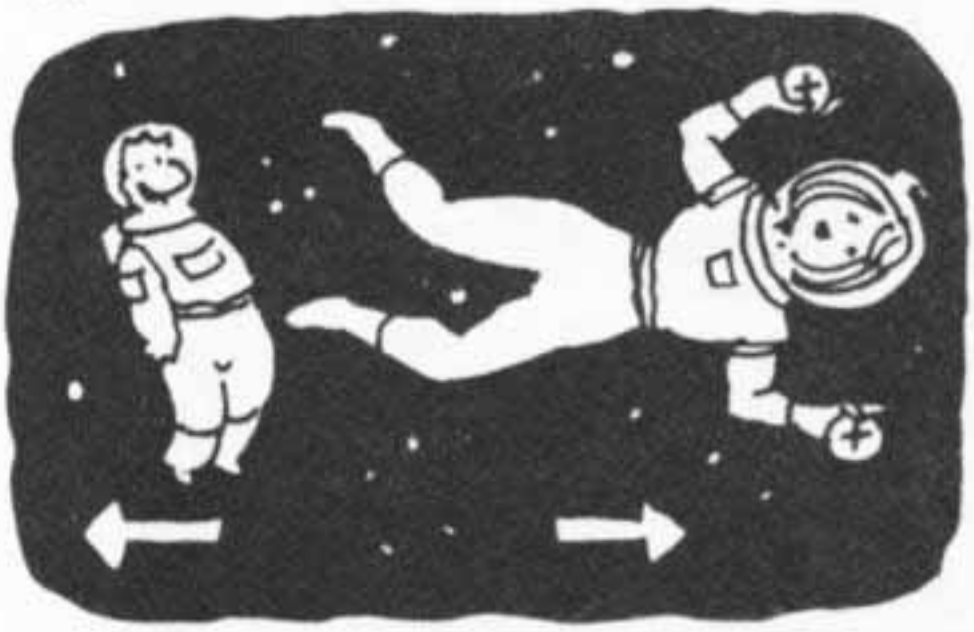


HERE'S AN EVEN SIMPLER ILLUSTRATION: A SINGLE CHARGE ZIPS THROUGH SPACE PAST RINGO:

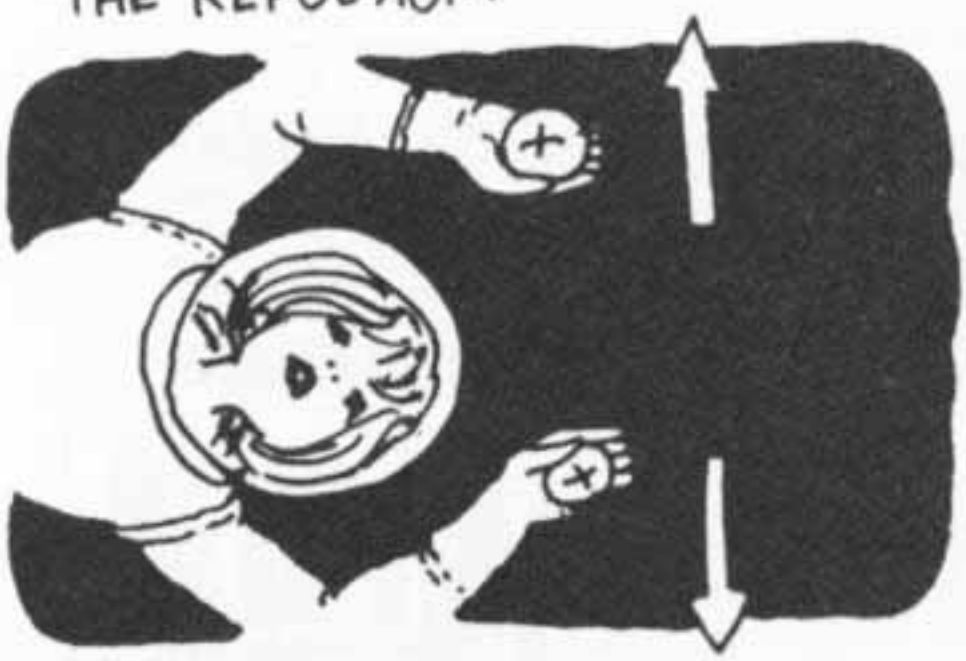
RINGO SEES A MOVING CHARGE — A CURRENT THAT GENERATES A MAGNETIC FIELD. THE NEEDLE OF RINGO'S COMPASS DEFLECTS!

BUT IF I AM MOVING WITH THE CHARGE, I SEE IT AS STATIONARY. THERE IS NO MAGNETIC FIELD, AND MY COMPASS IS NOT AFFECTED!

HERE'S THE FINAL DEMONSTRATION: WATCH CAREFULLY! I NOW CARRY **TWO** CHARGES SIDE BY SIDE PAST RINGO.

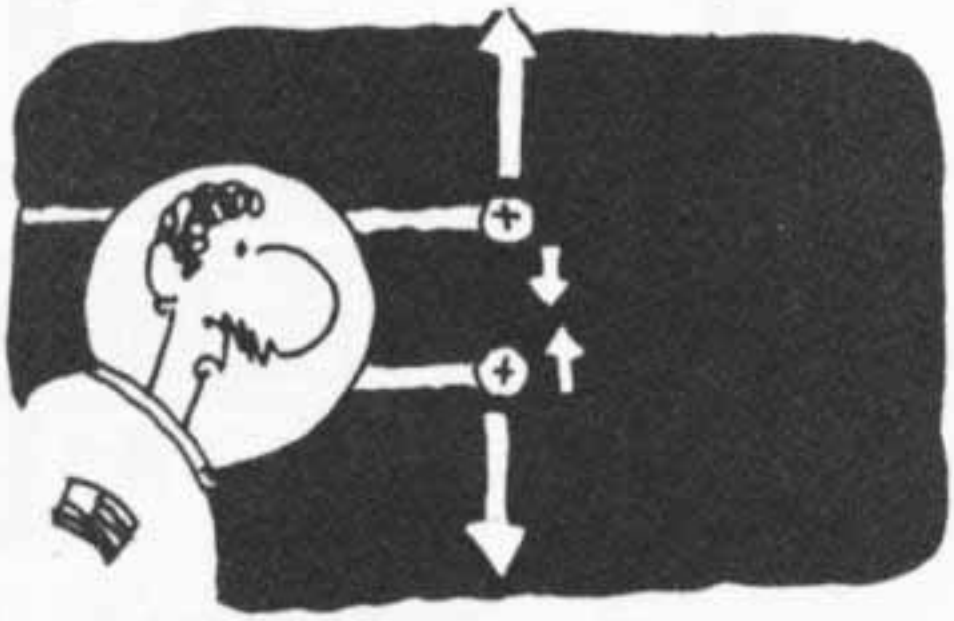


BUT TO ME, THE CHARGES ARE STATIONARY, SO I SEE ONLY THE REPULSION.

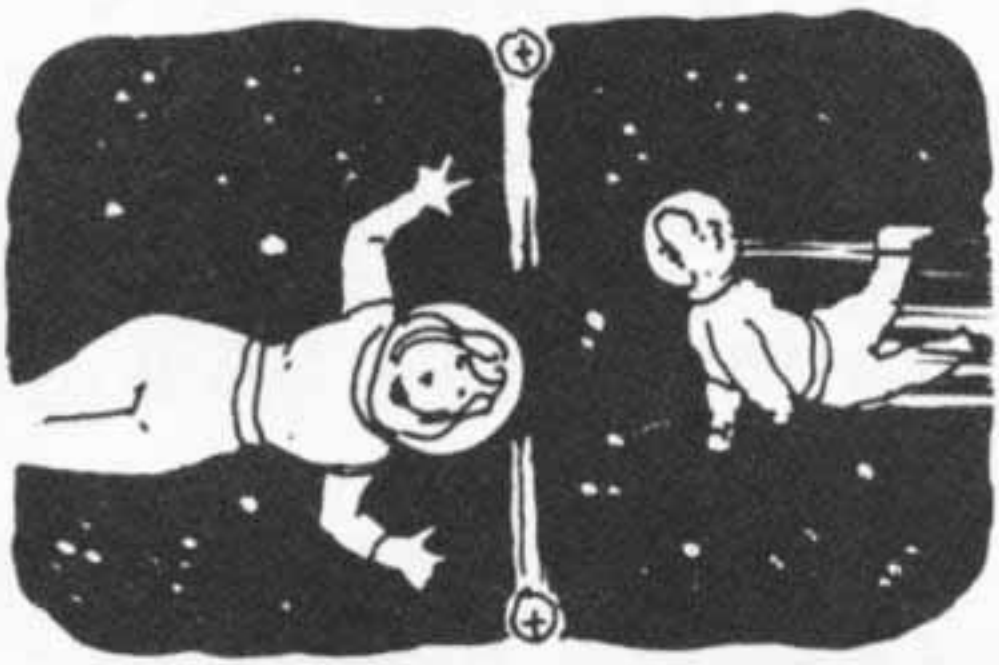


NOW THE STRANGE PART: RINGO SEES AN ATTRACTIVE MAGNETIC FORCE BETWEEN THE CHARGES, WHICH PARTLY OFFSETS THE REPULSIVE ELECTRIC FORCE — SO RINGO SEES THE CHARGES MOVE APART MORE SLOWLY THAN I DO!

THEY REPEL EACH OTHER ELECTRICALLY — BUT RINGO SEES THEM MOVING: TWO PARALLEL CURRENTS, WHICH ATTRACT MAGNETICALLY!

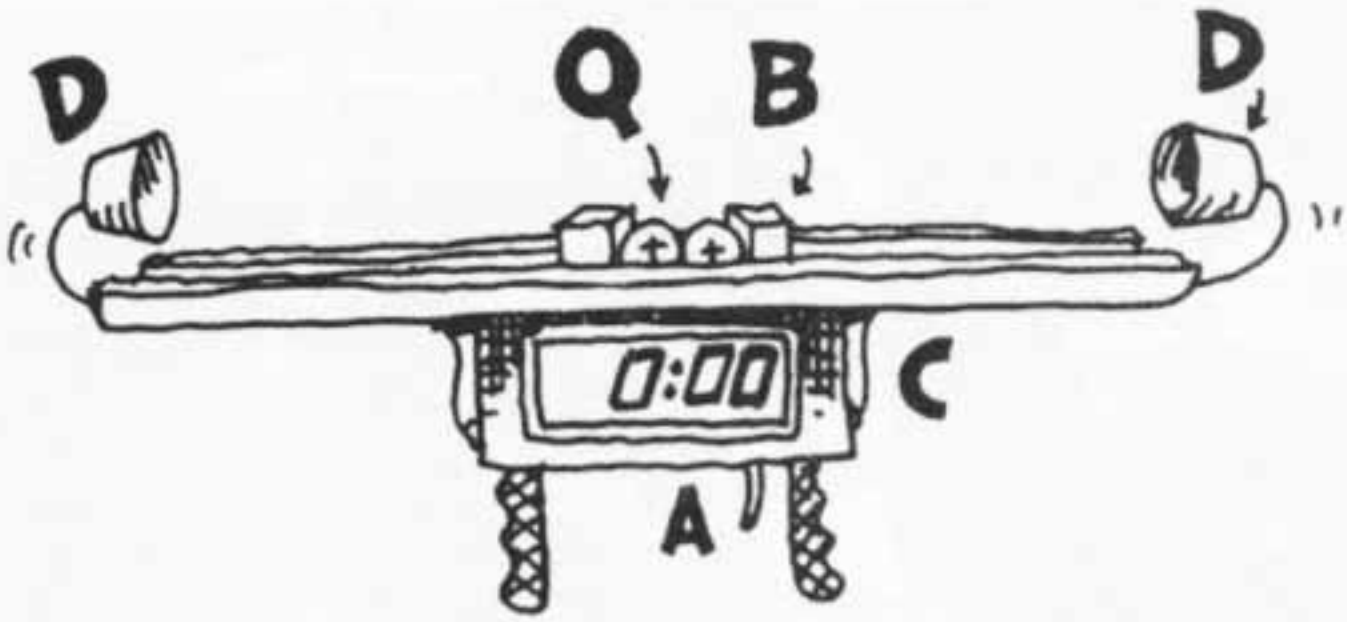


NOW I LET GO OF THE CHARGES. THEY FLY APART.



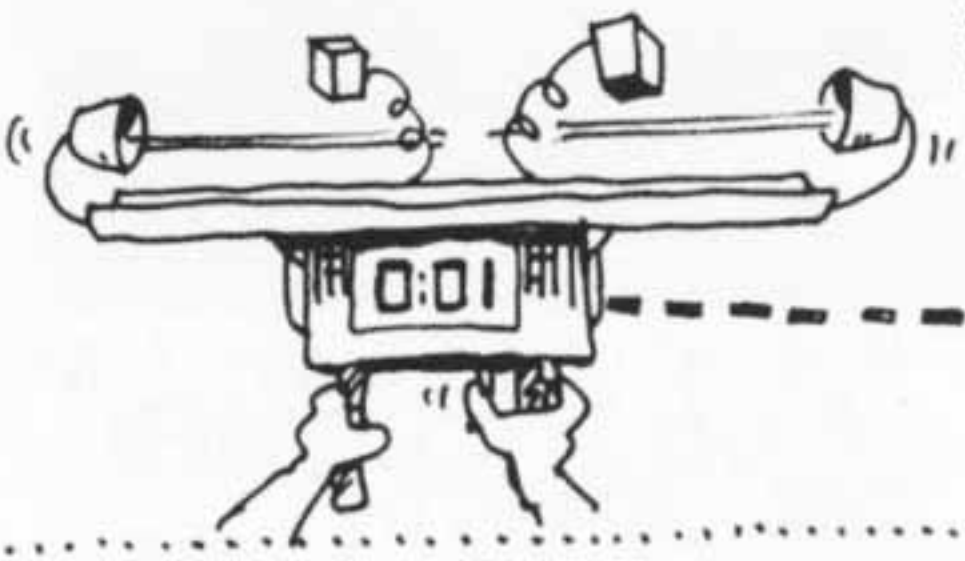
GOT THAT? RINGO, WHO IS MOVING WITH RESPECT TO ME, MEASURES THE CHARGES' OUTWARD VELOCITY TO BE **SLOWER** THAN I MEASURE IT!!

HERE IS AN APPARATUS FOR MEASURING HOW FAST THE CHARGES FLY APART.

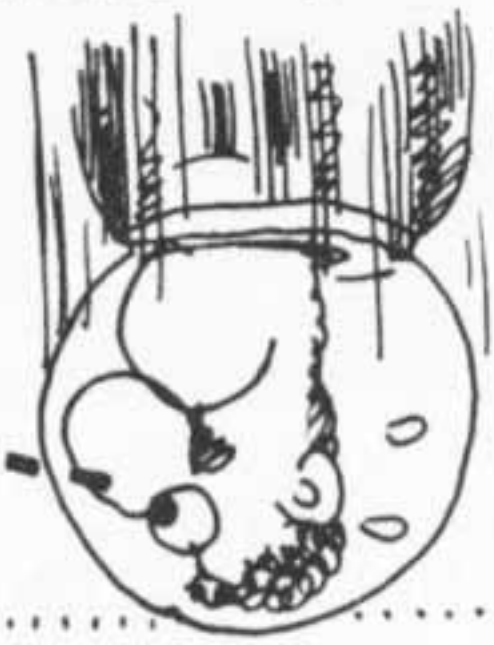


PULLING TRIGGER **A** RELEASES BLOCKS **B**, STARTING CLOCK **C** AND ALLOWING CHARGES **Q** TO FLY APART. CHARGES STRIKE CUPS **D**, STOPPING CLOCK **C**.

WITH THE THING AT REST IN FRONT OF ME, THE CHARGES FLY APART QUICKLY, SAY IN 0.01 SECONDS.



BUT, AS WE JUST SAW, THE SPEEDING RINGO SEES A MAGNETIC ATTRACTION THAT DELAYS THE CHARGES' FLYING APART.



RINGO MEASURES A **LONGER TIME** THAN I DO—SAY 0.02 SEC., FOR THE CHARGES TO FLY APART! HE ALSO NOTICES THAT MY CLOCK TICKS OFF ONLY 0.01 SEC. IN THE TIME IT TOOK HIS CLOCK TO REACH 0.02 SECONDS. CONCLUSION?

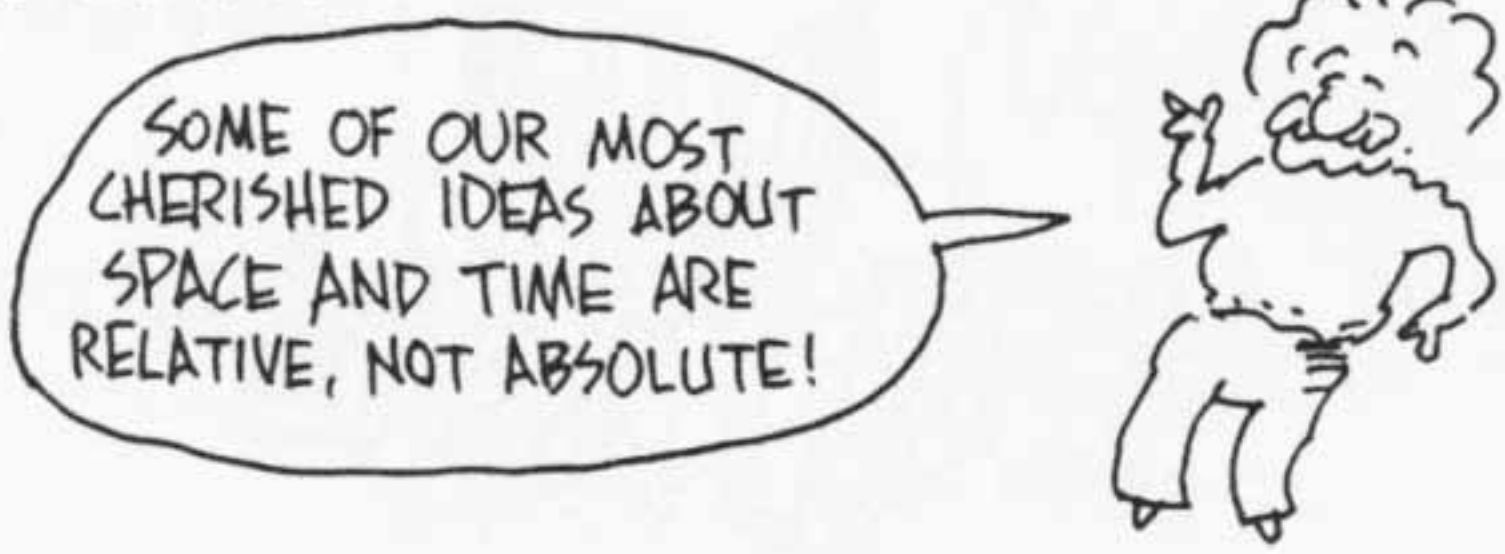
WHAT IS RINGO TO THINK? AS I SPEED BY, HE SEES MY CLOCK TICK OFF 0.01 SECONDS, WHILE HIS TICKS OFF TWICE AS MUCH. THERE IS ONLY ONE THING HE CAN CONCLUDE. RINGO DECIDES THAT—

MY RAPID MOTION CAUSED MY TIME TO SLOW DOWN!!

THAT IS JUST ONE OF THE WEIRD CONCLUSIONS OF RELATIVITY THEORY. AND THERE ARE MORE. ACCORDING TO EINSTEIN, A STATIONARY OBSERVER SEES THE FOLLOWING EFFECTS ON RAPIDLY MOVING OBJECTS:

* TIME SLOWS DOWN
* LENGTHS DECREASE (IN THE DIRECTION OF MOTION)
* MASSES INCREASE

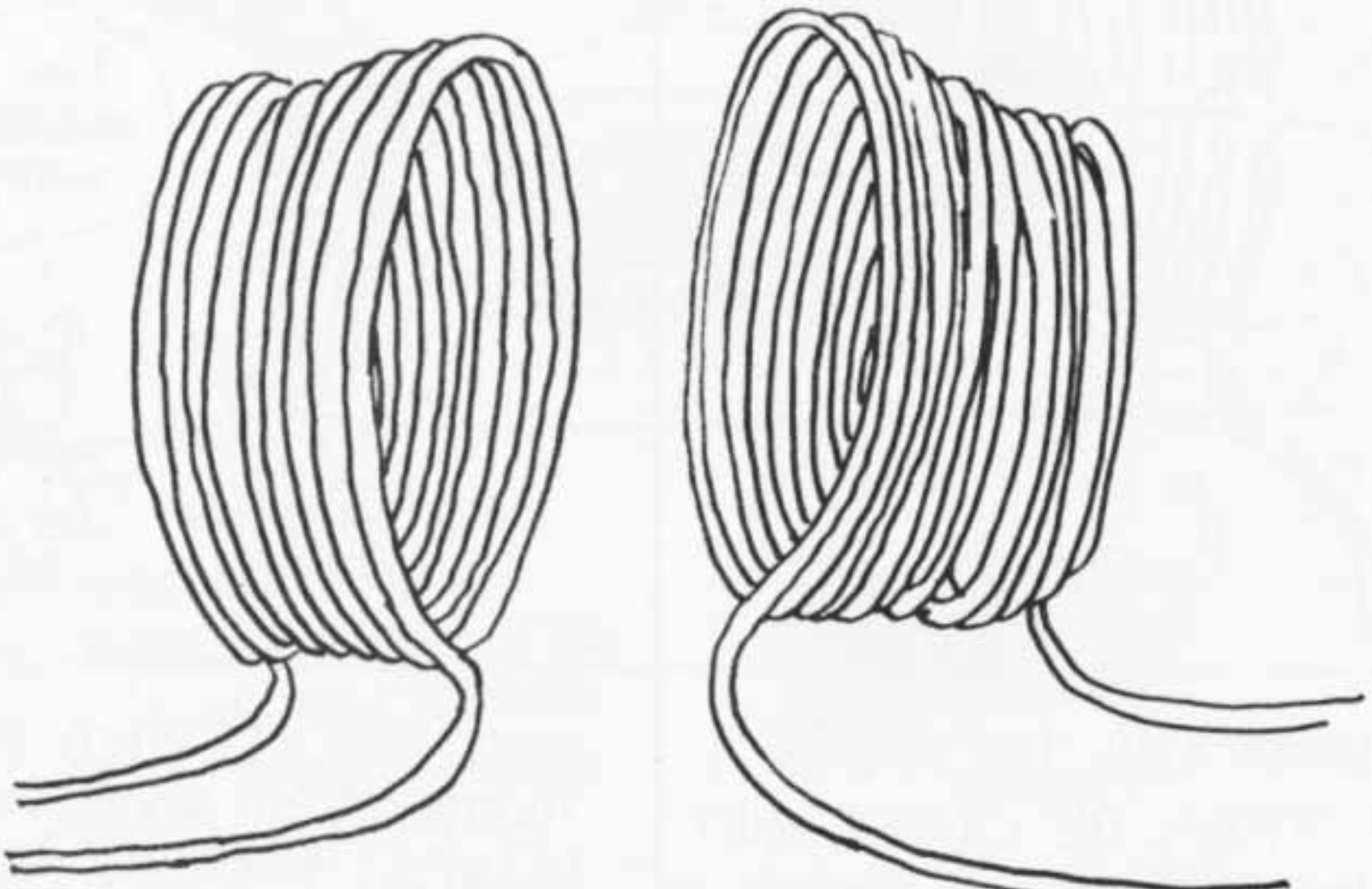
IN OTHER WORDS—



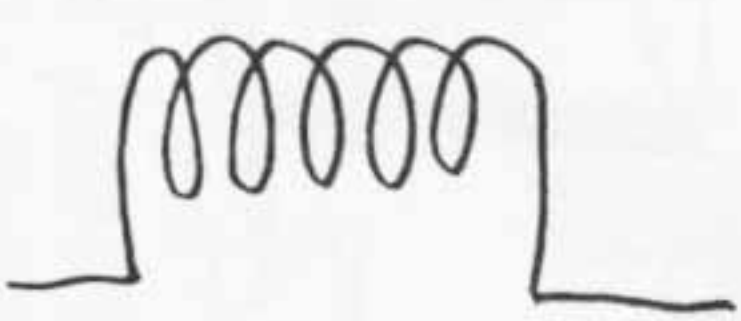
WE SAW THAT THE EFFECT OF TIME DILATION IS DERIVED FROM BASIC, OBSERVED FACTS ABOUT ELECTRICITY AND MAGNETISM. THE PHYSICISTS OF THE LATE NINETEENTH CENTURY ALREADY KNEW THAT THEIR E.M. EQUATIONS DID NOT AGREE WITH NEWTON'S MECHANICS, AND MOST OF THEM THOUGHT THE ANSWER WAS TO MODIFY THE EQUATIONS IN SOME WAY...

...BUT ONLY EINSTEIN SAW THAT THE ANSWER WAS TO REVISE THE VERY CONCEPTS OF SPACE AND TIME...

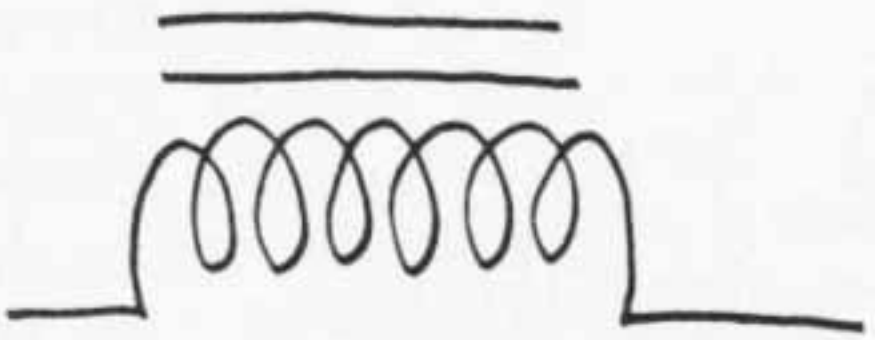
◊CHAPTER 21◊
INDUCTORS



AN INDUCTOR IS SIMPLY A COIL OF WIRE. SOMETIMES IT MAY SURROUND AN IRON CORE, TO INCREASE MAGNETIC EFFECTS. ITS ELECTRIC SYMBOL IS:

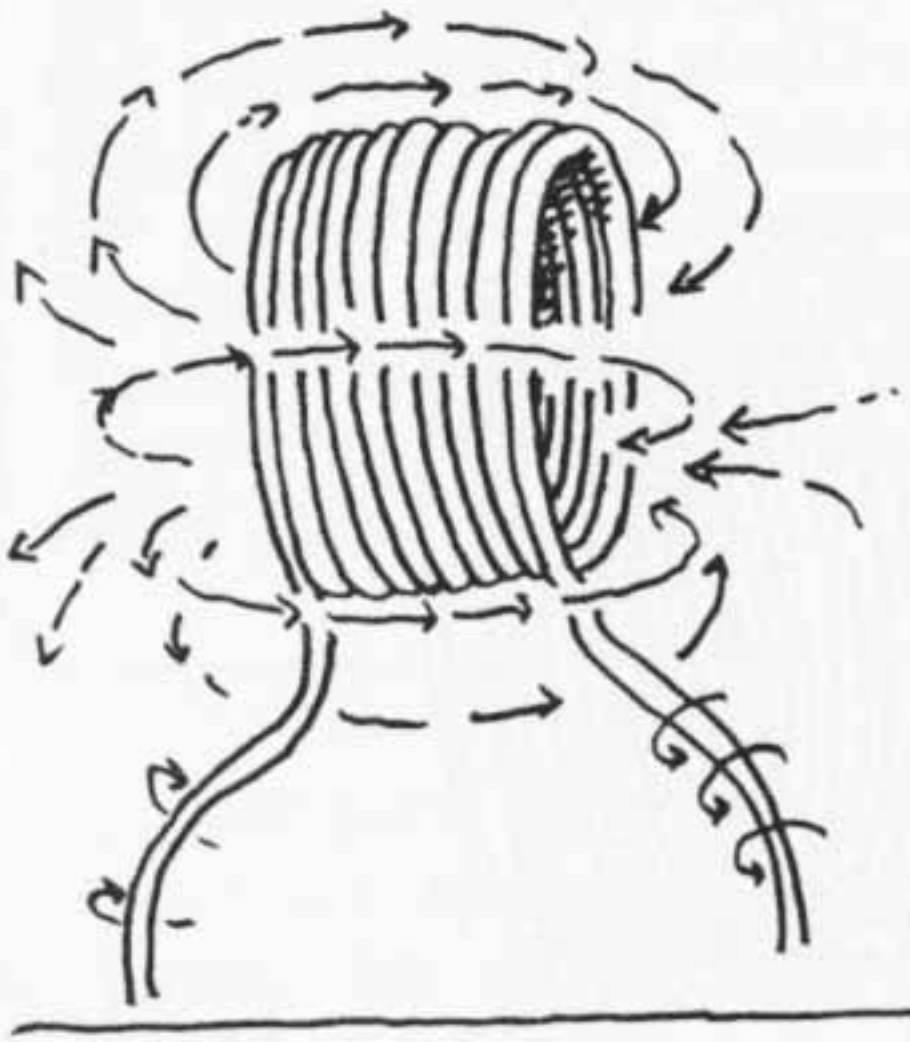


INDUCTOR **L**

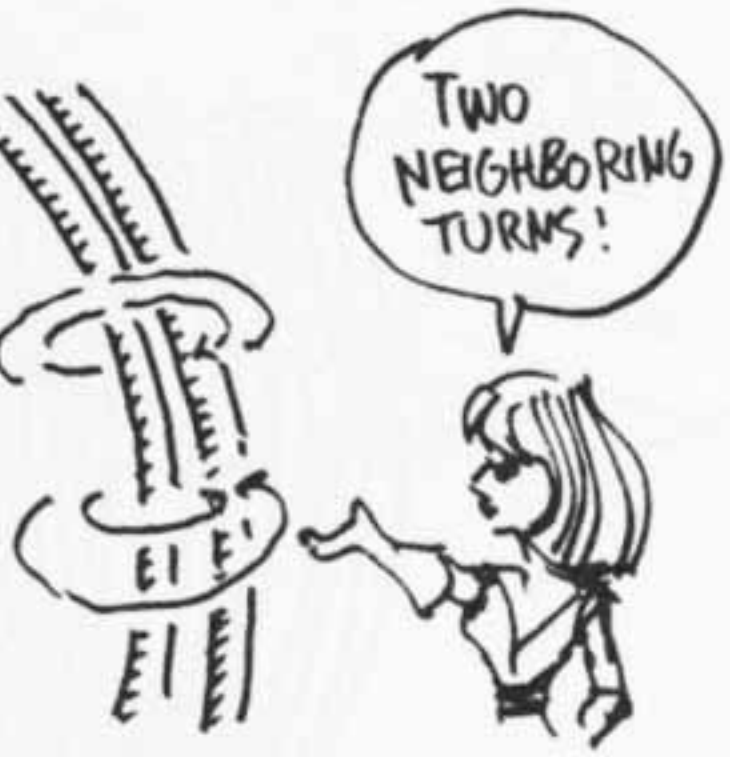


INDUCTOR **L** WITH IRON CORE.

IF A CURRENT FLOWS THROUGH AN INDUCTOR, A MAGNETIC FIELD WILL SURROUND IT, AS WE'VE SEEN.



IF THE CURRENT IS CHANGED, MAGNETIC FIELD LINES CUT ACROSS THE TURNS OF THE COIL, PRODUCING A **SELF-INDUCTANCE** EFFECT.

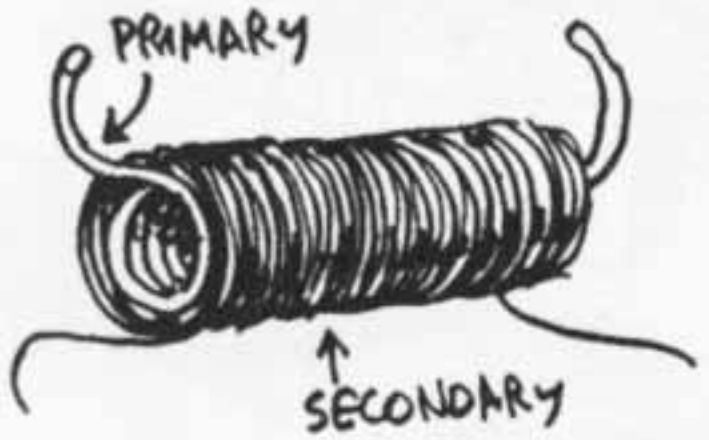


BY LENZ'S LAW, THE INDUCED EMF OPPOSES THE CHANGE THAT PRODUCED IT. IF YOU TRY TO TURN ON THE CURRENT IN THE COIL, THE SELF-INDUCED EMF RESISTS, AND THE CURRENT CAN ONLY BUILD UP SLOWLY. IF YOU TRY TO TURN IT OFF, THE SELF-INDUCED EMF TRIES TO KEEP THE CURRENT FLOWING.

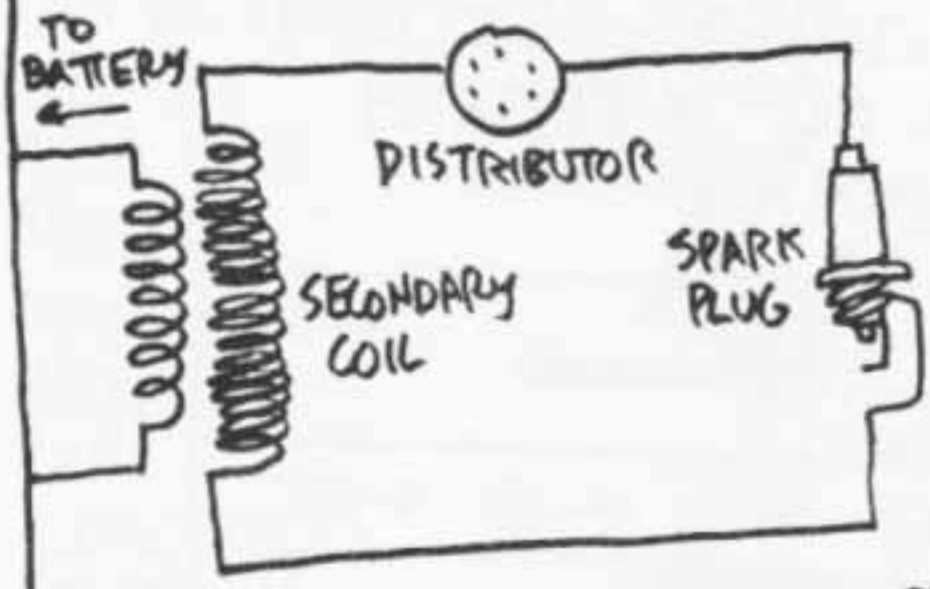
THESE EMFs CAN BUILD UP TO THOUSANDS OF VOLTS. FOR EXAMPLE, WHEN YOU OPEN A SWITCH, THIS EMF CAN SHOOT A SPARK THROUGH THE AIR, KEEPING THE CURRENT FLOWING FOR A MOMENT.

I SUPPOSE THERE'S SOME USE FOR THIS CHARMING PHENOMENON?

THE EFFECT IS EXPLOITED IN THE IGNITION CIRCUIT OF AN AUTOMOBILE.



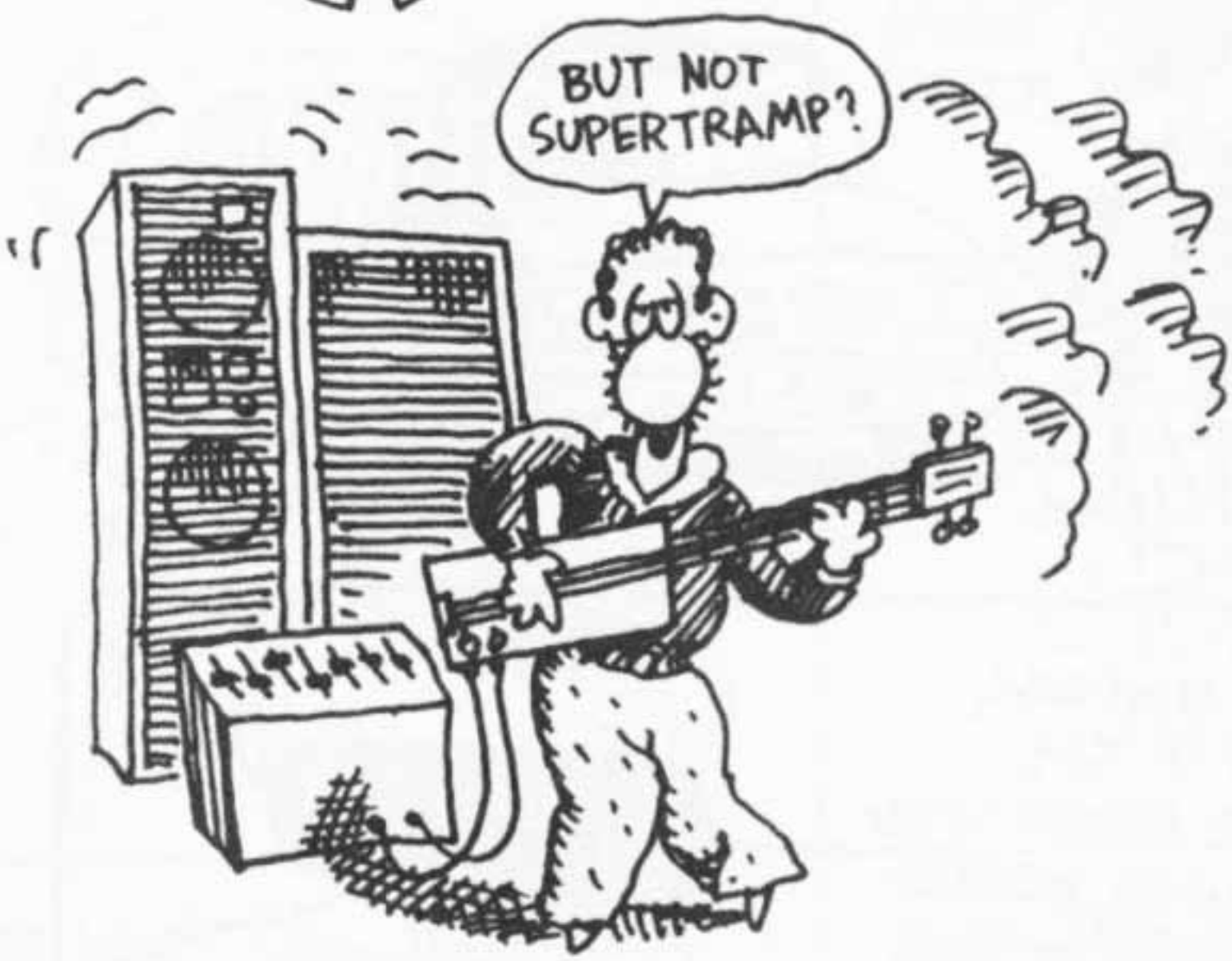
THE "COIL" HAS TWO WINDINGS, A PRIMARY WINDING OF, SAY, A HUNDRED TURNS OF MEDIUM-SIZED WIRE, AND A SECONDARY WINDING OF THOUSANDS OF TURNS OF FINE WIRE. THE PRIMARY IS ENERGIZED THROUGH THE "POINTS"* BY THE 12-VOLT BATTERY. WHEN THE POINTS OPEN, SWITCHING OFF THE CURRENT IN THE PRIMARY, THE COLLAPSING MAGNETIC FIELD INDUCES CURRENT IN THE SECONDARY. THE MANY TURNS AMPLIFY THE INDUCED EMF, AND GENERATE A MOMENTARY PULSE OF NEARLY **50,000 VOLTS!!**



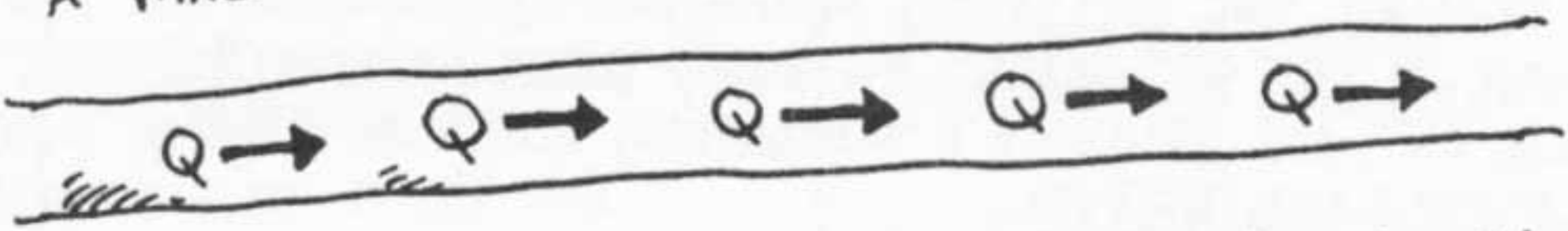
THIS IS DIRECTED BY THE DISTRIBUTOR TO THE SPARK PLUGS, PRODUCING A SPARK WHICH IGNITES THE GASOLINE. IN THIS WAY, A 12-VOLT BATTERY IS AMPLIFIED TO A HIGH-VOLTAGE SPARK.

*MODERN IGNITION SYSTEMS USE ELECTRONIC SWITCHES.

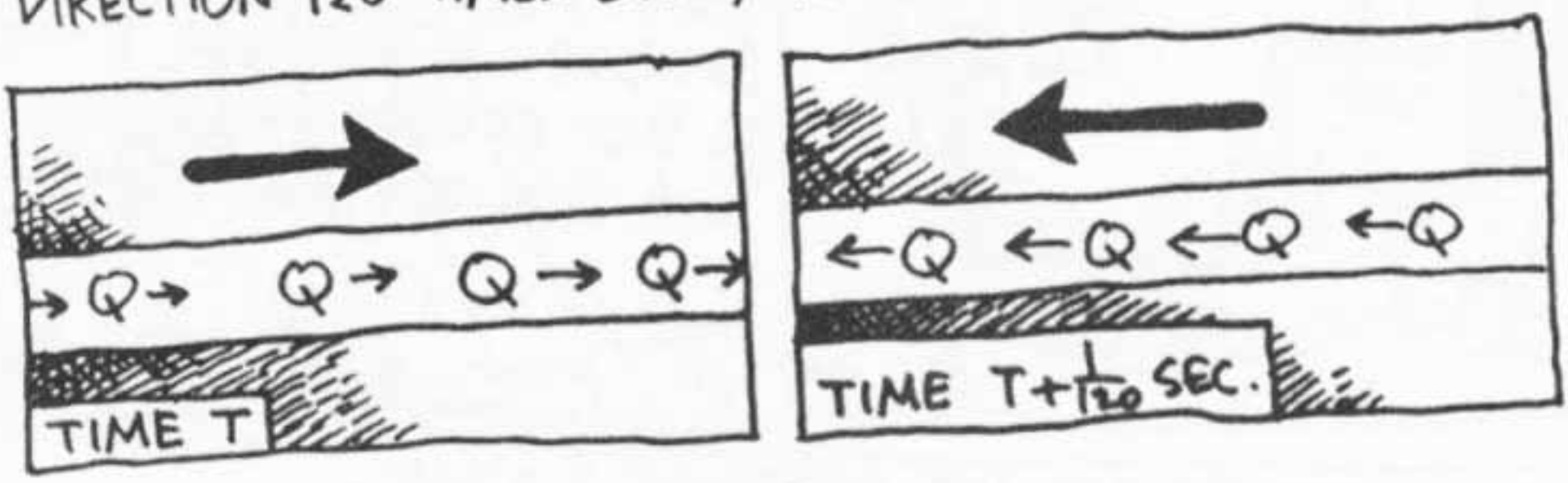
CHAPTER 22:
AC AND DC



SO FAR WE'VE BEEN LOOKING ONLY AT **DC** — DIRECT CURRENT: A FLOW OF CHARGE IN ONE DIRECTION DOWN A WIRE.

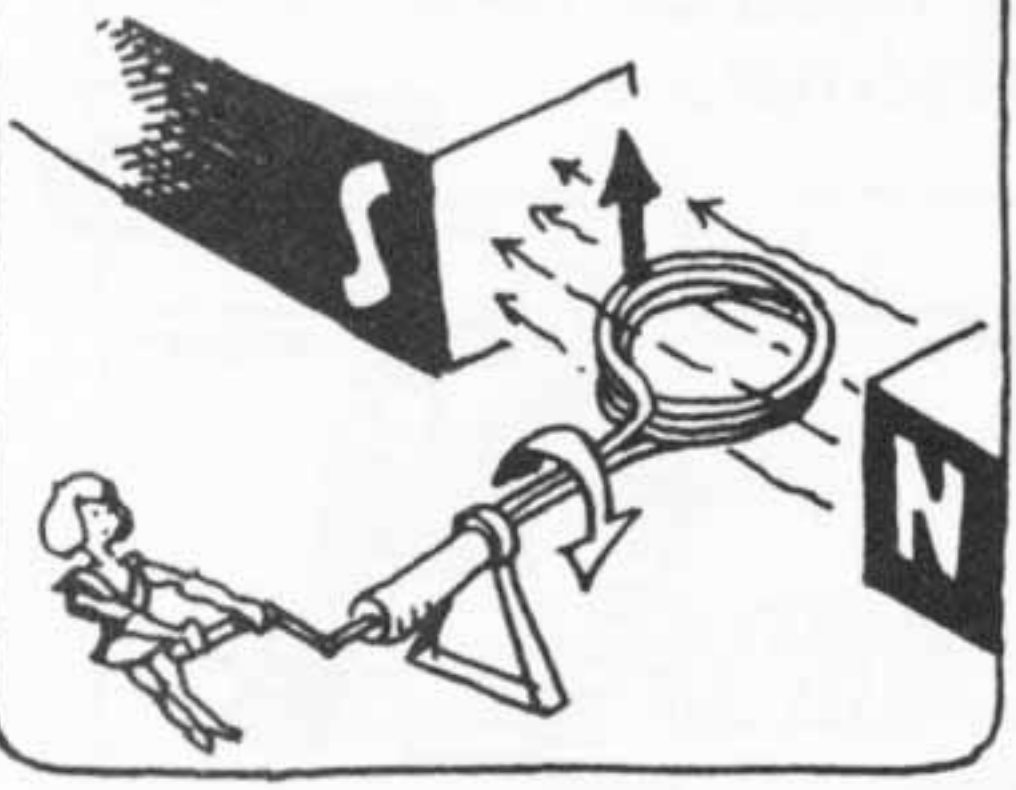


BUT WE USUALLY USE **AC** — ALTERNATING CURRENT, IN WHICH THE FLOW IS CONSTANTLY CHANGING DIRECTION. IN YOUR HOUSE WIRING, WHICH IS AC, IT REVERSES DIRECTION 120 TIMES EVERY SECOND!

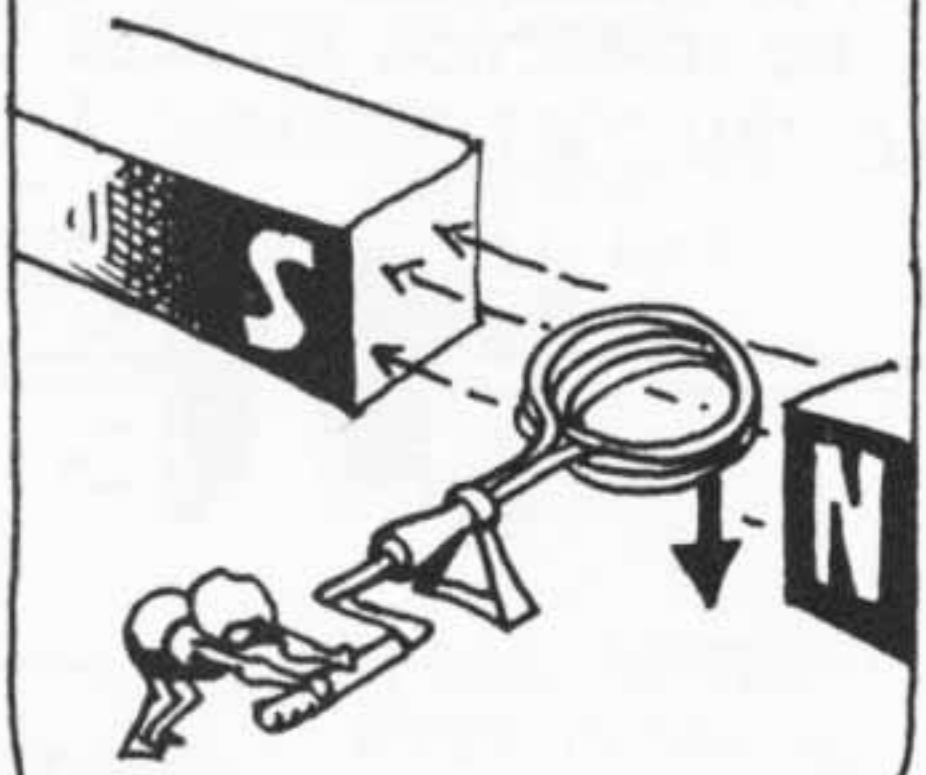


I CAN GENERATE AN ALTERNATING CURRENT BY SPINNING THIS EGGBEATER-LIKE INDUCTOR IN A PERMANENT MAGNETIC FIELD. IT DEVELOPS A CURRENT AS IT CUTS ACROSS THE MAGNETIC FIELD LINES.

THE CURRENT ALTERNATES BECAUSE THE LOOP CUTS THE FIELD LINES FIRST ONE WAY...

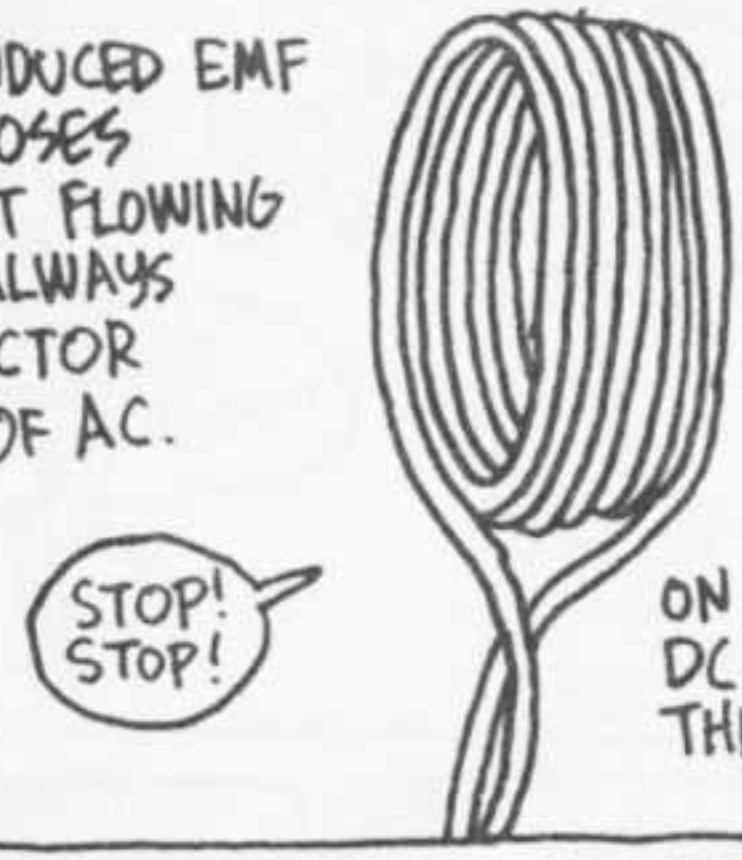


..AND THEN THE OTHER, A HALF TURN LATER.



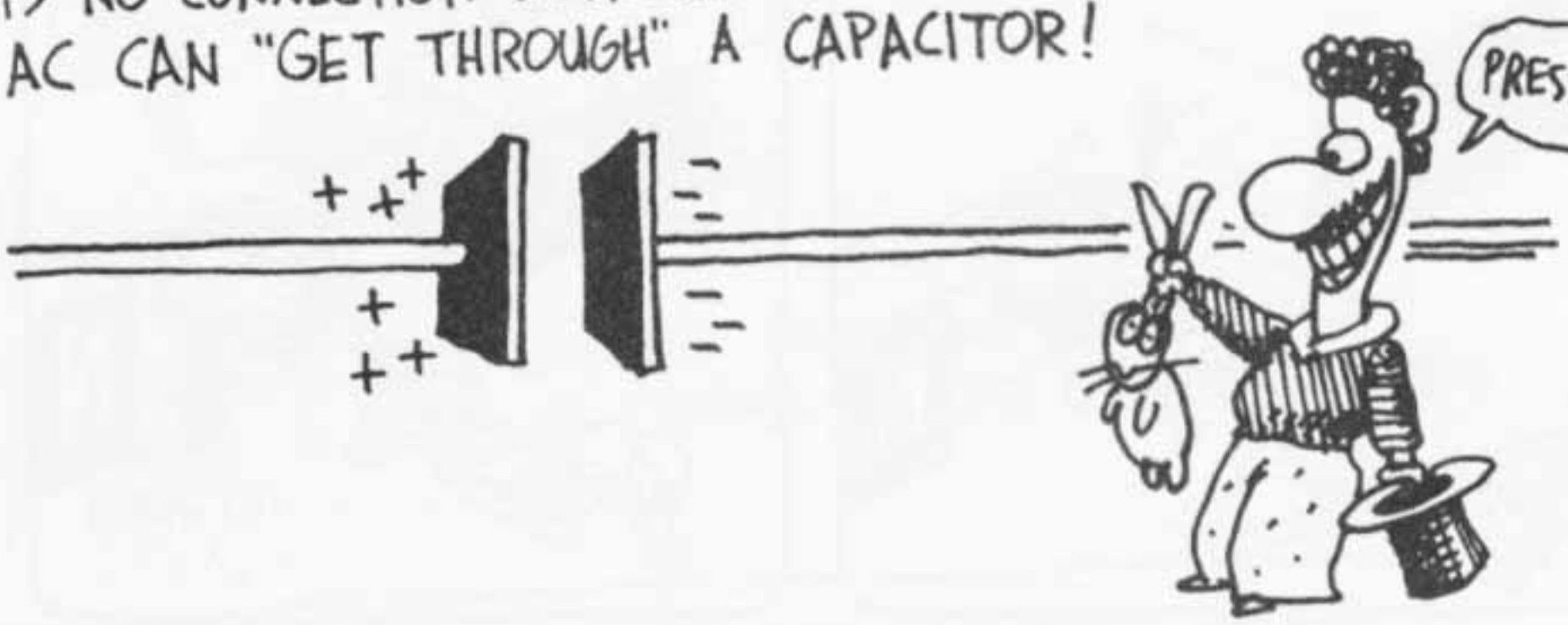
THE AC THUS GENERATED CAN BE TAKEN OFF BY SLIP RING "BRUSHES." THIS IS HOW MOST OF OUR ELECTRIC POWER IS GENERATED.

CAPACITORS AND INDUCTORS HANDLE AC AND DC DIFFERENTLY. THE INDUCED EMF IN AN INDUCTOR OPPOSES CHANGES IN CURRENT FLOWING IN IT. SINCE AC IS ALWAYS CHANGING, THE INDUCTOR RESISTS THE FLOW OF AC.

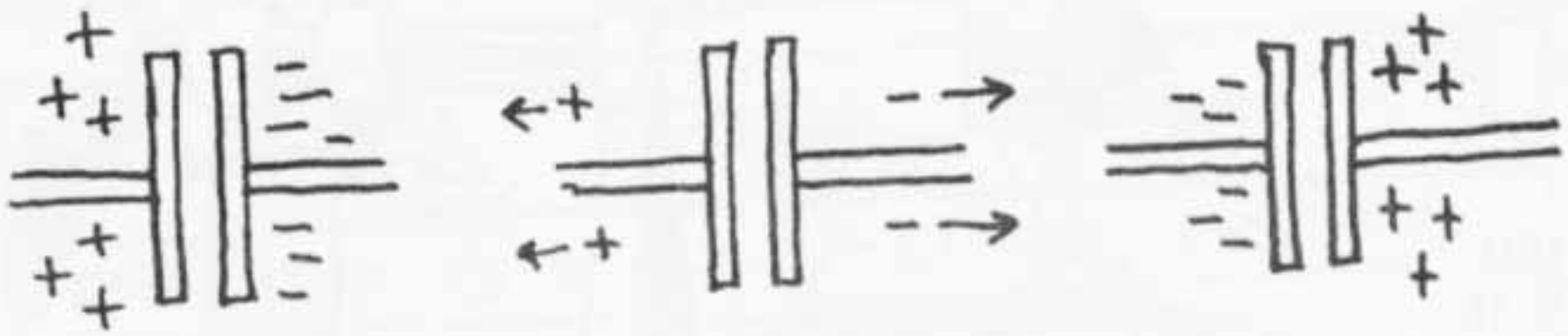


ON THE OTHER HAND, DC FLOWS RIGHT THROUGH AN INDUCTOR.

DC, OF COURSE, WON'T FLOW THROUGH A CAPACITOR—THERE IS NO CONNECTION BETWEEN THE CAPACITOR PLATES. BUT AC CAN "GET THROUGH" A CAPACITOR!

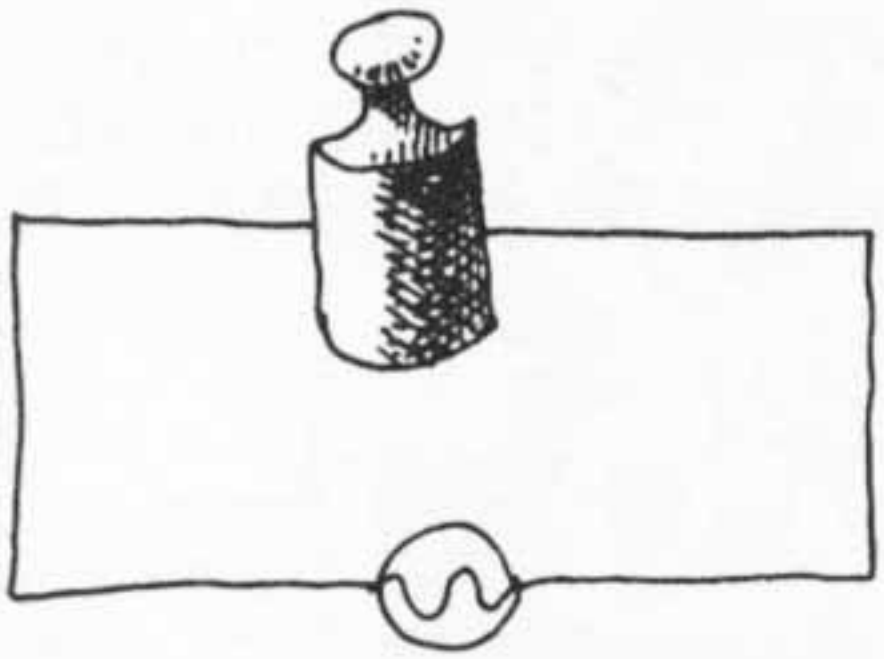


IT WORKS LIKE THIS: CHARGE MOVES BACK AND FORTH IN THE CIRCUIT, ALTERNATELY CHARGING A PLATE, DISCHARGING IT, AND RECHARGING IT THE OPPOSITE WAY. THE CURRENT APPEARS TO CROSS THE GAP.

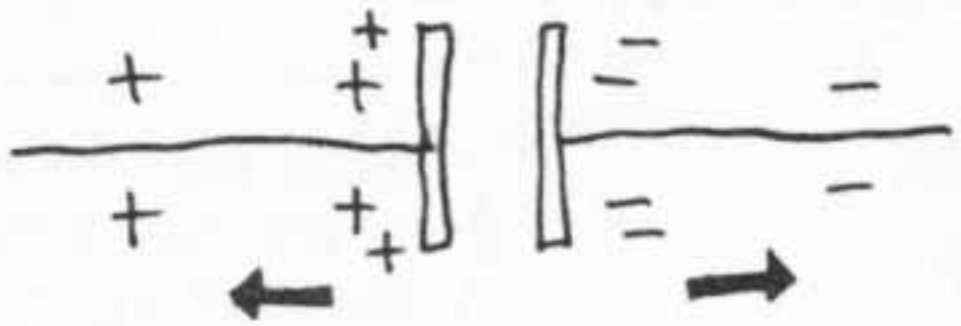


1. 2. 3.

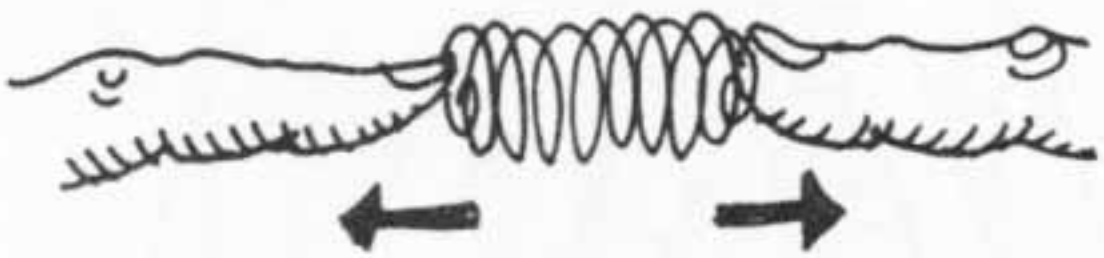
AN INDUCTOR'S RESISTANCE TO **AC** GIVES IT A KIND OF INERTIA. IN FACT, AN INDUCTOR IS AN ELECTRICAL ANALOG OF A MASS.



IF AN INDUCTOR IS MASSLIKE, A CAPACITOR IS SPRINGY. WHEN YOU TRY TO PUMP CHARGE TO AN ALREADY CHARGED PLATE, IT PUSHES BACK — LIKE A SPRING.

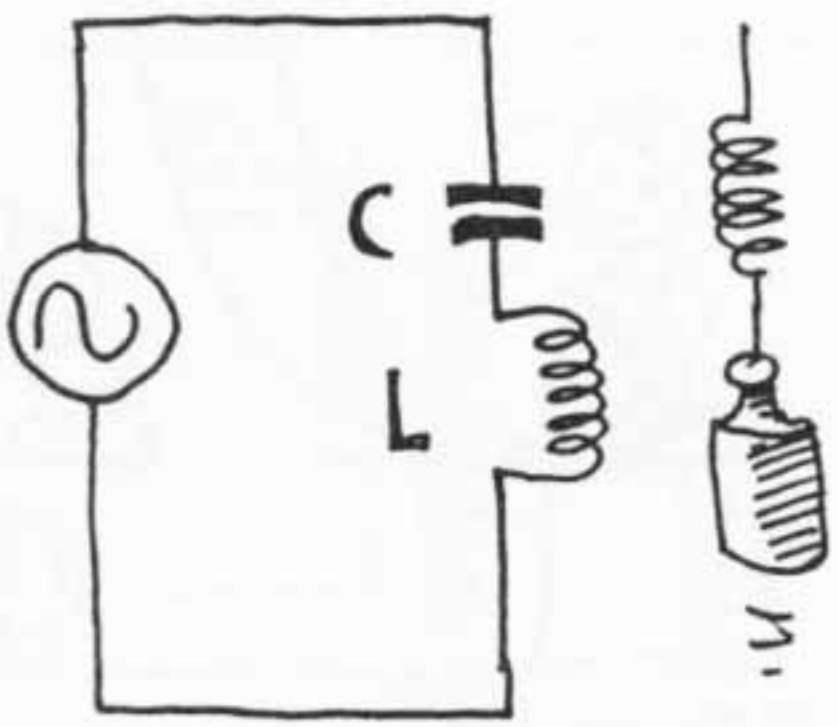


CAPACITOR REPELS ADDED CHARGE

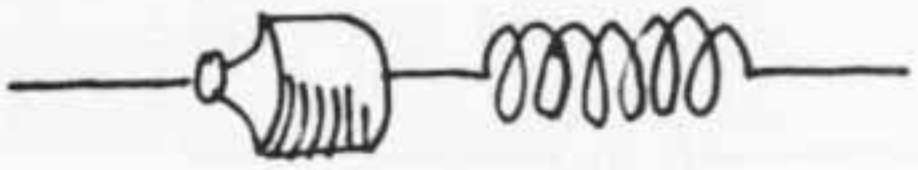


SPRING REPELS ADDED PRESSURE

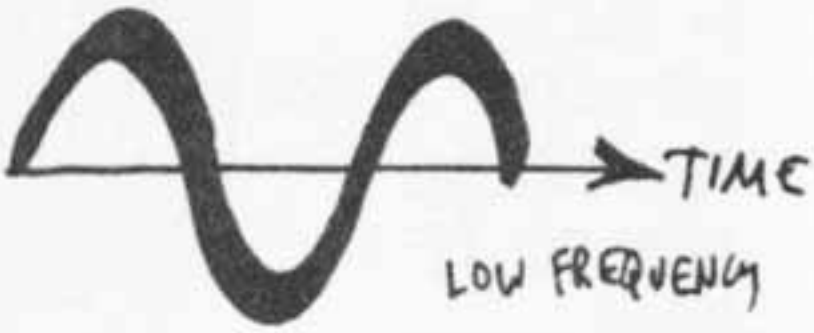
CONNECT AN INDUCTOR AND A CAPACITOR IN AN **AC** CIRCUIT, AND YOU HAVE THE ELECTRICAL EQUIVALENT OF — A MASS ON A SPRING!

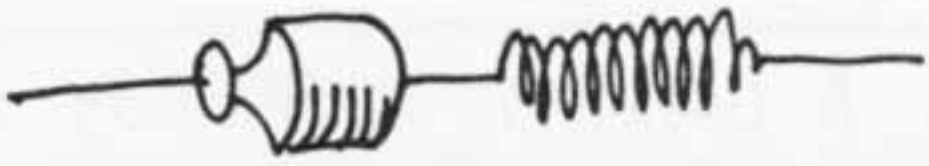


LIKE A SPRING AND MASS, THESE
LC CIRCUITS TEND TO VIBRATE
AT A PREFERRED ("RESONANT") FREQUENCY.

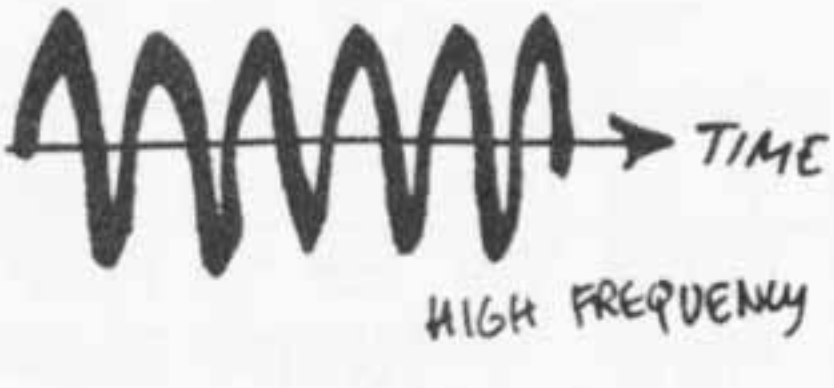


SPRING #1

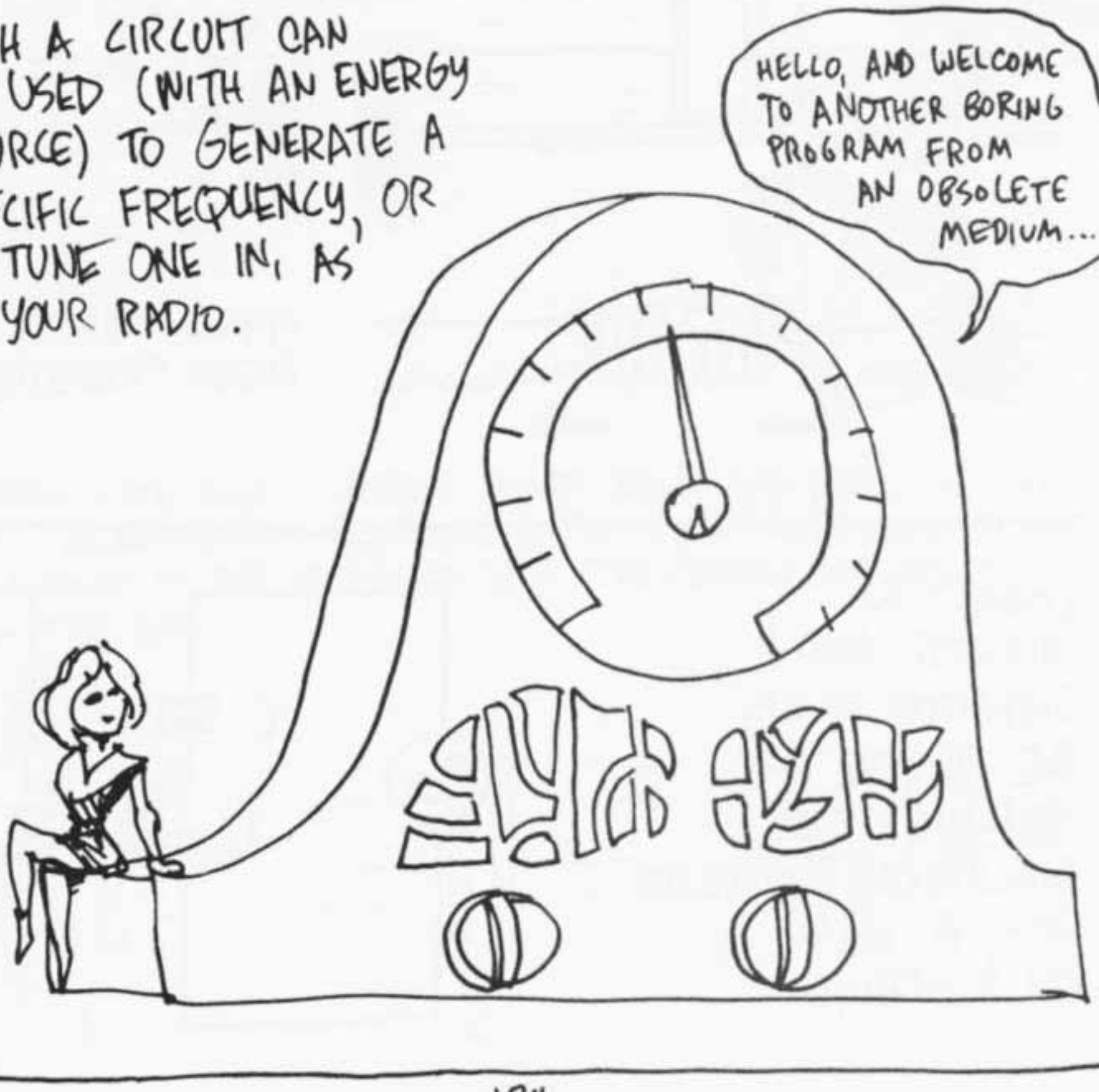




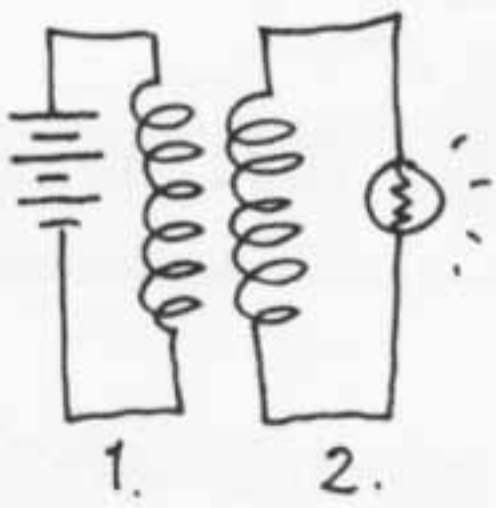
SPRING #2

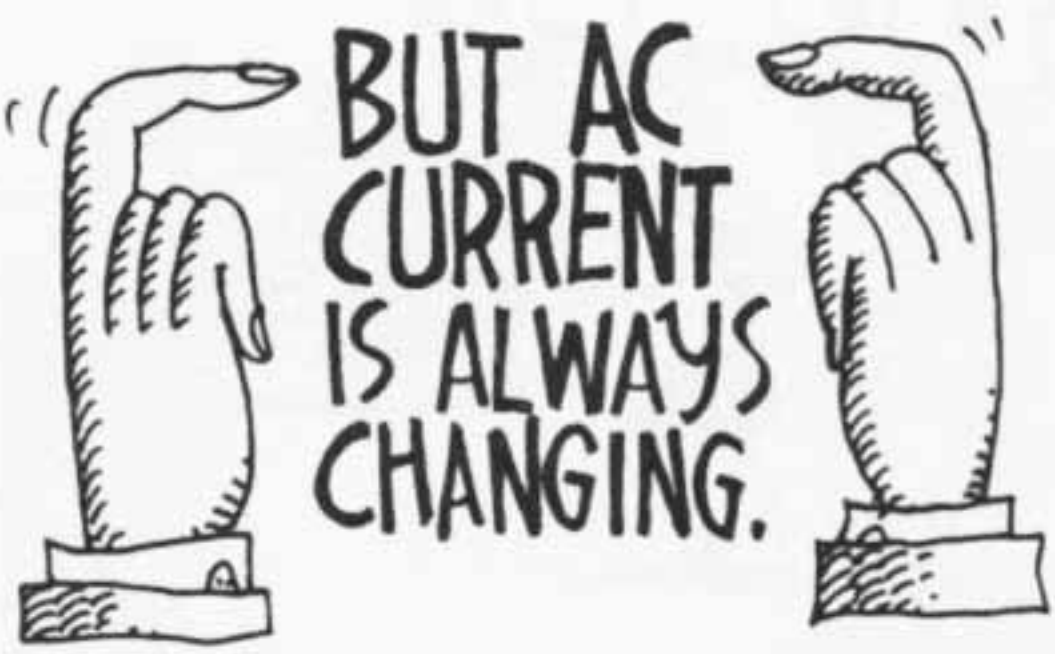


SUCH A CIRCUIT CAN BE USED (WITH AN ENERGY SOURCE) TO GENERATE A SPECIFIC FREQUENCY, OR TO TUNE ONE IN, AS IN YOUR RADIO.



RECALL THE TWO INDUCTION COILS FROM THE FARADAY EXPERIMENT (OR FROM YOUR CAR STARTER). CURRENT WAS INDUCED IN COIL #2 ONLY WHEN THE CURRENT TO COIL #1 WAS TURNED ON OR OFF. ONLY CHANGING CURRENT CAN INDUCE CURRENT.

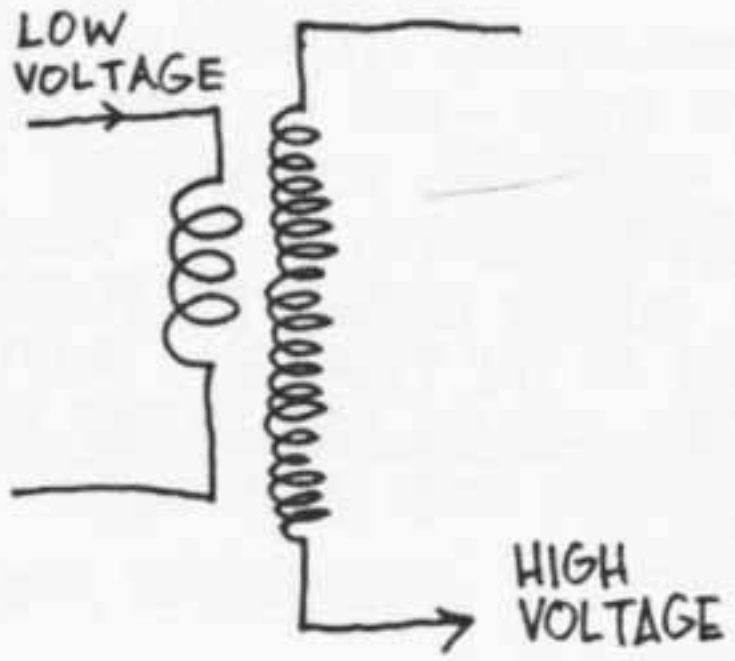


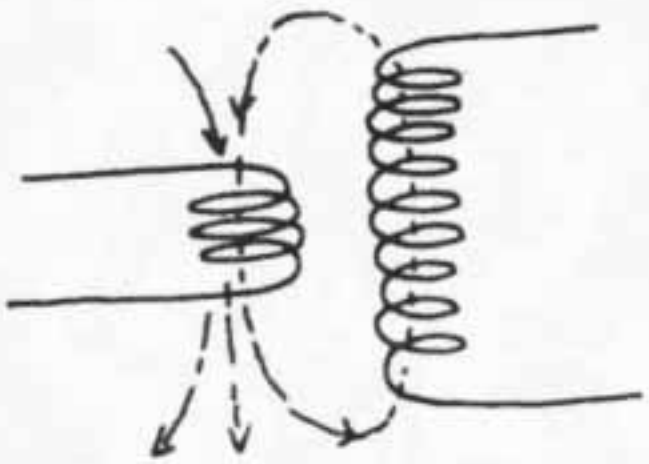


THE BEST PART IS THIS: THE INDUCED VOLTAGE IS PROPORTIONAL TO THE

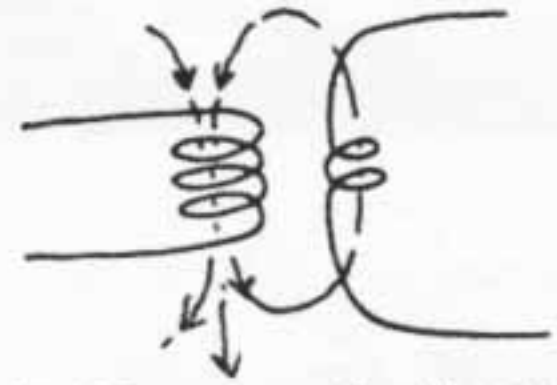
TURNS RATIO:

THE MORE TURNS IN COIL #2 AS COMPARED TO COIL #1, THE HIGHER THE VOLTAGE INDUCED IN COIL #2!





STEPPING UP VOLTAGE



STEPPING DOWN VOLTAGE

IT IS NOT HARD TO SEE WHY: IN THE SECONDARY, THE MORE WIRE IS CUT BY THE CHANGING MAGNETIC FIELD LINES, THE MORE EMF IS GENERATED. IF

N_P = NUMBER OF TURNS IN PRIMARY

N_S = NUMBER OF TURNS IN SECONDARY

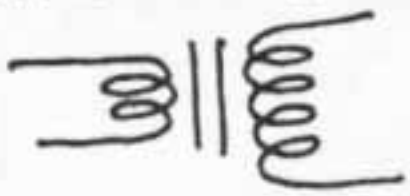
THEN

$$V_{OUT} = \frac{N_S}{N_P} V_{IN}$$

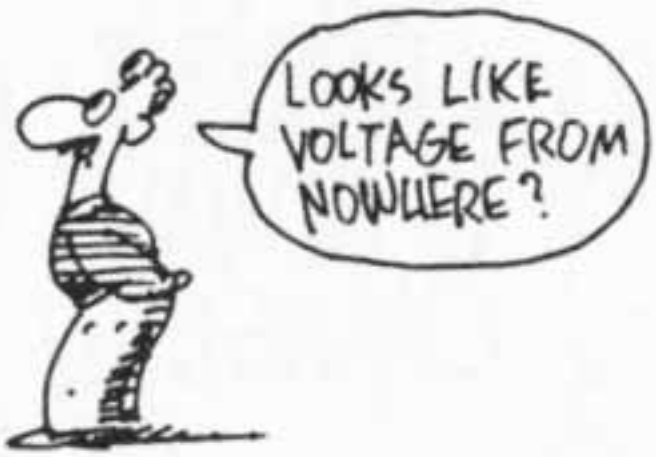
THE RESULTING DEVICE, FOR STEPPING VOLTAGE UP OR DOWN, IS CALLED A

TRANSFORMER

WITH THE SYMBOL

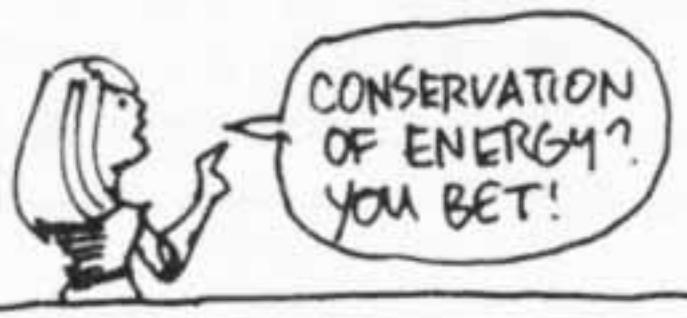


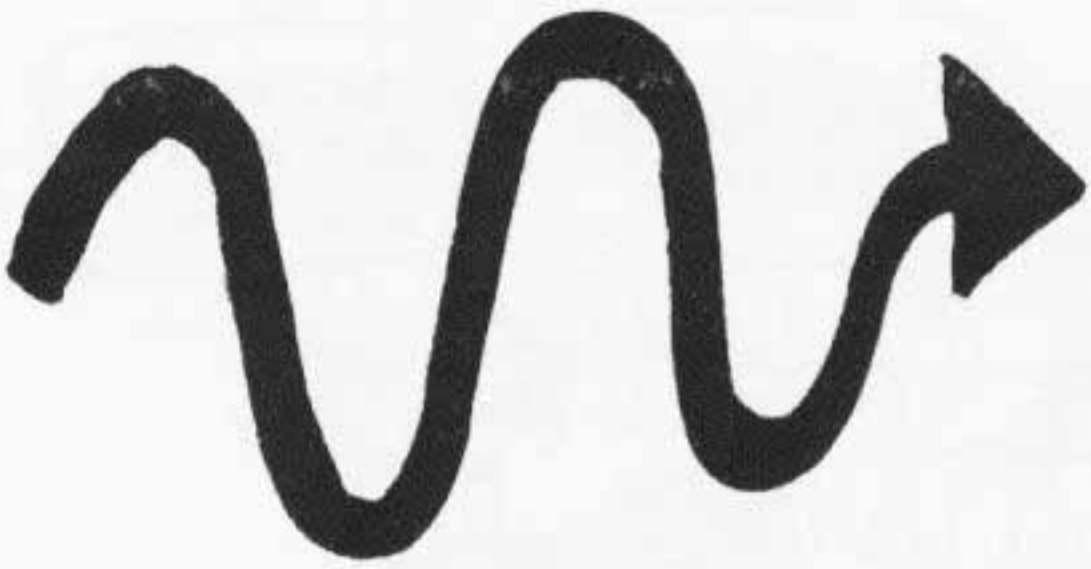
AND IT WORKS ONLY FOR **AC**.



A TRANSFORMER "TRANSFORMS" VOLTAGES UP OR DOWN — AND NO, YOU CAN'T GET SOMETHING FOR NOTHING. THE **POWER** OUTPUT OF THE SECONDARY COIL CAN NOT EXCEED THE POWER INPUT OF THE PRIMARY. IN OTHER WORDS, AS YOU STEP UP THE VOLTAGE, YOU MUST STEP DOWN THE CURRENT.

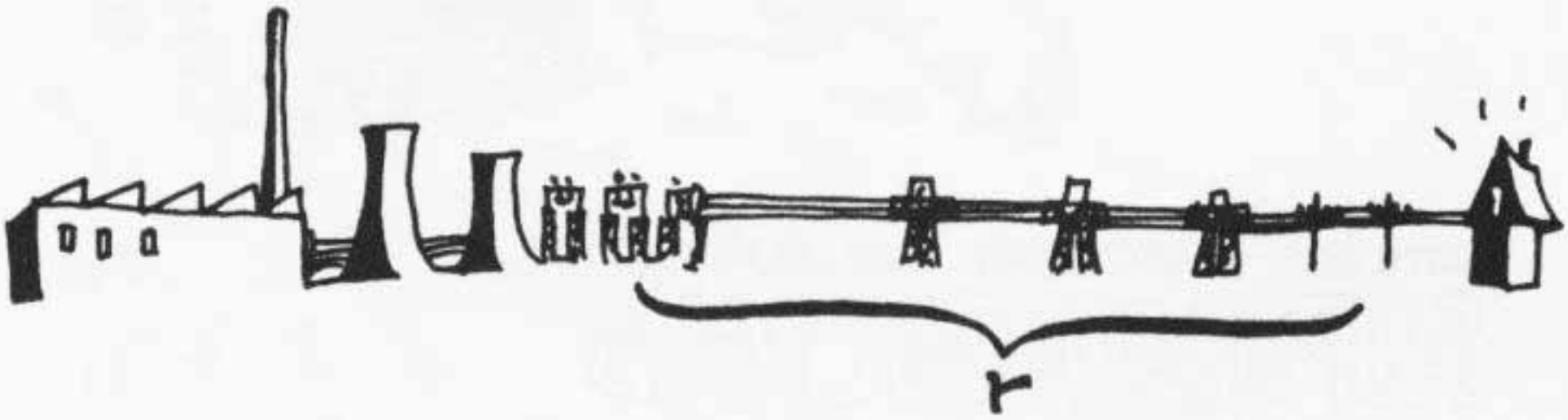
$$P_{OUT} = V_{OUT} i_{OUT} \leq P_{IN} = V_{IN} i_{IN}$$



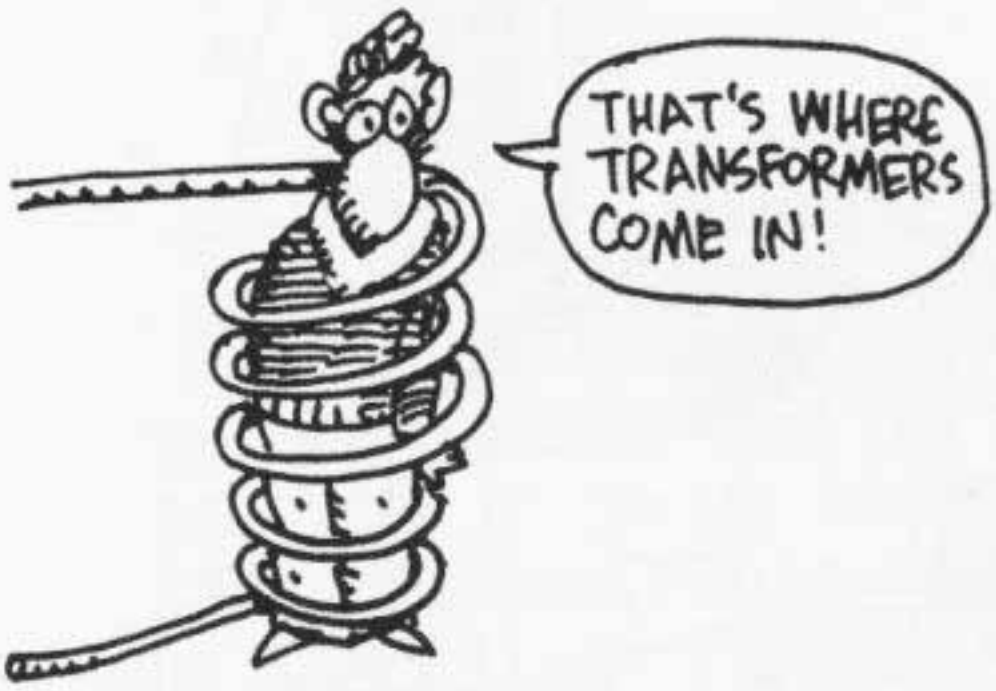


THIS, THEN, IS THE GREAT ADVANTAGE OF ALTERNATING CURRENT: ITS VOLTAGE CAN BE EASILY STEPPED UP OR DOWN.

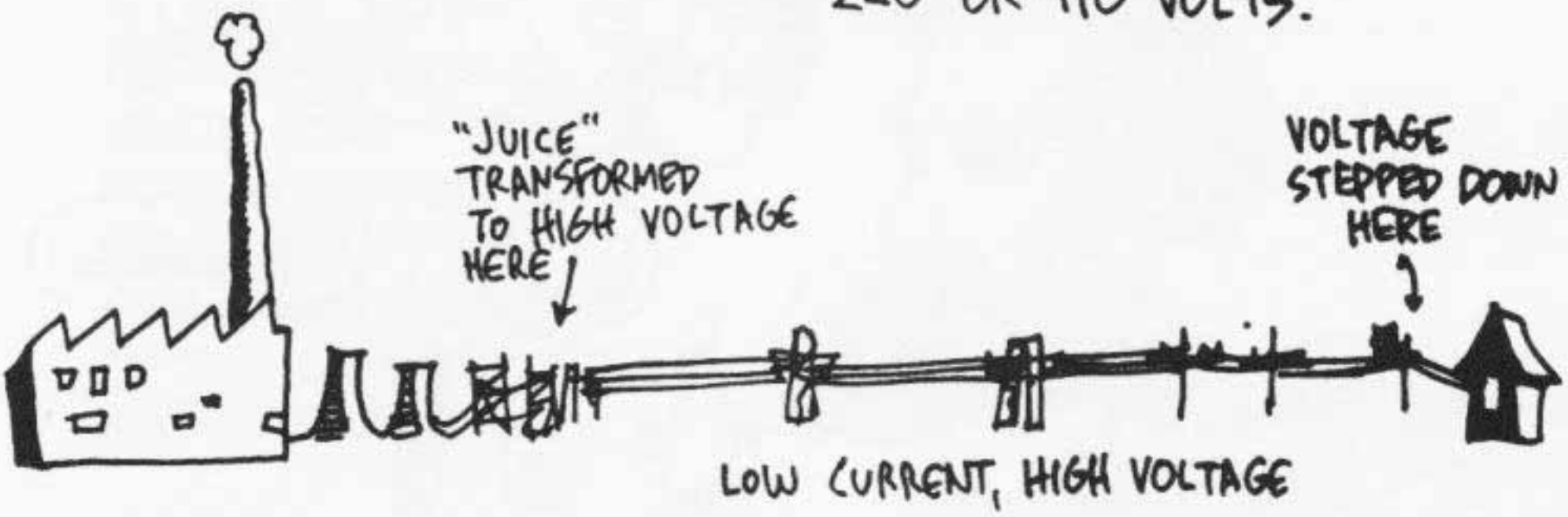
THIS IS ESPECIALLY IMPORTANT BETWEEN POWER GENERATING STATIONS AND THE CUSTOMERS THEY SERVE:



THE TRANSMISSION WIRES HAVE A RESISTANCE **r**, SO THERE IS A VOLTAGE DROP $V = ir$ AND POWER LOSS $P = iV = i^2 r$ ALONG THE LINE. AT HIGH CURRENT **i**, ENORMOUS AMOUNTS OF POWER ARE WASTED.



BY STEPPING UP TO VERY HIGH VOLTAGE (MORE THAN 100,000 VOLTS!) AT THE SOURCE, CURRENT IS REDUCED IN THE WIRES, AND THE POWER LOSS IS MINIMIZED. THEN, AT THE USER'S END, VOLTAGE IS STEPPED DOWN TO A RELATIVELY SAFE 220 OR 110 VOLTS.



OUR HUGE ELECTRIC POWER SYSTEM IS ALL DUE TO THE HUMBLE TRANSFORMER.

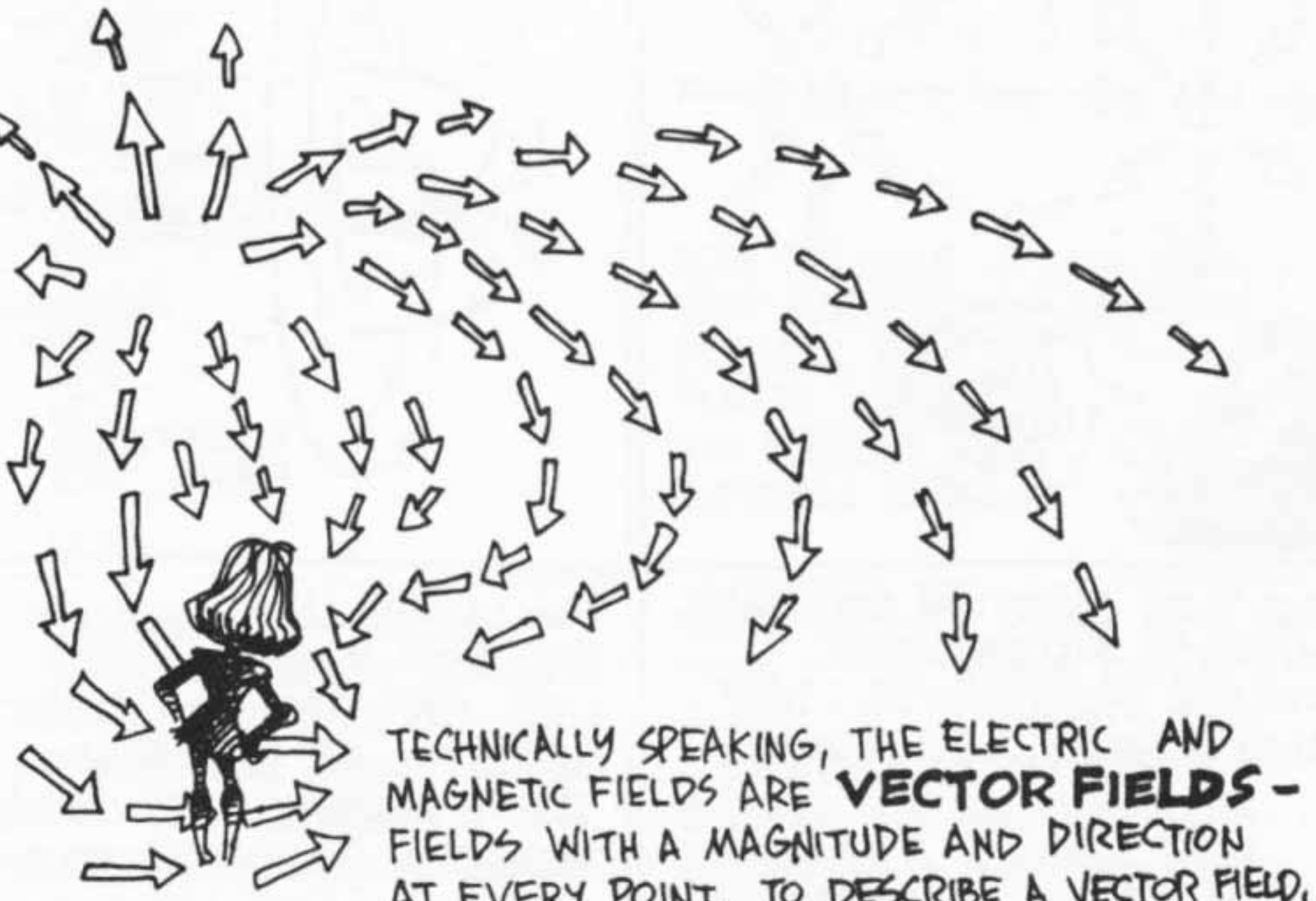
WITH THE INVENTION OF HIGH-TEMPERATURE

SUPERCONDUCTORS

AND HIGH-TECH DEVICES FOR TRANSFORMING DC VOLTAGES, WE MAY SEE SOME DC POWER LINES IN COMING DECADES.

◊CHAPTER 23◊

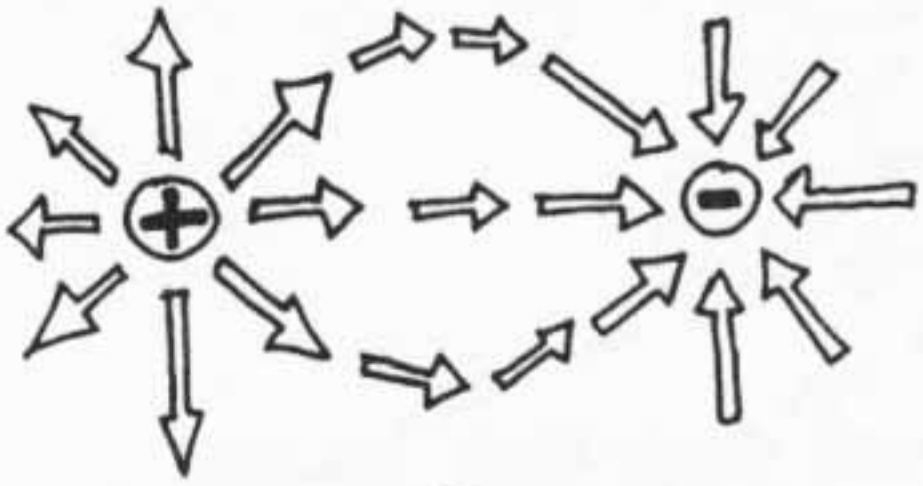
MAXWELL'S EQUATIONS AND LIGHT (AND HOW!)



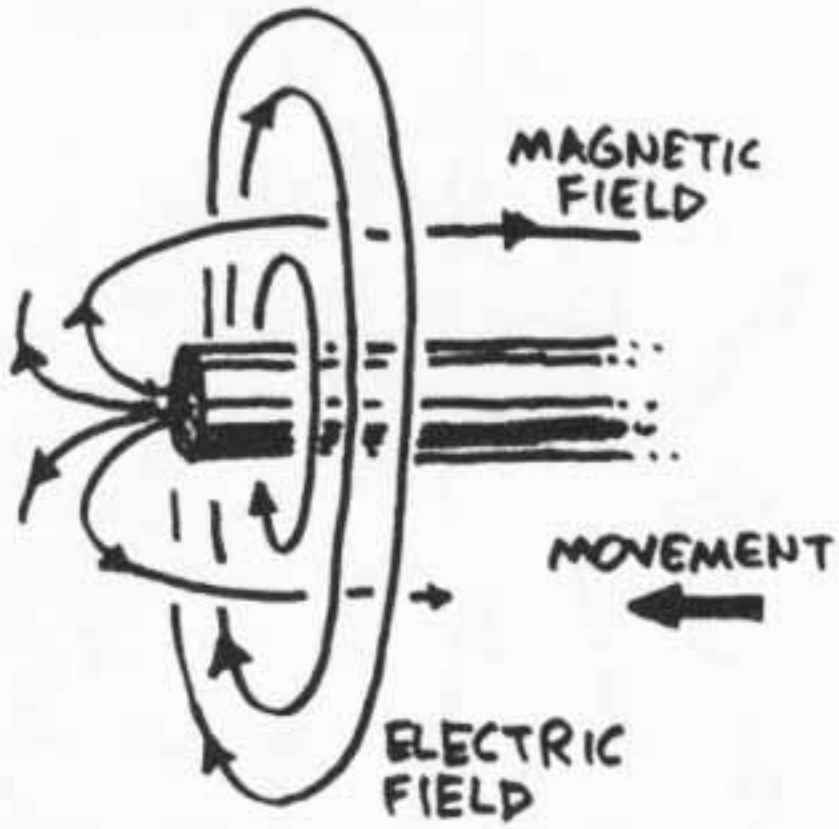
TECHNICALLY SPEAKING, THE ELECTRIC AND MAGNETIC FIELDS ARE **VECTOR FIELDS** - FIELDS WITH A MAGNITUDE AND DIRECTION AT EVERY POINT. TO DESCRIBE A VECTOR FIELD, YOU MUST SPECIFY HOW THE FIELD SPREADS OUT, OR **DIVERGES**, AND HOW IT CIRCLES AROUND, OR **CURLS**. (DIVERGENCE AND CURL ARE MATHEMATICAL TERMS.)

IN 1873, JAMES CLERK **MAXWELL** WROTE DOWN FOUR EQUATIONS WHICH SPECIFY THE CURL AND DIVERGENCE OF THE ELECTRIC AND MAGNETIC FIELDS.

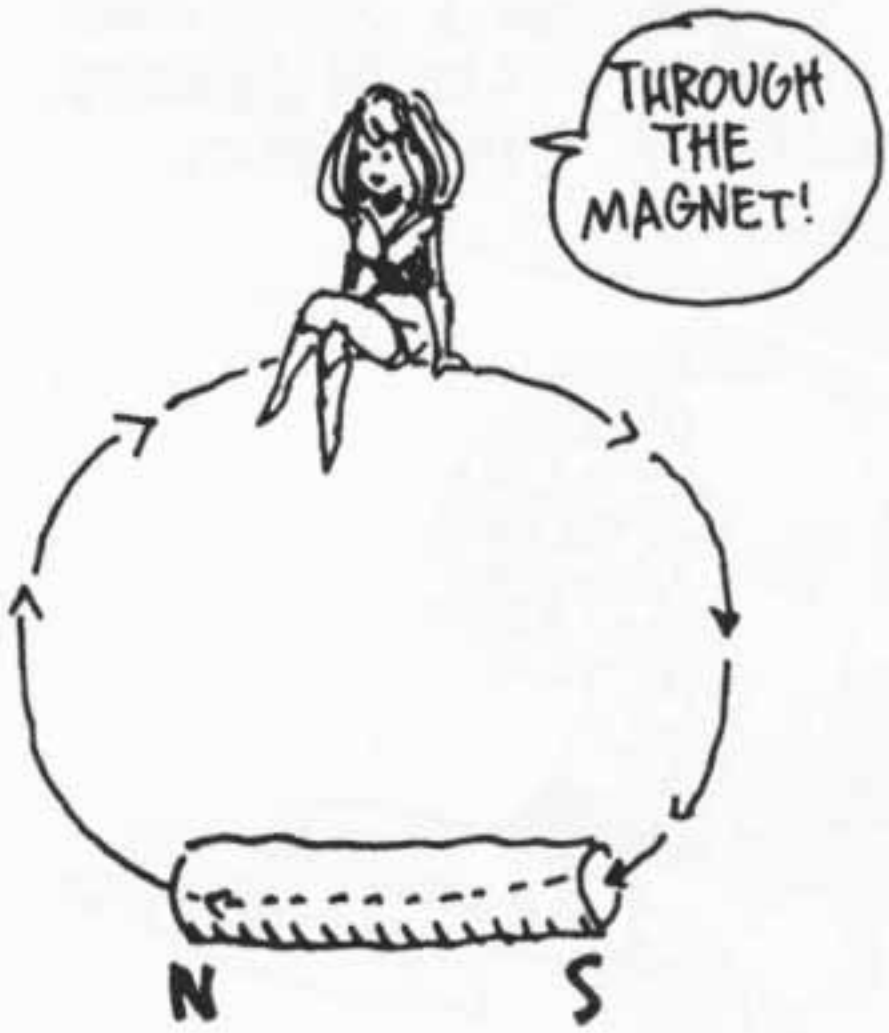
MAXWELL'S FIRST EQUATION IS GAUSS'S LAW. IT SAYS THAT ELECTRIC FIELD LINES **DIVERGE** FROM POSITIVE CHARGES AND **CONVERGE** TO NEGATIVE CHARGES.



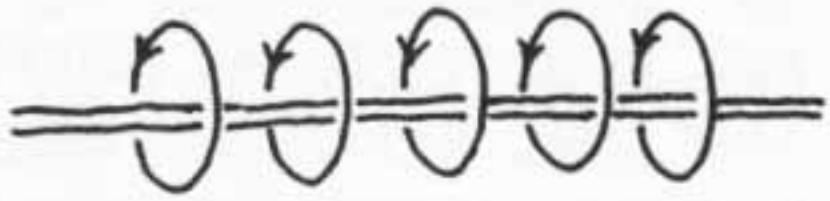
THE SECOND EQUATION IS FARADAY'S LAW: ELECTRIC FIELD LINES **CURL** AROUND CHANGING MAGNETIC FIELDS. CHANGING MAGNETIC FIELDS INDUCE ELECTRIC FIELDS.



THE THIRD EQUATION SAYS THAT MAGNETIC FIELDS NEVER DIVERGE OR CONVERGE. THEY ALWAYS GO IN CLOSED CURVES.



FINALLY, THE LAST EQUATION SAYS THAT MAGNETIC FIELD LINES **CURL** AROUND ELECTRIC CURRENTS. WE HAVE SEEN THAT A MAGNETIC FIELD CIRCLES AROUND A CONDUCTING WIRE.



...AND HERE MAXWELL HAD A CRITICAL BRAINSTORM! (AN ELECTRICAL STORM, OF COURSE!)

AS YOU SEE, THE EQUATIONS EXPRESS LAWS THAT CAME TO MAXWELL FROM OTHER SOURCES. BUT MAXWELL'S GENIUS WAS TO SEE THAT LAW #4 WAS INCOMPLETE.

CONSIDER A CAPACITOR BEING CHARGED. AS THE CURRENT FLOWS TO THE CAPACITOR PLATES, A MAGNETIC FIELD RINGS THE WIRE. BUT WHAT ABOUT BETWEEN THE PLATES?

NO MAGNETIC FIELD HERE?

DOES THE FIELD STOP ABRUPTLY BETWEEN THE PLATES, WHERE THE CURRENT STOPS? MAXWELL SAID—

MAXWELL FELT THAT NATURE DISLIKES DISCONTINUITIES. ALSO, HE REASONED THAT IF CHANGING MAGNETIC FIELDS INDUCE ELECTRIC FIELDS (FARADAY), THEN, SYMMETRICALLY, CHANGING ELECTRIC FIELDS MIGHT INDUCE MAGNETIC FIELDS. THERE WAS NO EVIDENCE FOR THIS, OF COURSE, BUT...

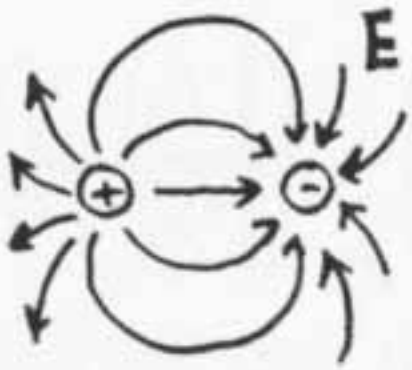
THUS, MAXWELL ADDED AN EXTRA TERM TO HIS FOURTH EQUATION, SAYING THAT MAGNETIC FIELDS ALSO **CURL** AROUND CHANGING ELECTRIC FIELDS. THIS TERM GENERATES A MAGNETIC FIELD BETWEEN THE CAPACITOR PLATES AS THE ELECTRIC FIELD BUILDS UP.

SOME YEARS LATER, THIS MAGNETIC FIELD WAS DETECTED.

SO, WITHOUT FURTHER ADO, HERE ARE

MAXWELL'S EQUATIONS

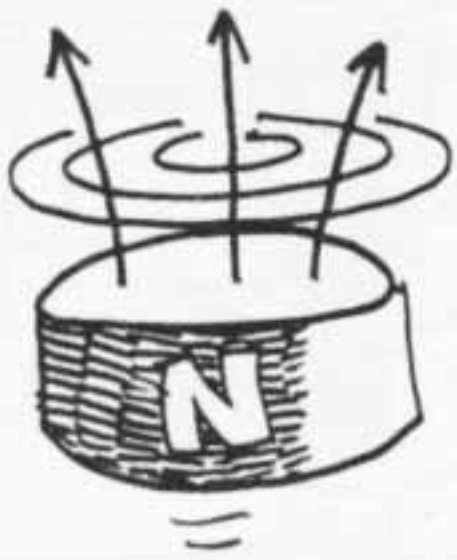
IN FULL-BLOWN MATHEMATICAL NOTATION TO THRILL AND INTIMIDATE YOU!

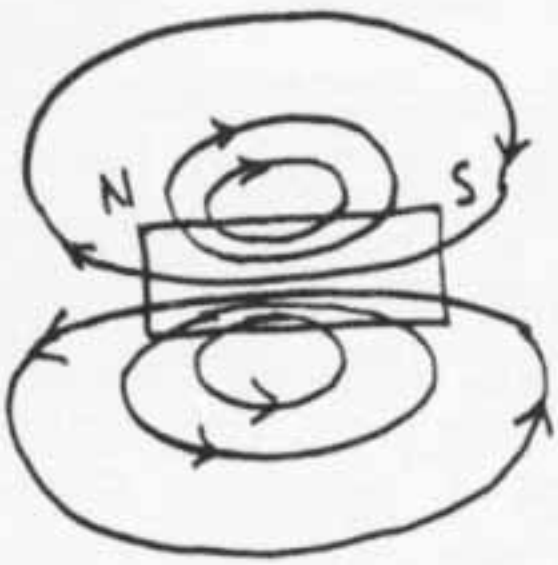


$\nabla \cdot \mathbf{E} = 4\pi\rho$ (ρ, GREEK "RHO" = CHARGE DENSITY; $\mathbf{E}$ = ELECTRIC FIELD) SAYS $\mathbf{E}$ DIVERGES OUTWARD FROM PLUS CHARGES AND INWARD TO MINUS CHARGES.

$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{d\mathbf{B}}{dt}$ ($\mathbf{B}$ = MAGNETIC FIELD)

SAYS $\mathbf{E}$ CURLS AROUND CHANGING $\mathbf{B}$ FIELDS.
(c = SPEED OF LIGHT)

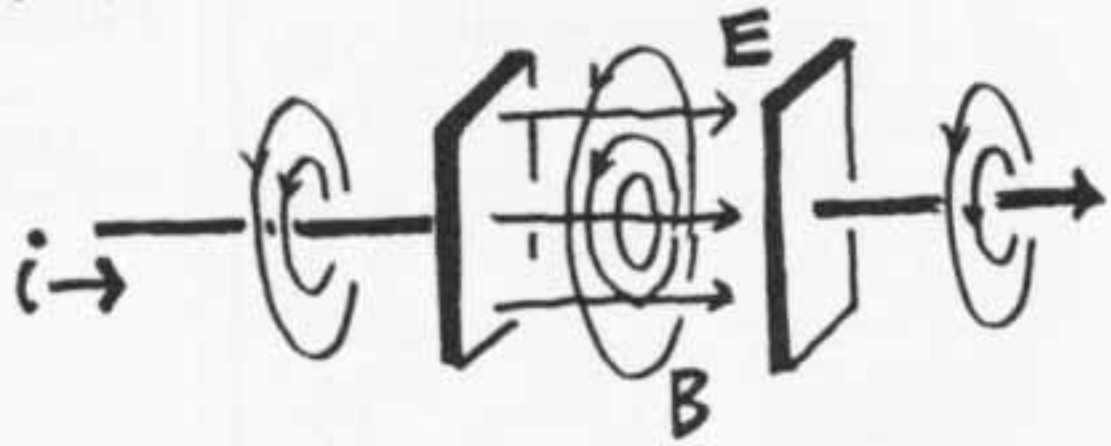




$\nabla \cdot \mathbf{B} = 0$ SAYS $\mathbf{B}$ NEVER DIVERGES, ALWAYS LOOPS AROUND.

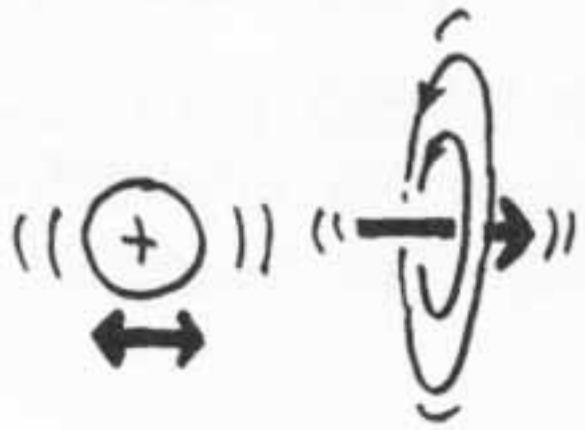
$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{d\mathbf{E}}{dt}$

SAYS $\mathbf{B}$ CURLS AROUND CURRENTS ($\mathbf{J}$ = CURRENT DENSITY) AND CHANGING $\mathbf{E}$ FIELDS.



THAT ONE LITTLE TERM ADDED TO MAXWELL'S FOURTH EQUATION HAD AN UNEXPECTED PAYOFF — AND A BIG ONE.

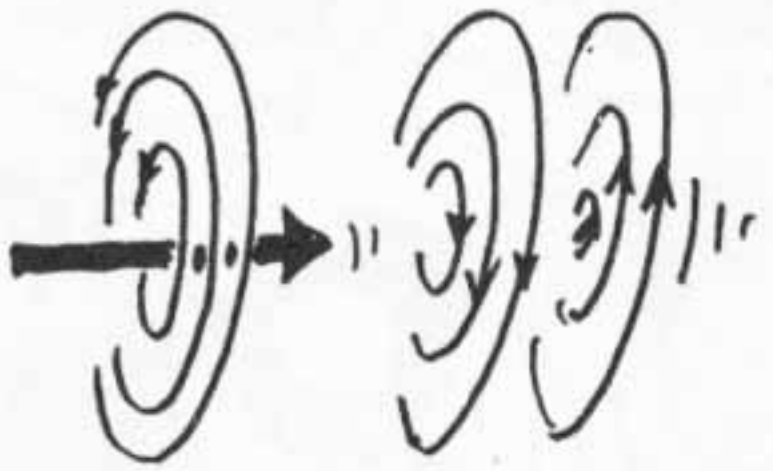
IMAGINE A SINGLE ELECTRIC CHARGE BEING **VIBRATED**:



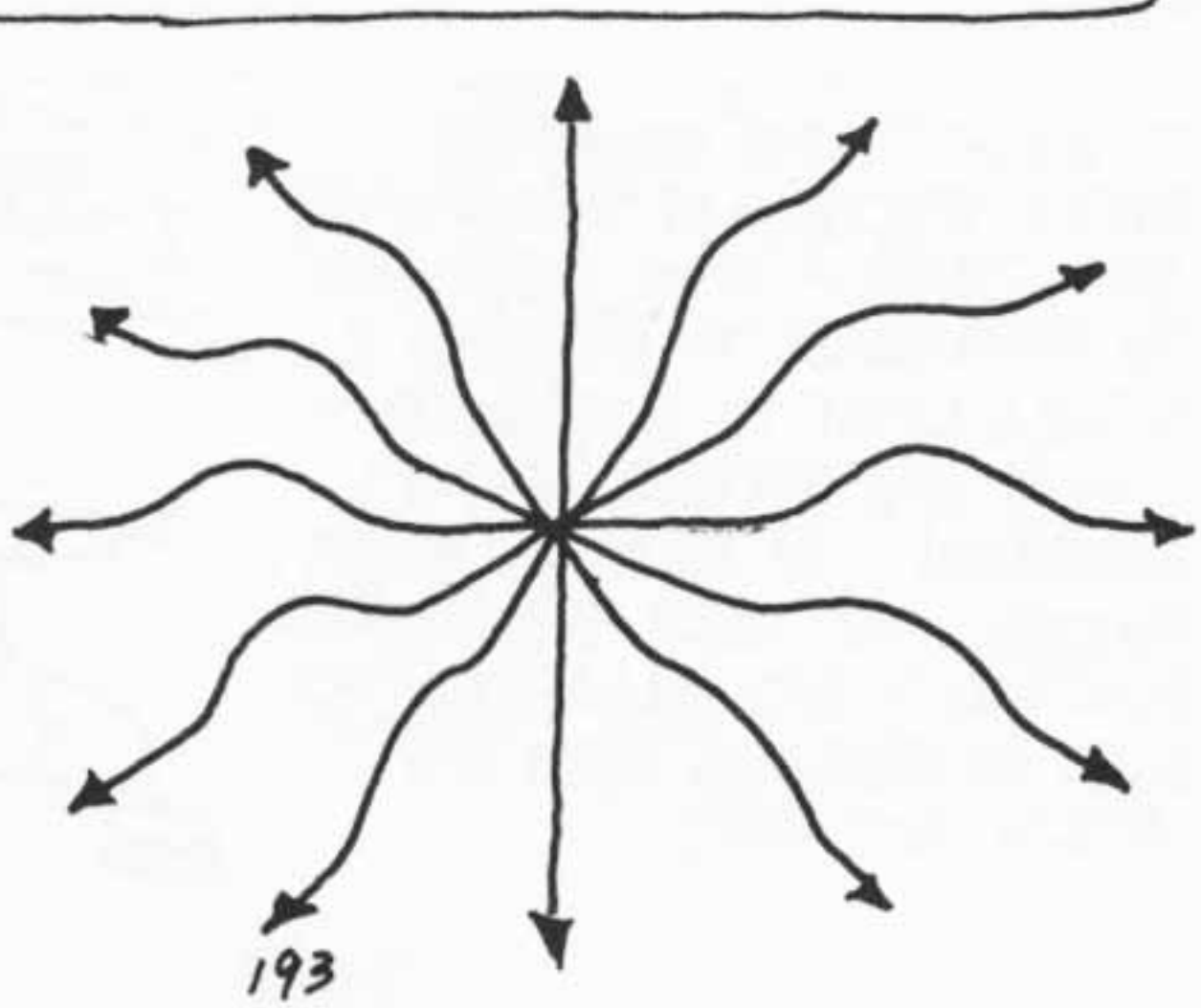
IN THE SPACE NEAR THE VIBRATING CHARGE, THE CHARGE'S ELECTRIC FIELD IS CHANGING, SO IT INDUCES A MAGNETIC FIELD CURLING AROUND IT.

BUT THE MAGNETIC FIELD IS ALSO CHANGING — SO IT INDUCES MORE ELECTRIC FIELD, WHICH INDUCES MORE MAGNETIC FIELD...

ETC.!



THE RESULT IS A WAVE OF FIELDS RIPPLING OUT FROM THE VIBRATING CHARGE — AT THE SPEED OF LIGHT, ACCORDING TO MAXWELL'S CALCULATIONS!



MAXWELL HAD A FLASH OF ILLUMINATION! **LIGHT** ITSELF, HE HYPOTHESIZED, IS SUCH AN **ELECTRO-MAGNETIC WAVE.**

SOON AFTERWARD, HERTZ AND OTHERS DID INDEED PRODUCE LONG ELECTROMAGNETIC WAVES FROM WIGGLING CHARGES— AND DETECTED THEM AT A DISTANCE FROM THE SOURCE!

IT WASN'T LONG BEFORE A WHOLE SPECTRUM OF THESE WAVES WAS FOUND — FROM RADIO WAVES TO MICROWAVES TO INFRARED TO VISIBLE LIGHT TO ULTRAVIOLET TO X-RAYS AND NUCLEAR GAMMA RADIATION. IN FOUR EQUATIONS, MAXWELL NOT ONLY SUMMARIZED ELECTRICITY AND MAGNETISM, BUT ALSO ENCOMPASSED LIGHT AND OPTICS! NOT BAD!!

·CHAPTER 24·
QUANTUM ELECTRODYNAMICS

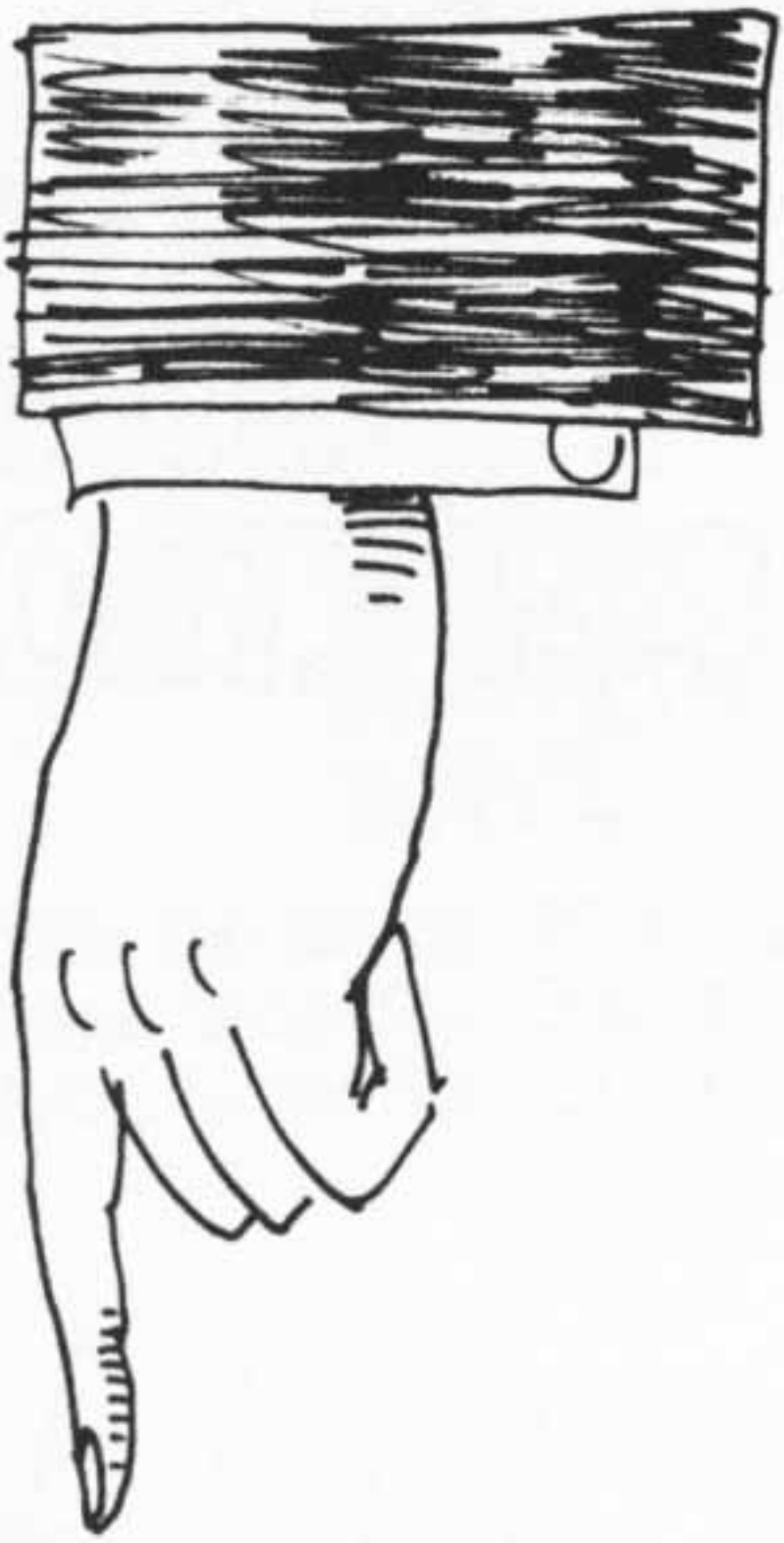
NOW WE'RE GOING TO FIND OUT WHAT CHARGE "REALLY IS."

WE SAW THAT ELECTROMAGNETIC THEORY ALREADY CONTAINS RELATIVITY (SEE P. 176). WHEN QUANTUM MECHANICS IS ADDED, THE THEORY BECOMES KNOWN AS

QUANTUM ELECTRO-DYNAMICS

(OR **QED**).

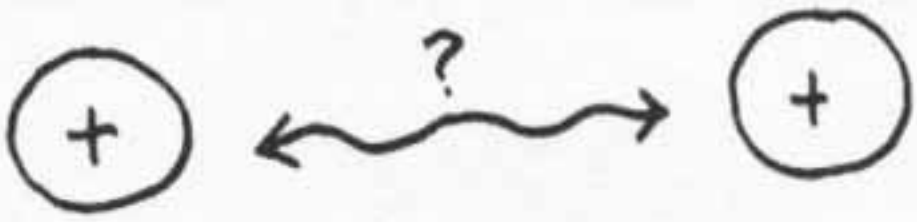
TO DISCUSS THIS, WE HAVE TO SAY A LITTLE ABOUT QUANTUM MECHANICS, THE STRANGE SYSTEM THAT PHYSICS NOW USES TO DESCRIBE THE WORLD. AMONG ITS STRANGER IDEAS ARE THESE:



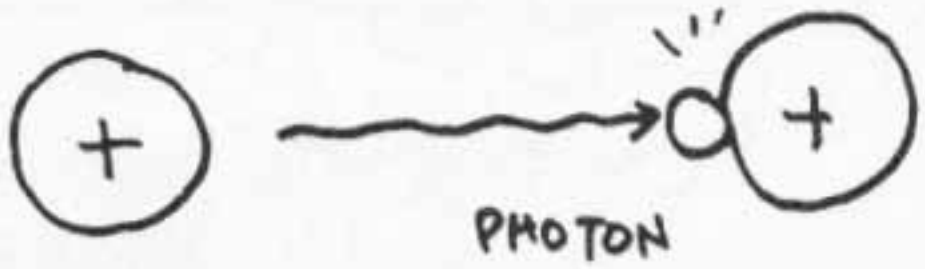
* **LIGHT** IS MADE UP OF MASSLESS PARTICLES CALLED **PHOTONS**. THIS IS O.K., BECAUSE PARTICLES CAN ACT LIKE WAVES.

* NATURE IS INHERENTLY **UNCERTAIN**. IN PARTICULAR, IT IS IMPOSSIBLE TO SPECIFY A PARTICLE'S PRECISE MOMENTUM AND POSITION AT THE SAME TIME.

SO LET'S GO BACK TO THE POINT WHERE TWO POSITIVE CHARGES WERE REPELLING EACH OTHER. WE WONDERED HOW THE ELECTRIC FORCE GETS ACROSS SPACE?

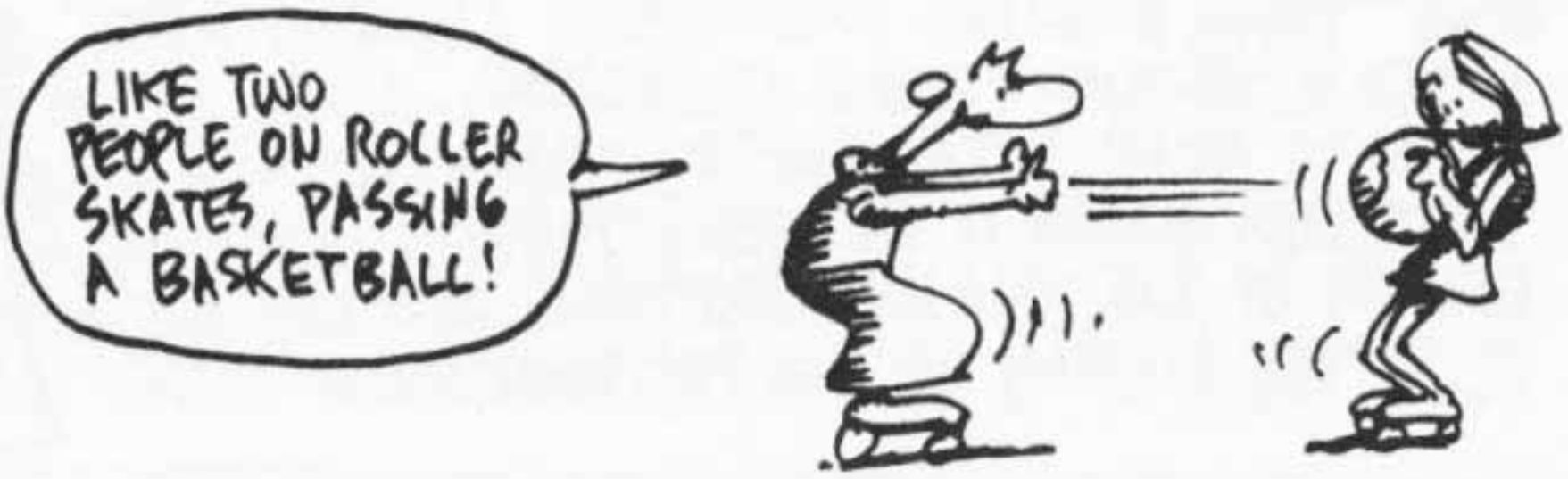


QUANTUM ELECTRODYNAMICS SAYS THAT THE FORCE IS CAUSED BY PARTICLES PASSING BETWEEN THE CHARGES — PARTICLES OF LIGHT, OR **PHOTONS**. THESE PHOTONS HAVE ENERGY BUT NO MASS, AND THEY TRAVEL AT THE SPEED OF LIGHT.

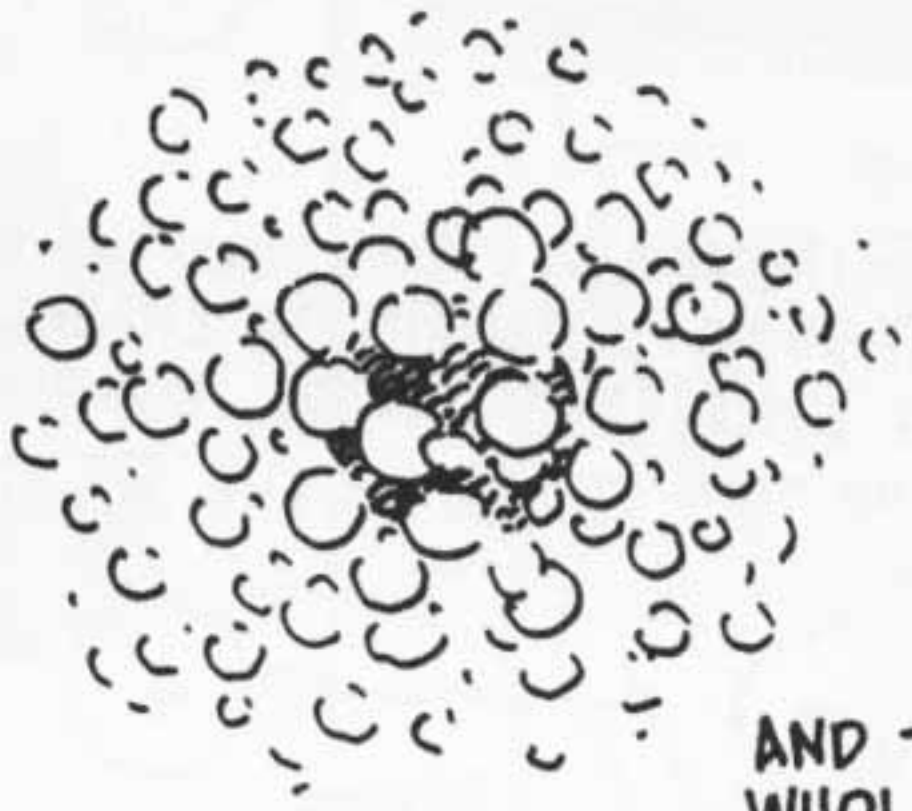


THE STRANGE PART IS THAT THESE ARE NOT "REAL" PHOTONS LIKE THE ONES YOU SEE WITH YOUR EYES, BUT **VIRTUAL** PHOTONS — A SORT OF GHOSTLIKE PARTICLE THAT VIOLATES THE CONSERVATION OF ENERGY AND "EXISTS" FOR ONLY A LIMITED TIME.

THE FORCE IS QUANTUM MECHANICAL IN NATURE, BUT A CLASSICAL ANALOGY IS THAT WHEN ONE CHARGE EJECTS A PHOTON, IT RECOILS SLIGHTLY. WHEN THE OTHER CHARGE CATCHES IT, IT ALSO RECOILS. THE NET EFFECT OF MANY SUCH EXCHANGES IS A REPULSIVE FORCE!



WHAT ABOUT THESE "VIRTUAL" PHOTONS? EVEN A SINGLE CHARGE HAS A CLOUD OF VIRTUAL PHOTONS AROUND IT. THE CHARGE CONSTANTLY CREATES, EJECTS, AND ABSORBS VIRTUAL PHOTONS.

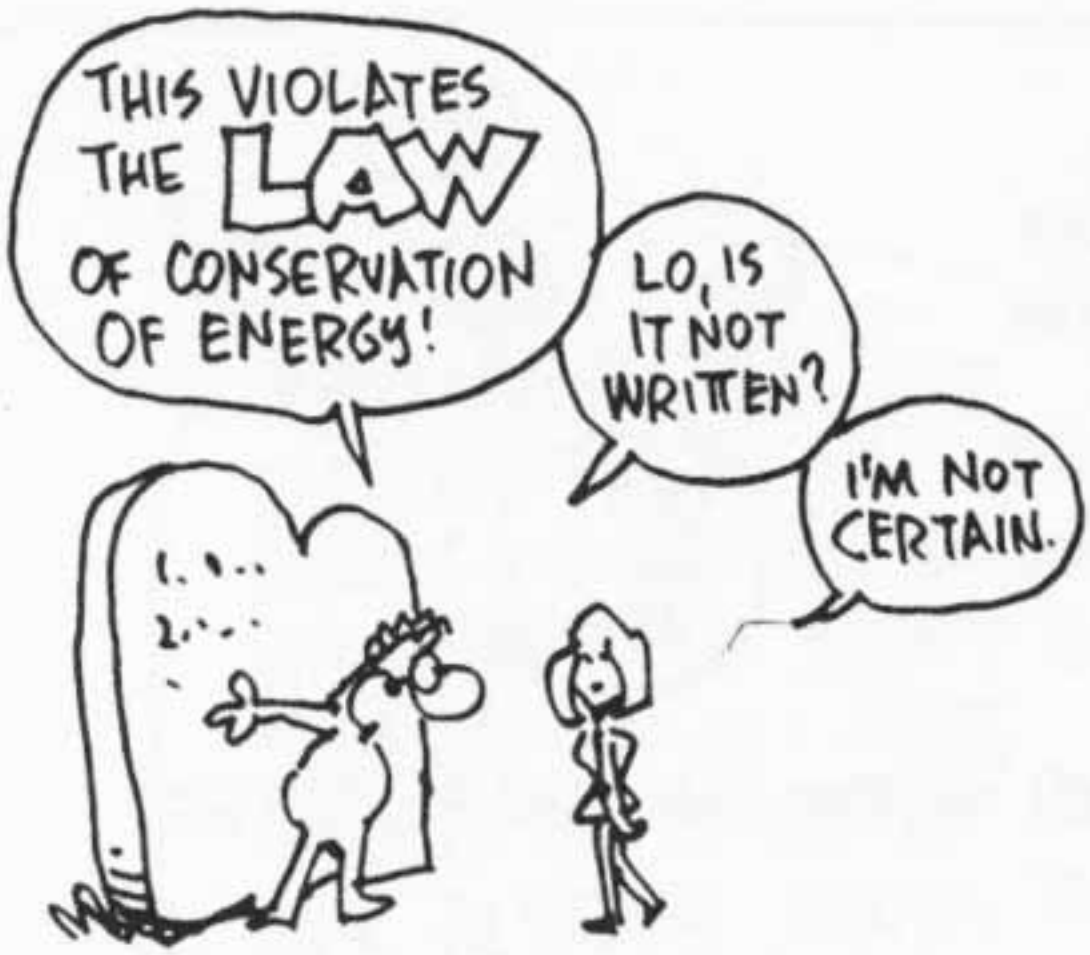


AND THIS IS THE WHOLE **QED** PICTURE (ALMOST!).

CHARGE IS JUST THE ABILITY TO MAKE VIRTUAL PHOTONS!

* * * * * * * * * *
AND THE ELECTRIC FIELD **IS** NOTHING BUT THE VIRTUAL PHOTON CLOUD!
* * * * * * * * * *

THE STRANGEST PART OF THIS, OF COURSE, IS THAT THE VIRTUAL PHOTONS COME "FROM NOWHERE." THAT IS, AFTER A VIRTUAL PHOTON IS CREATED, THERE IS MORE TOTAL ENERGY THAN THERE WAS BEFORE IT EXISTED: THE ENERGY OF THE ORIGINAL PARTICLE PLUS THE ENERGY OF THE PHOTON.

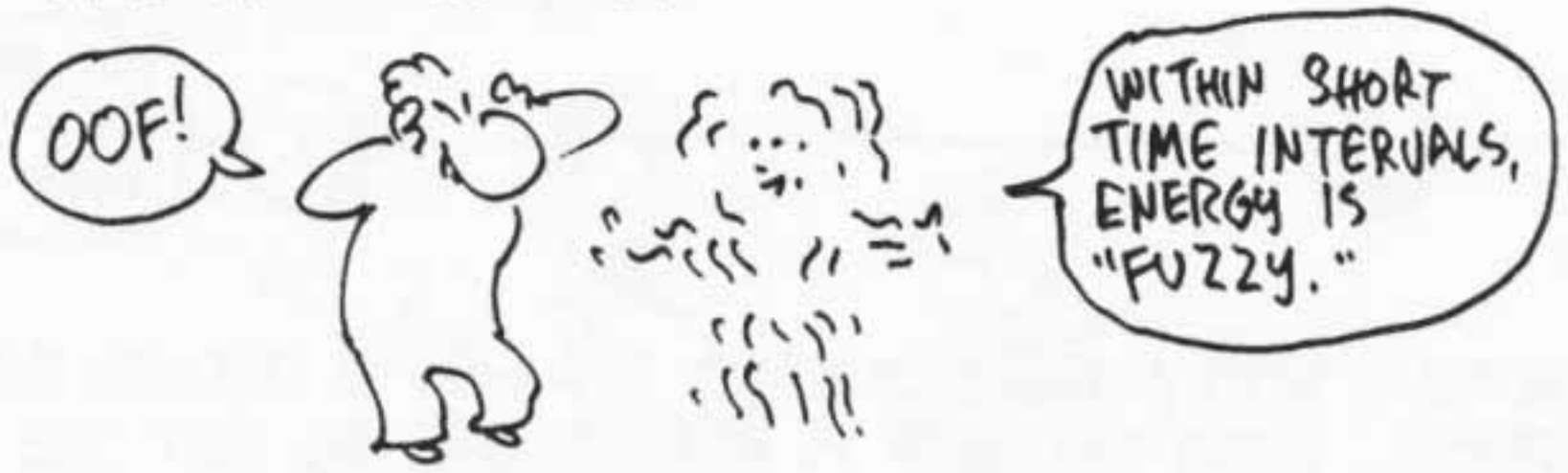


THIS IS WHERE QUANTUM UNCERTAINTY COMES IN.

ONE FORM OF THE

UNCERTAINTY PRINCIPLE

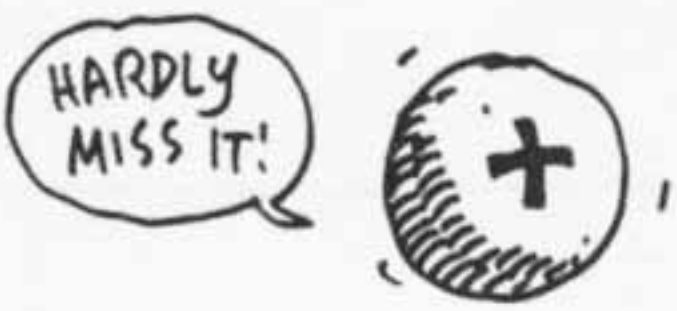
IS THIS: YOU CANNOT MAKE AN EXACT DETERMINATION OF ENERGY AND TIME SIMULTANEOUSLY.



THIS MEANS THAT THE ENERGY ACCOUNT CAN BE UNBALANCED — BUT ONLY FOR A TIME. A LARGE ENERGY DEFICIT MUST BE MADE UP IN A VERY SHORT TIME, WHILE A SMALL DEFICIT CAN "SIT" FOR A WHILE. (MATHEMATICALLY, $\Delta E \cdot \Delta t \geq h$: THE PRODUCT OF THE ENERGY VIOLATION TIMES THE TIME OF THE VIOLATION CAN'T BE LESS THAN A CERTAIN SMALL NUMBER h.)

IN OTHER WORDS, A VERY ENERGETIC VIRTUAL PHOTON, ONE WITH A LARGE KICK, CAN'T GET FAR, EVEN AT THE SPEED OF LIGHT, BUT MUST BE REABSORBED QUICKLY TO BALANCE THE ENERGY...

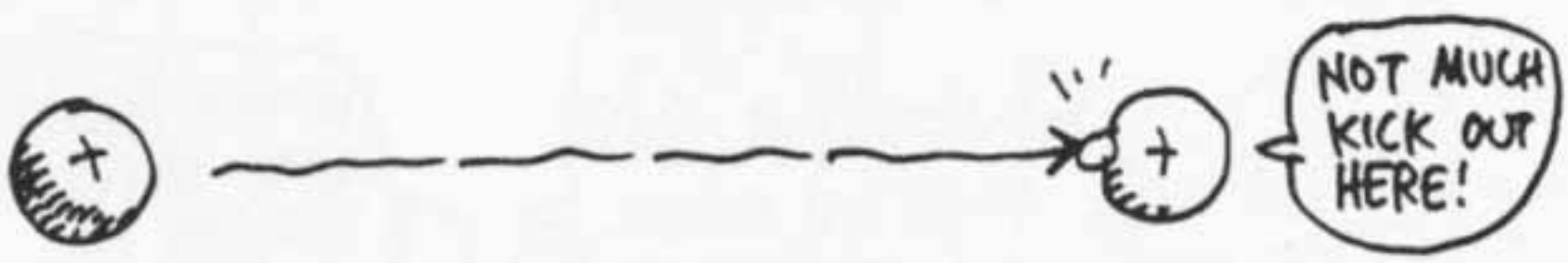
WHEREAS A LOW-ENERGY PHOTON CAN TRAVEL FARTHER.



THE SMALL ENERGY VIOLATION CAN BE TOLERATED LONGER.

THIS EXPLAINS WHY THE ELECTRIC FORCE

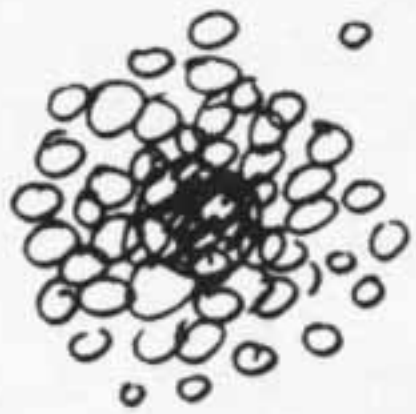
GROWS WEAKER WITH DISTANCE!



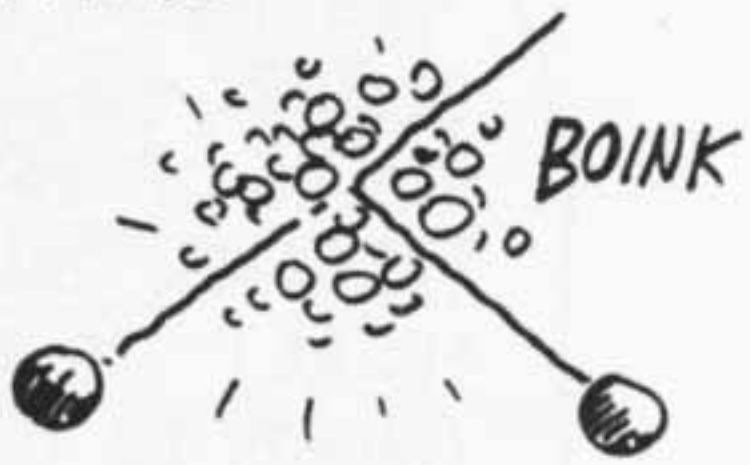
PHOTONS WITH A BIG KICK CAN'T GET FAR TO DELIVER THEIR ENERGY. WHEN THE MATH IS WORKED OUT, WE GET THE FAMILIAR INVERSE-SQUARE LAW OF CLASSICAL PHYSICS. AND THERE'S NO LOWER LIMIT ON THE ENERGY OF A VIRTUAL PHOTON. A VERY LOW-ENERGY ONE CAN LAST FOR YEARS, AND TRAVEL LIGHT-YEARS. THE RANGE OF THE ELECTRIC FORCE IS UNLIMITED!

WAIT!!
THIS THEORY SAYS THAT ELECTRIC FIELDS ARE CLOUDS OF VIRTUAL PHOTONS— PARTICLES THAT AREN'T EVEN "REAL!" IF ALL THESE GHOSTS DO IS EXPLAIN WHAT WE ALREADY KNOW, THEN **WHAT GOOD ARE THEY?**
HOW DO WE KNOW THEY ARE "REALLY THERE?"

THERE IS A WAY TO MAKE VIRTUAL PHOTONS REAL! HERE'S A CHARGE IN ITS CLOUD OF VIRTUAL PHOTONS:

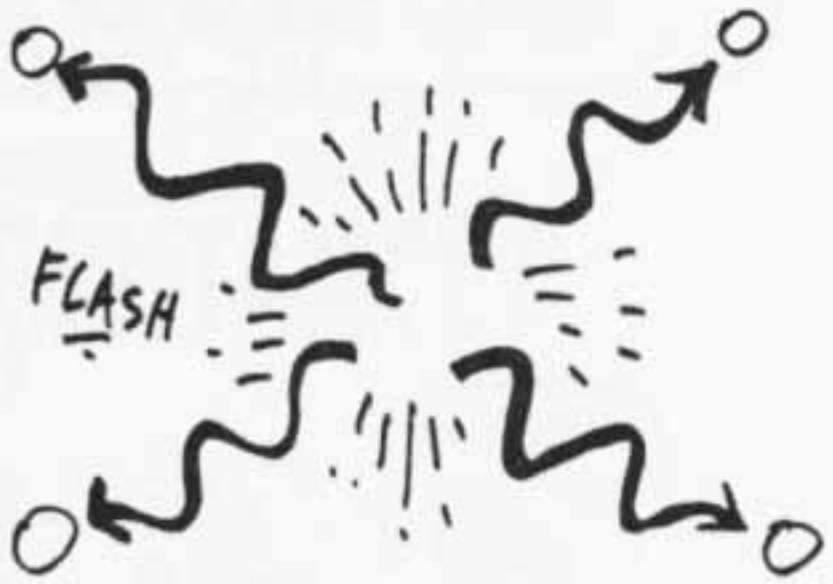


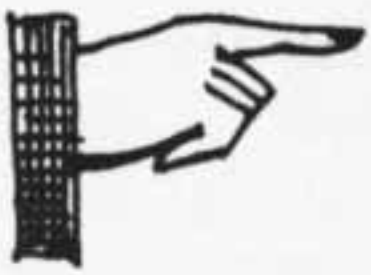
SUPPOSE WE KNOCK THE CHARGE AWAY FROM ITS VIRTUAL PHOTONS, SAY BY HITTING IT WITH ANOTHER PARTICLE.



THE VIRTUAL PHOTONS ARE ORPHANED, WITHOUT THEIR SOURCE CHARGE TO REABSORB THEM!

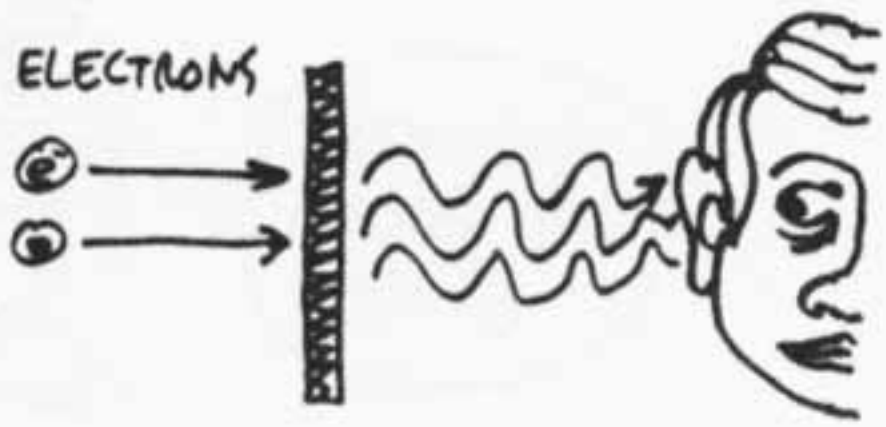
SO THEY BECOME REAL, FLYING AWAY WITH THE ENERGY PICKED UP FROM THE COLLISION.



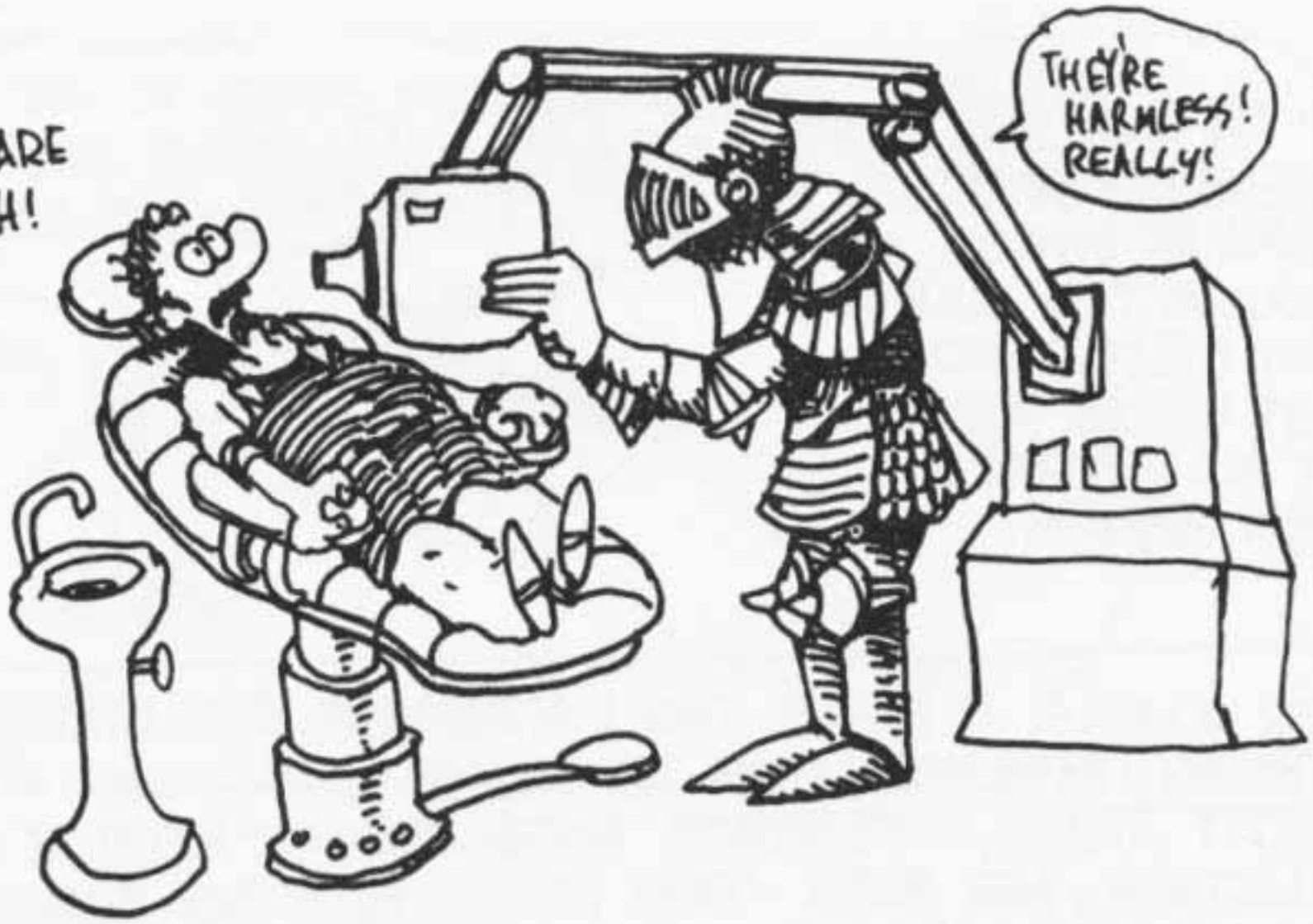


IF WE SHAKE OR MOVE A CHARGE, REAL PHOTONS SHOULD COME FLYING OUT!

THIS IS HOW X-RAYS ARE MADE: SHOOT ELECTRONS INTO A HEAVY METAL, WHERE THEY ARE JERKED TO A STOP. THEIR VIRTUAL PHOTONS FLY OUT AS REAL X-RAYS.



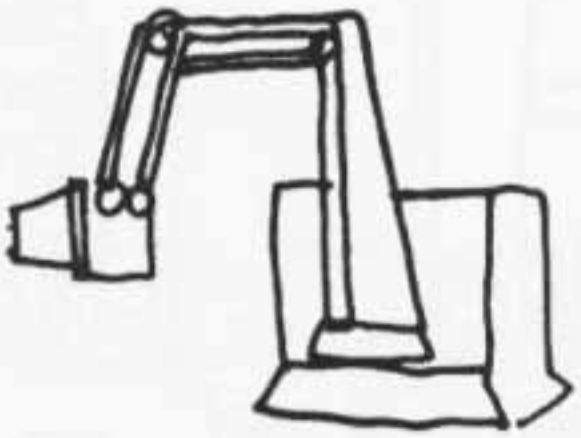
AND X-RAYS ARE REAL ENOUGH!



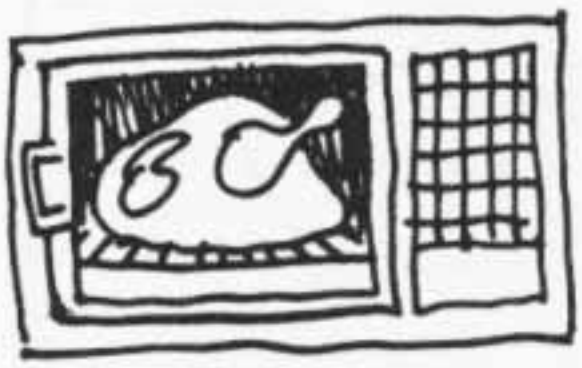
THE PHOTONS NEEDN'T BE X-RAYS. A RADIO TRANSMITTER JIGGLES ELECTRONS, SHAKING OFF PHOTONS, WHICH YOU PICK UP WITH YOUR RECEIVER. IN A LIGHT BULB, ELECTRONS IN THE HOT FILAMENT SHAKE OFF VISIBLE LIGHT PHOTONS. AS WE HAVE SEEN FROM THE CLASSICAL THEORY, WHENEVER A CHARGE IS ACCELERATED, AN ELECTROMAGNETIC WAVE — VIRTUAL PHOTONS MADE REAL — RADIATE OUT. MOST OF THE FAMILIAR SOURCES OF RADIATION SHAKE THEIR PHOTONS OUT OF THE VIRTUAL CLOUDS OF CHARGES.

FIRE

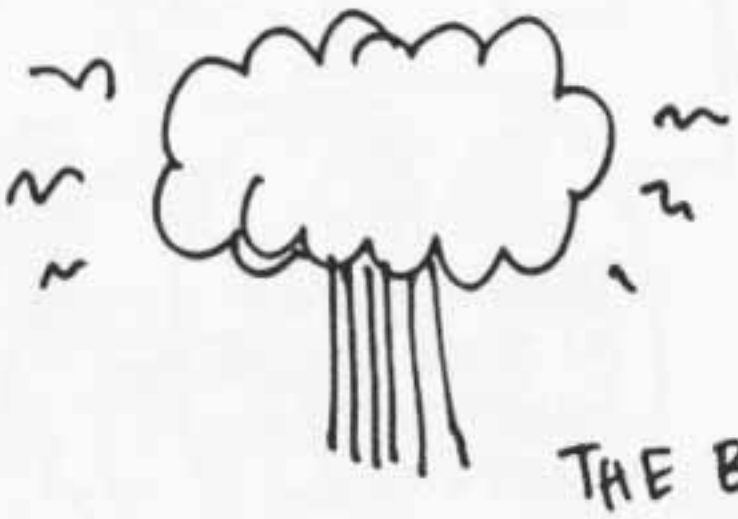
FIREFLY



X-RAYS



MICROWAVES



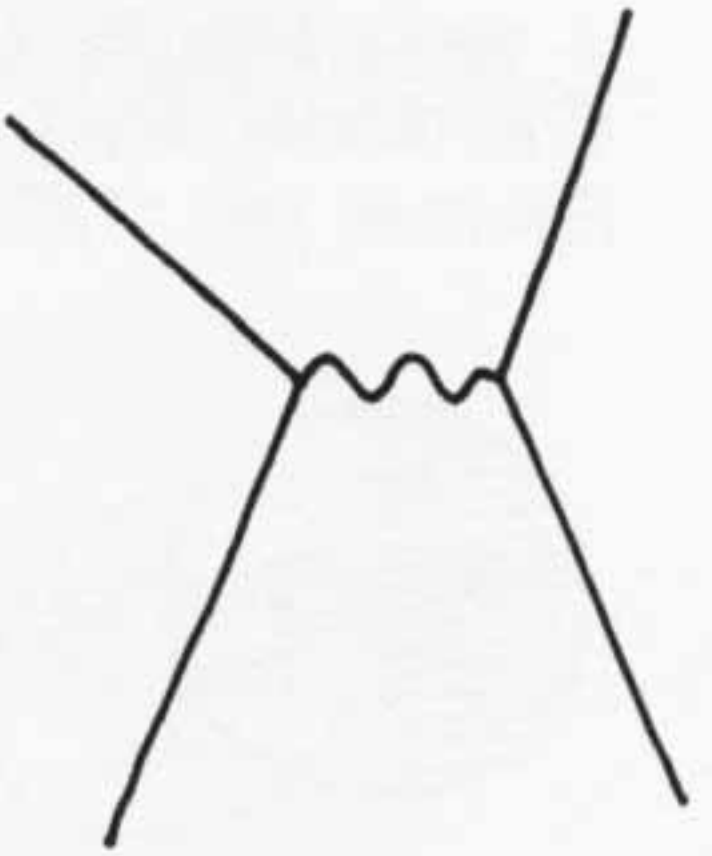
THE BOMB

IF THE QUANTUM THEORY PREDICTED ONLY FAMILIAR EFFECTS, IT WOULDN'T BE MUCH TO GET EXCITED ABOUT. BUT IT DOES MORE: IT ALSO PREDICTS NEW RESULTS.

FOR EXAMPLE, IT IMPLIES TINY DISCREPANCIES FROM THE CLASSICAL THEORY: DEVIATIONS FROM THE INVERSE-SQUARE LAW AT VERY SHORT RANGE, DIFFERENCES IN THE MAGNETIC FIELD OF THE ELECTRON, AND MORE. THESE EFFECTS HAVE BEEN CONFIRMED BY DELICATE EXPERIMENTS, GIVING US CONFIDENCE THAT WE NOW HAVE THE CORRECT THEORY OF THE ELECTROMAGNETIC FORCE.

THE WHOLE IDEA OF FORCES BEING CARRIED BY "EXCHANGE PARTICLES" LIKE PHOTONS HAS BEEN BROADLY EXTENDED IN PHYSICS. THE PHYSICIST'S MOTTO:

THE **STRONG** NUCLEAR FORCE, WHICH BINDS PROTONS TOGETHER IN THE NUCLEUS, IS NOW DESCRIBED BY AN EXCHANGE OF PARTICLES CALLED **MESONS**. THE **WEAK** NUCLEAR FORCE HAS BEEN UNIFIED TO THE ELECTROMAGNETIC FORCE BY THEORIZING, AND THEN FINDING, "BROTHERS" OF THE PHOTON THAT CARRY THE FORCE.

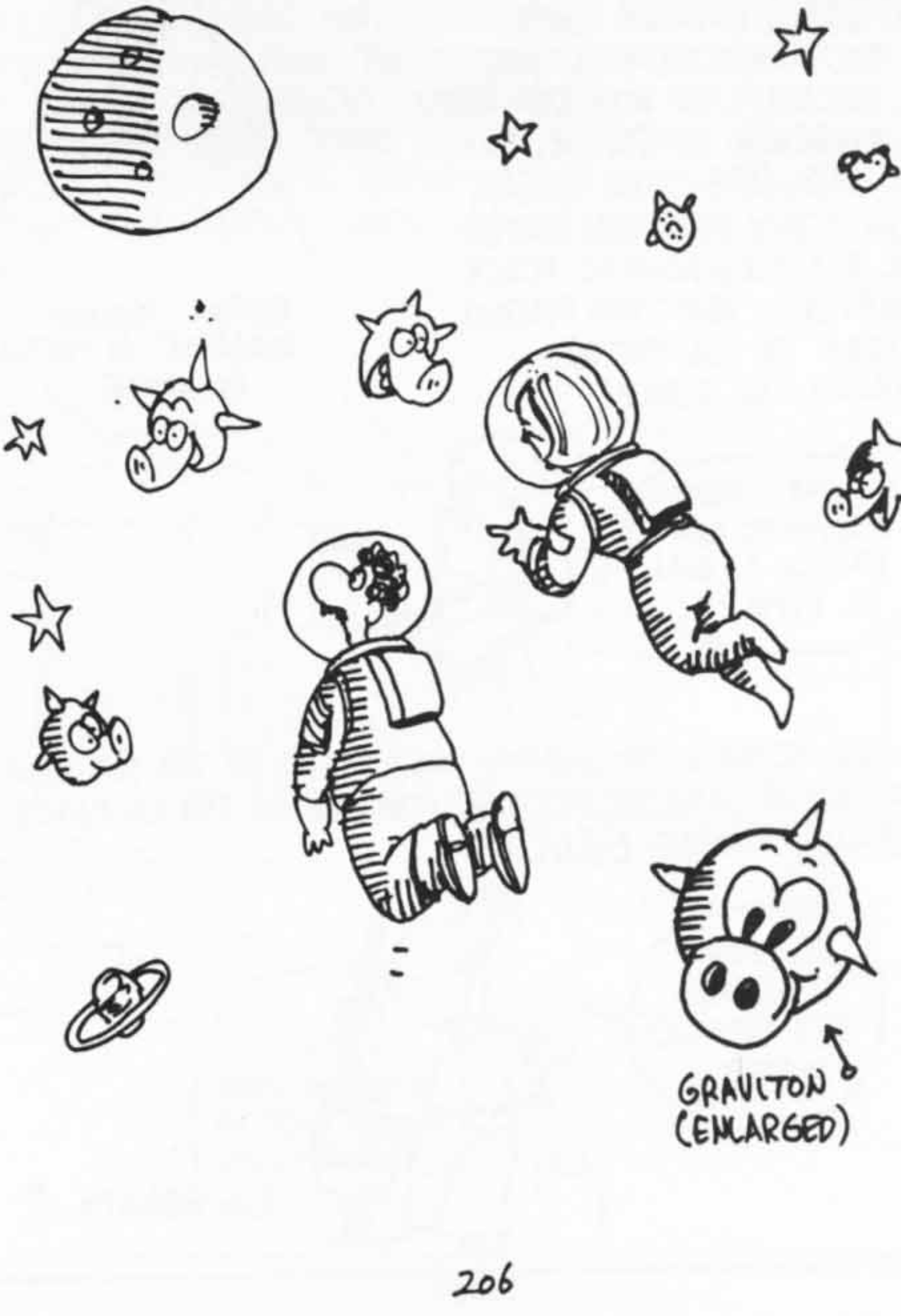
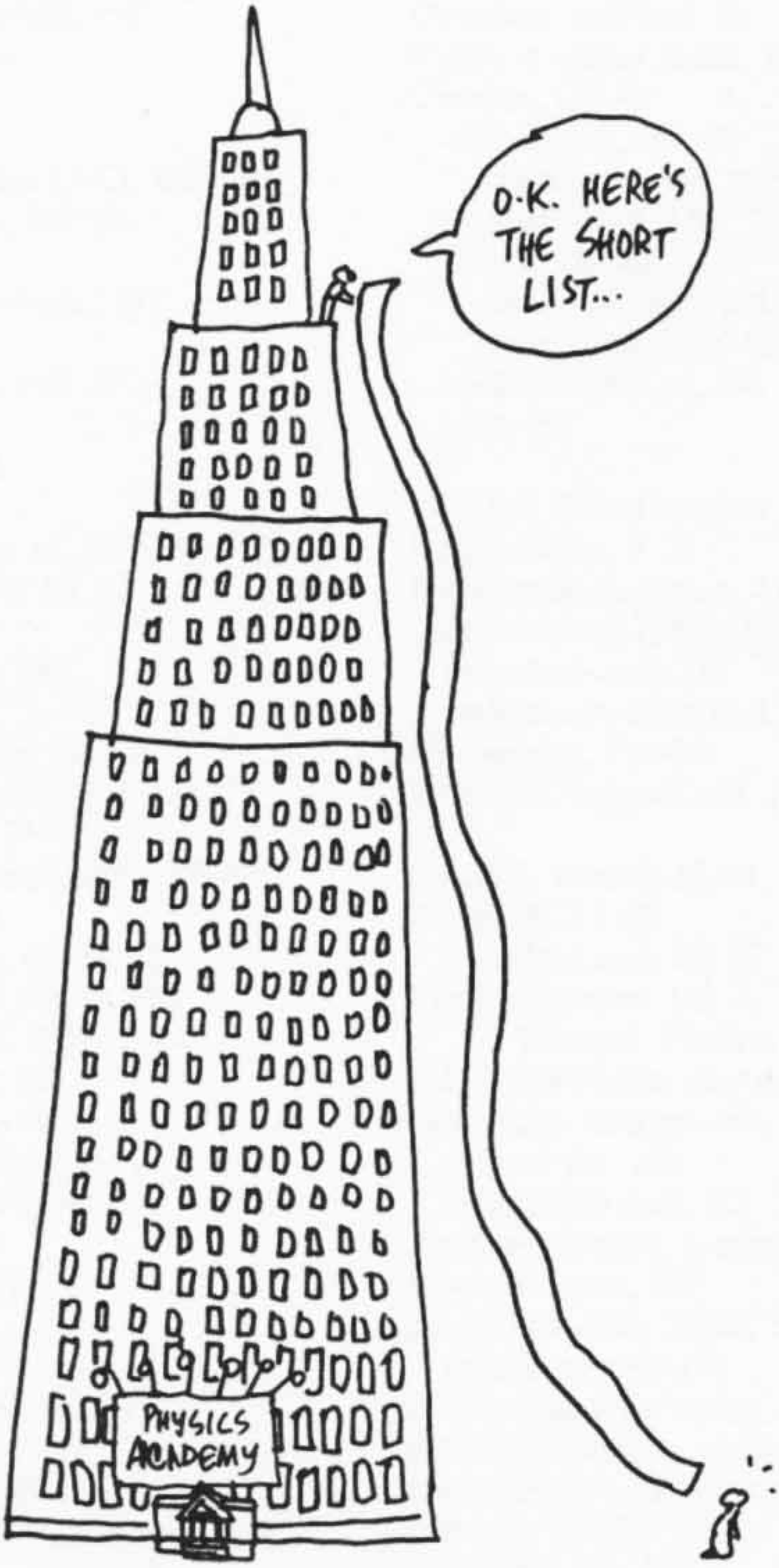


GENERIC "FEYNMAN DIAGRAM" OF PARTICLE EXCHANGE

THE FORCE BETWEEN THE QUARKS WHICH MAKE UP THE NEUTRONS AND PROTONS IS ALSO THEORIZED TO COME FROM THE EXCHANGE OF PARTICLES CALLED ***GLUONS***.

AND GRAVITY...?

AH, GRAVITY... GRAVITY SHOULD BE CAUSED BY THE EXCHANGE OF **GRAVITONS**... BUT WE DON'T EXPECT TO SEE ANY GRAVITONS SOON. THE GRAVITATIONAL FORCE IS JUST TOO WEAK. IT TAKES A WHOLE MOON OR PLANET TO EXERT AN APPRECIABLE GRAVITATIONAL FORCE. BUT WE'RE CONFIDENT THE GRAVITONS ARE "THERE."



PHYSICISTS STILL BELIEVE THAT ALL THE FORCES OF NATURE RESULT FROM THE EXCHANGE OF PARTICLES. BY RELATING THESE PARTICLES, WE HOPE TO DEVELOP A UNIFIED PICTURE OF ALL FORCES WITH A SMALL LIST OF RULES WHICH WILL DESCRIBE THE BASIS OF — EVERYTHING.