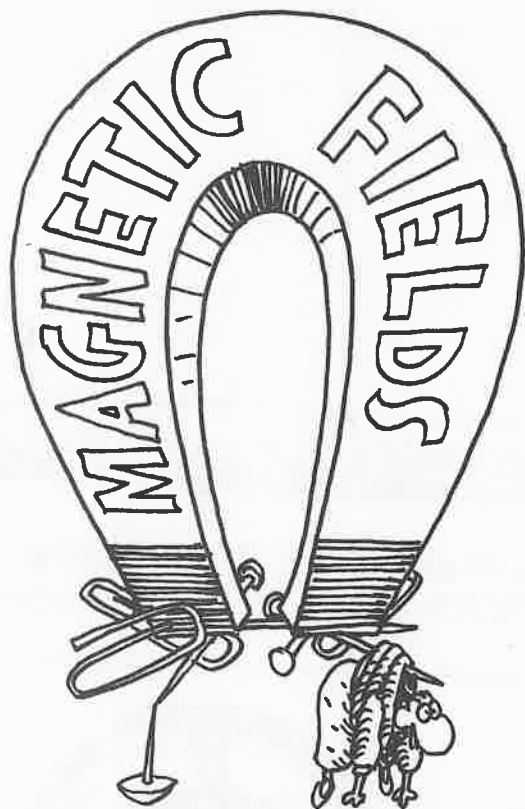


◊ CHAPTER 17 ◊



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..."

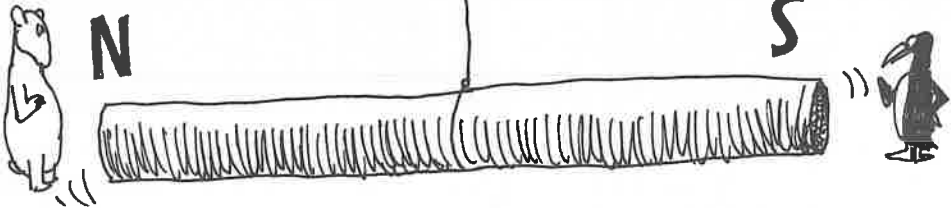


GOOD THING THEY WEREN'T FROM AMNESIA.

YEH, WE'D HAVE HAD TO FORGET ALL ABOUT 'EM...



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

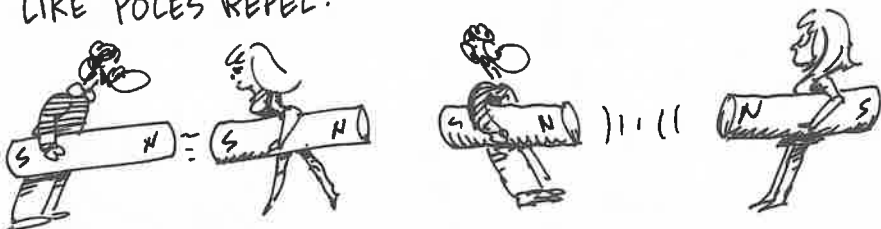


IF YOU ALLOW A MAGNET TO PIVOT, ITS **NORTH** POLE IS
THE ONE THAT POINTS TOWARD THE EARTH'S (GEOGRAPHIC)
NORTH.

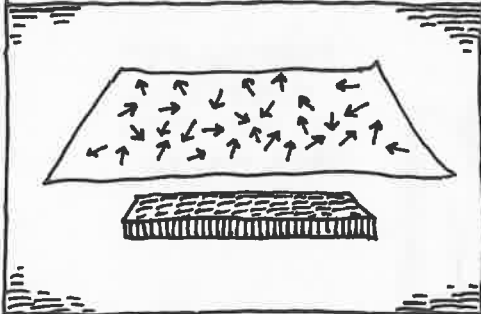
A **COMPASS** IS
JUST A MAGNETIC
NEEDLE ON A
PIVOT.



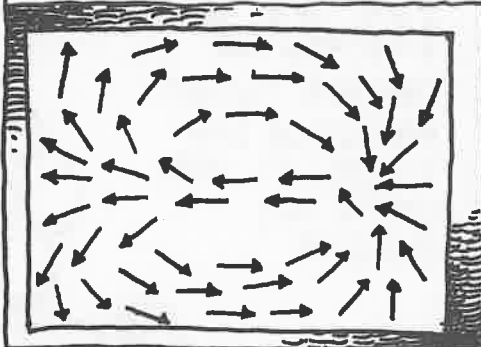
WE ALSO NOTE THAT UNLIKE POLES ATTRACT, WHILE
LIKE POLES REPEL.



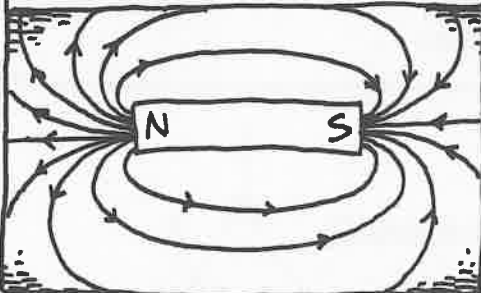
NOW IMAGINE THAT WE HAD SCATTERED TINY COMPASS NEEDLES ON A SHEET OF PAPER AND BROUGHT A BAR MAGNET UNDERNEATH THEM:



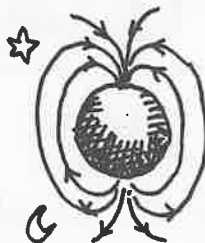
THE NEEDLES WILL LINE UP, REVEALING THE BAR MAGNET'S **MAGNETIC FIELD.**



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

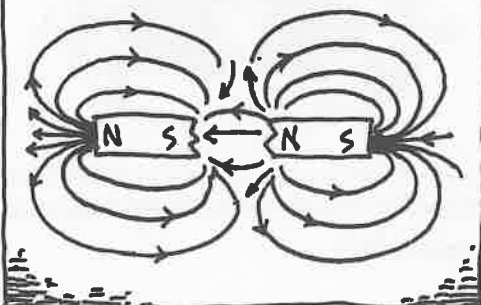


BY CONVENTION, WE AGREE THAT THE FIELD LINES EMERGE FROM THE **NORTH** MAGNETIC POLE AND POINT TOWARD THE **SOUTH** MAGNETIC POLE.

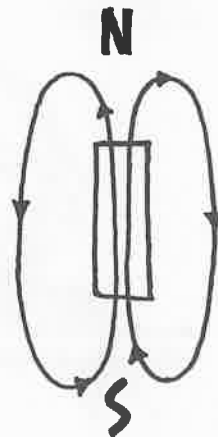


(NOTE THAT THIS MAKES THE EARTH'S SOUTH MAGNETIC POLE BE THE ONE IN THE GEOGRAPHIC NORTH!)

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

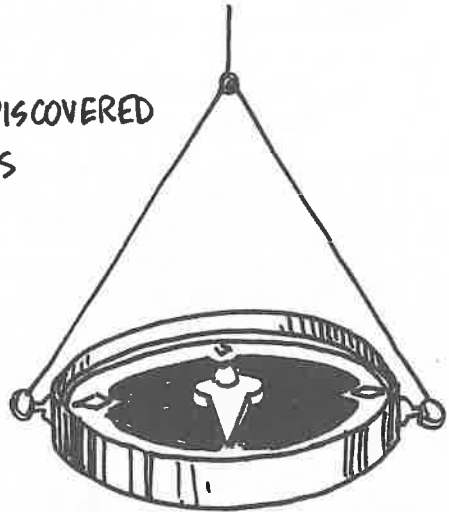
1820

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.



CURRENT →

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



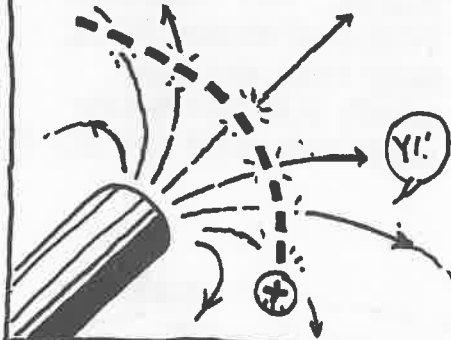
FIRST, IF THE CHARGE IS NOT MOVING, THERE IS **NO FORCE.**



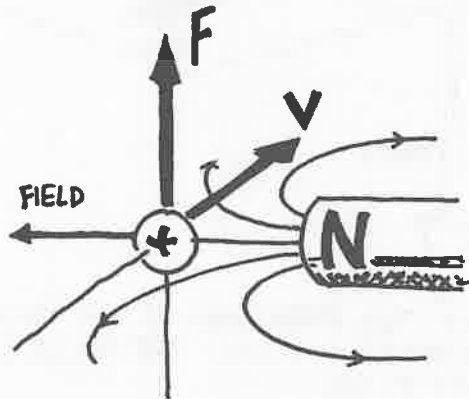
...AND THERE IS NO FORCE IF THE CHARGE IS MOVING **ALONG** A FIELD LINE...



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



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

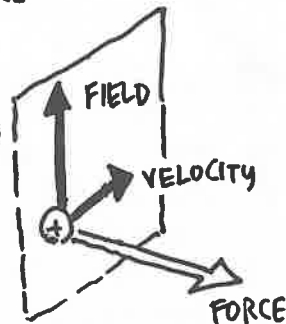
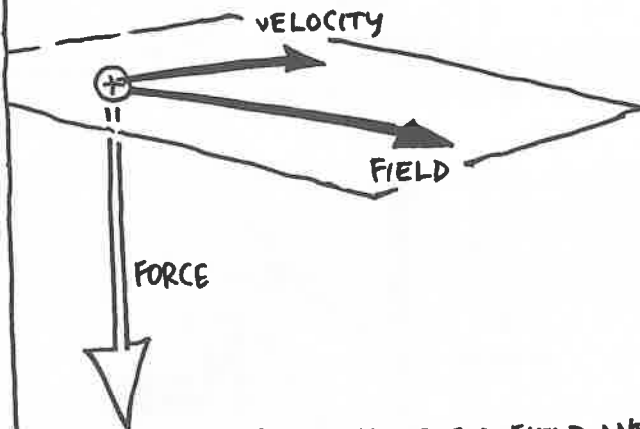
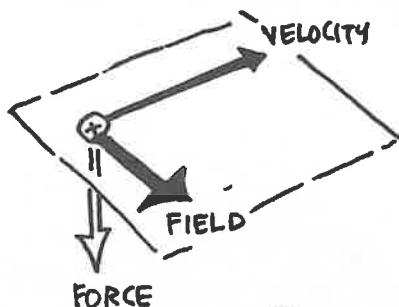




AGAIN!

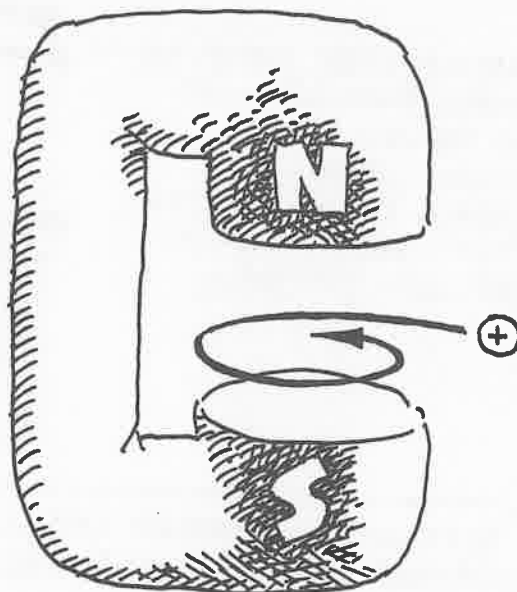
MAGNETIC FIELDS PRODUCE FORCES ON MOVING CHARGED PARTICLES. THE FORCES ARE PERPENDICULAR TO BOTH THE VELOCITY OF THE PARTICLE AND THE DIRECTION OF THE MAGNETIC FIELD.

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.

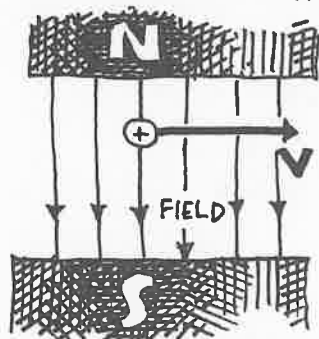


NOTE: THE DIRECTIONS OF THE FIELD AND THE VELOCITY DETERMINE A PLANE. THE FORCE IS PERPENDICULAR TO THAT PLANE.

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

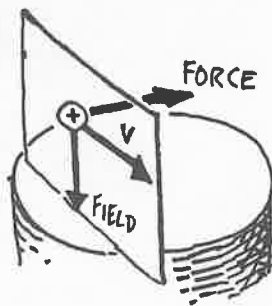


THE MAGNETIC FIELD BETWEEN THE FACES IS ALWAYS PERPENDICULAR TO THE PARTICLE'S VELOCITY: SO THE

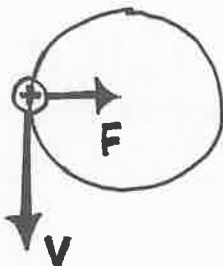


SIDE VIEW

FORCE, PERPENDICULAR TO BOTH, POINTS TO THE CENTER OF THE CIRCLE!



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

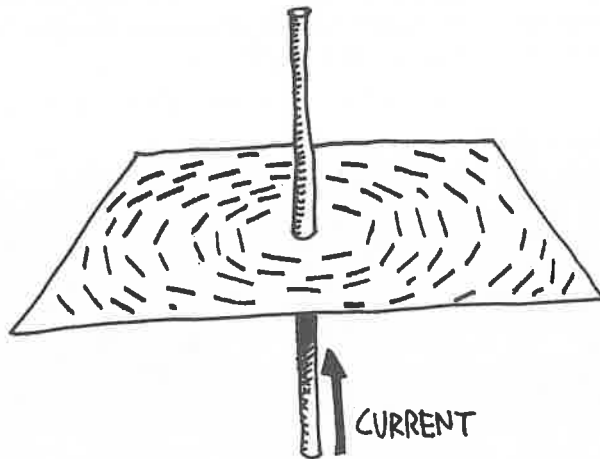


THIS IS THE BASIS FOR THE LARGE PARTICLE ACCELERATORS AND STORAGE RINGS.

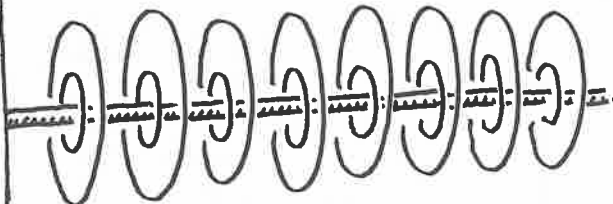
MAGNETS EXERT FORCES ON MOVING PARTICLES — AND, AS OERSTED SHOWED, MOVING CHARGES ALSO CREATE MAGNETIC FIELDS. THAT'S WHAT DEFLECTED OERSTED'S COMPASS...



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 .

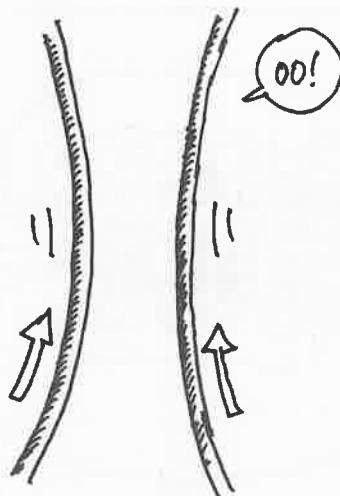
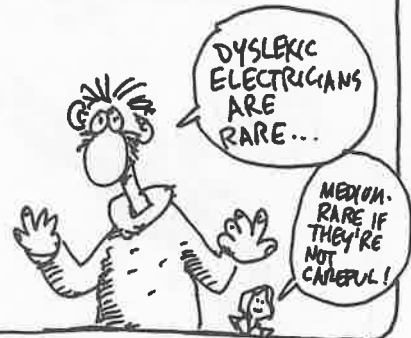


THE MAGNETIC FIELD OF A CURRENT IS CIRCLES CENTERED ON THE WIRE AND LYING IN THE PLANE PERPENDICULAR TO THE CURRENT.



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.

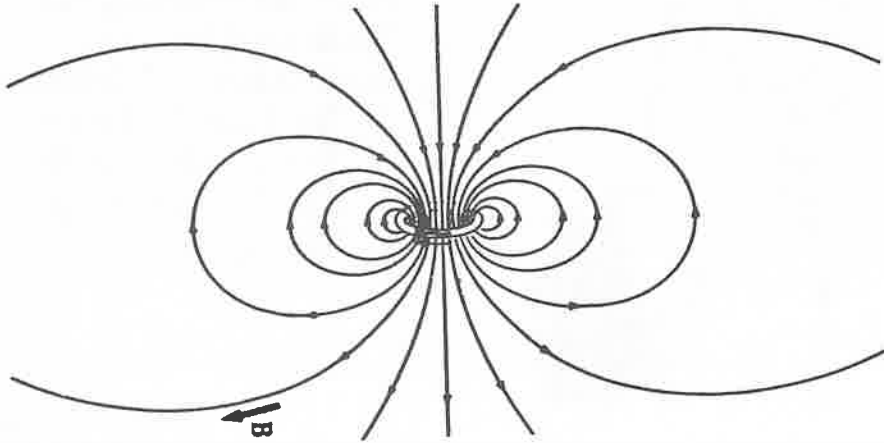


TWO PARALLEL CURRENTS ATTRACT EACH OTHER. THE MAGNETIC FIELD CIRCLING EACH WIRE CAUSE FORCES ON THE CURRENT IN THE OTHER WIRE, PULLING IT CLOSER. SEE IF YOU CAN CONVINCE YOURSELF THAT THIS IS THE RIGHT DIRECTION, USING THE RIGHT-HAND RULE!



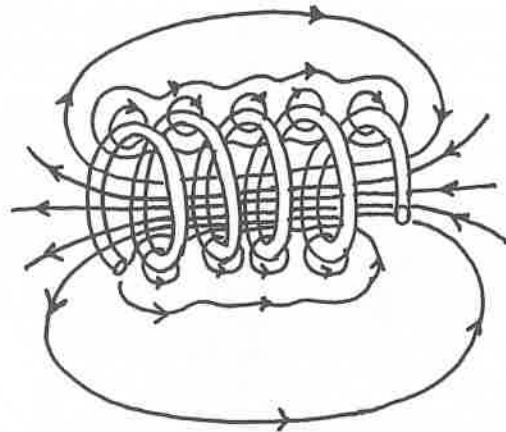
AMPERE,
DISCOVERER
OF THE FORCE
BETWEEN
PARALLEL
WIRES

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...

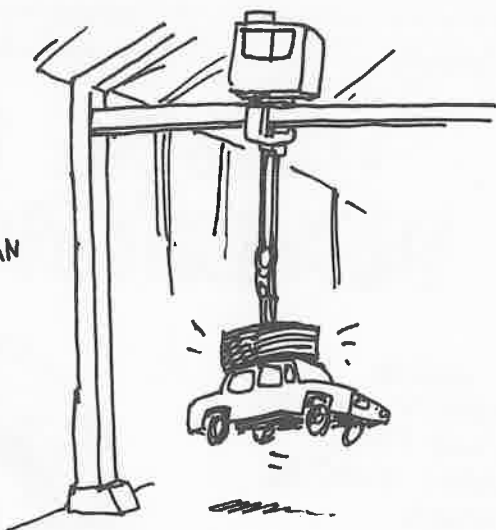
BY WINDING MANY TURNS, THE MAGNETIC FIELD IS MADE PROPORTIONALLY LARGER. BY WINDING TURNS ALONG A CYLINDER, WE GET A **SOLENOID COIL**, WITH A MAGNETIC FIELD JUST LIKE A BAR MAGNET!





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.



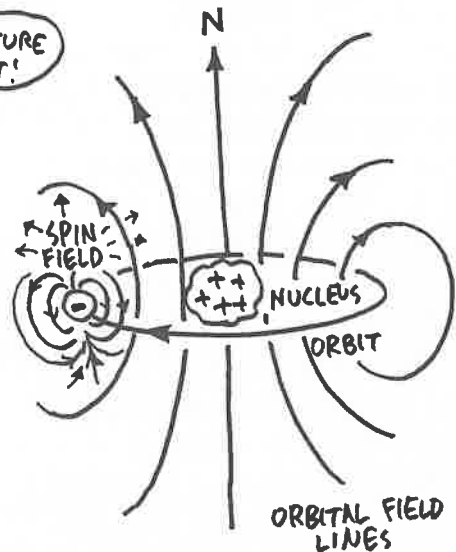
WHERE ARE THE CHARGES THAT CREATE THE MAGNETIC
FIELD OF AN IRON MAGNET? THEY ARE THE ELECTRONS IN
THE IRON ATOMS THEMSELVES!



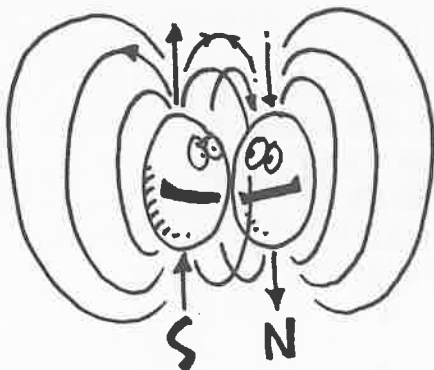
A MINIATURE
MAGNET!



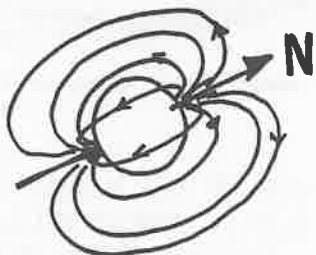
AN ELECTRON ORBITING THE
ATOMIC NUCLEUS IS LIKE A
SMALL CIRCULAR CURRENT,
SO IT PRODUCES AN
**ORBITAL MAGNETIC
FIELD.** ALSO, THE ELECTRON
SPINS ON ITS OWN AXIS,
GENERATING A
SPIN MAGNETIC FIELD.



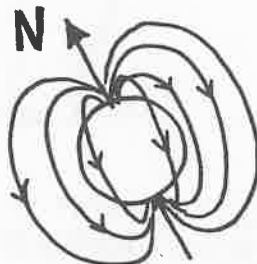
MOST ELECTRONS IN ATOMS HAVE THEIR MAGNETIC FIELDS CANCELLED OUT BY THE MAGNETIC FIELDS OF OTHER ELECTRONS...



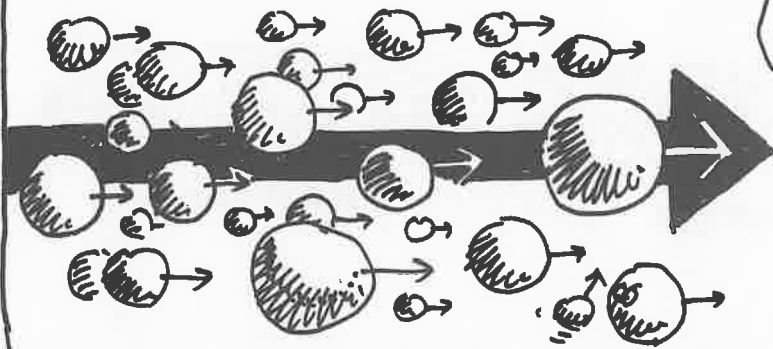
BUT IN **MAGNETIC** MATERIALS — LIKE THE METALS **IRON, NICKEL, AND COBALT** — THERE ARE LONE ELECTRONS THAT CONTRIBUTE A NET MAGNETIC FIELD TO EACH ATOM.



... AND FURTHERMORE,



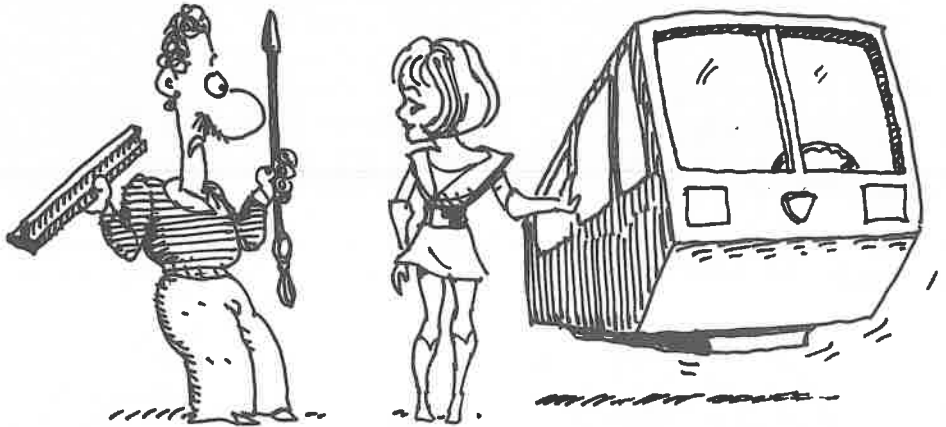
IN THESE "FERROMAGNETIC" ELEMENTS, THE ATOMS THEMSELVES LINE UP SO THAT THEIR MAGNETIC FIELDS ALL POINT IN THE SAME DIRECTION. RESULT: A BIG MAGNETIC FIELD!



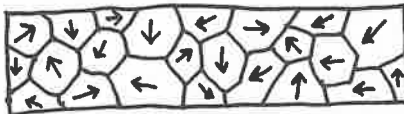
ELECTRONIC FASCISM!



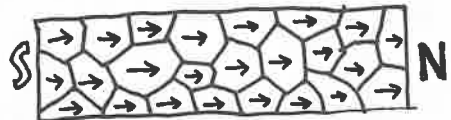
BUT IF ALL THE ATOMS ARE LINED UP, WHY AREN'T ALL PIECES OF IRON MAGNETIC?



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

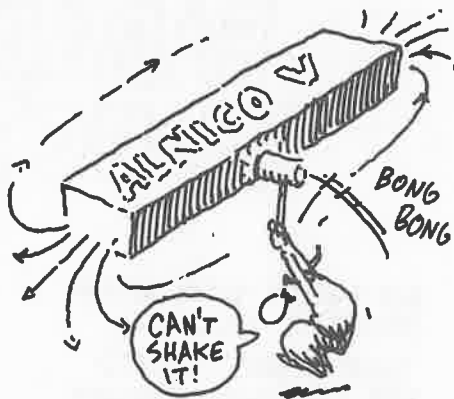


MAGNETIZED

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 V₉

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.

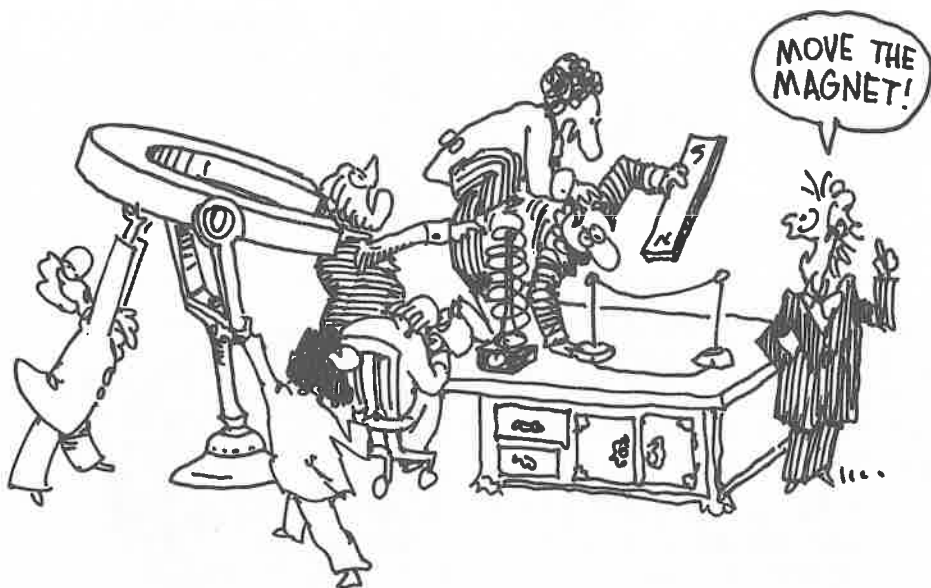


PRESUMABLY, THE EARTH'S MAGNETISM IS CAUSED BY CIRCULATING ELECTRIC FIELDS IN THE EARTH'S CORE. THE EXACT MECHANISM REMAINS A MYSTERY. DO YOU FIND IT RATHER AMUSING THAT THE FIRST MAGNETIC EFFECTS EVER DISCOVERED ARE STILL NOT SATISFACTORILY EXPLAINED?

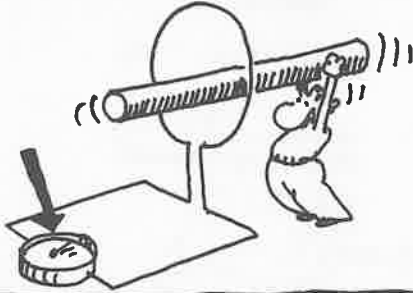


•CHAPTER 19• FARADAY INDUCTION

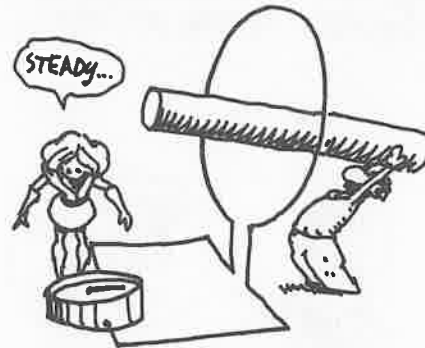
FOR TWELVE YEARS AFTER
OERSTED'S DISCOVERY,
"ELECTRICIANS" LOOKED
FOR THE COMPLEMENTARY
EFFECT: HOW TO MAKE
A MAGNETIC FIELD PRODUCE
A CURRENT? AT LAST, IN
1832, MICHAEL FARADAY
MADE A SUGGESTION —



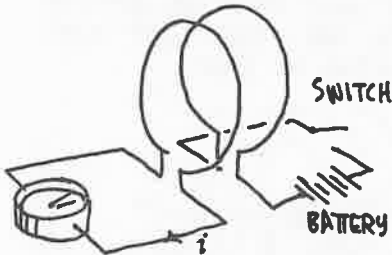
HERE RINGO THRUSTS A MAGNET INTO A LOOP OF WIRE CONNECTED TO A SENSITIVE CURRENT METER, A GALVANOMETER. THE GALVANOMETER NEEDLE DEFLECTS!



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??

NOT IF YOU BELIEVE IN FIELDS, IT ISN'T...

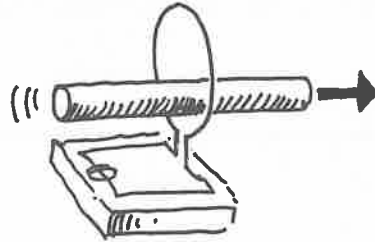


FARADAY DESCRIBED THIS BY SAYING THAT **ELECTRO-MOTIVE FORCES** ARE GENERATED IN THE WIRE WHENEVER MAGNETIC FIELD LINES CUT ACROSS THE WIRE.

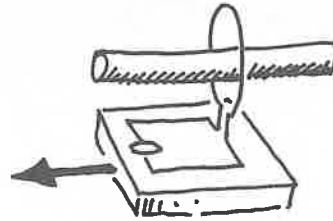
EMF
FOR SHORT!



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

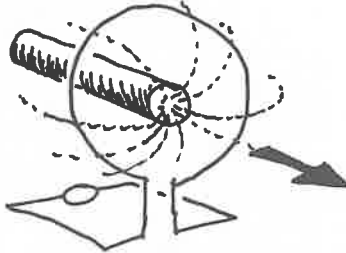


IS EQUIVALENT TO



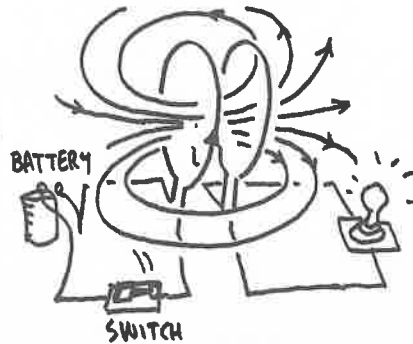
IGNORANT WIRE CAN'T TELL THE DIFFERENCE!

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.



TWELVE YEARS TO MOVE THE MAGNET?



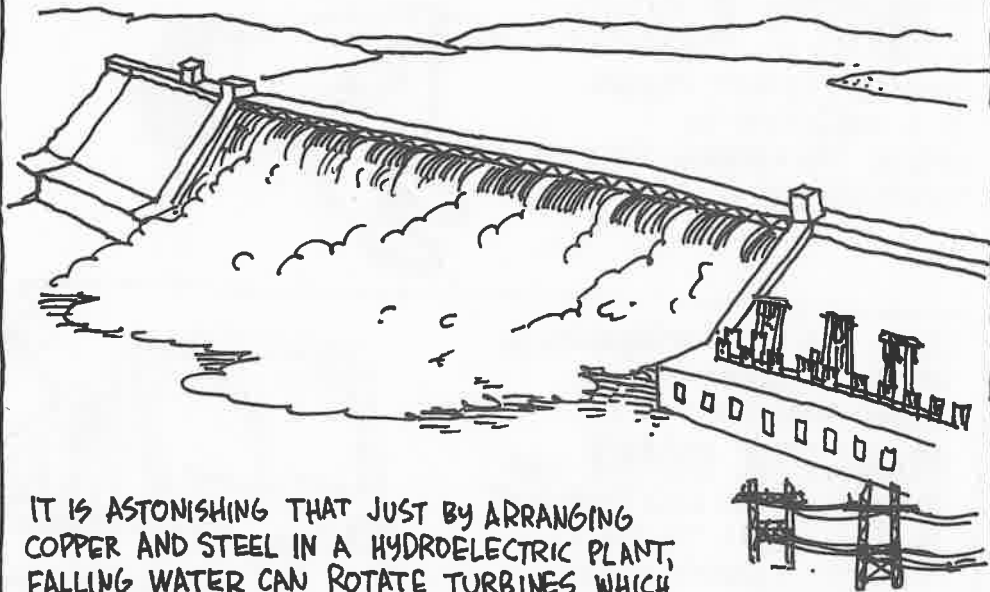
A MILDLY
AMUSING
BUT HARDLY
USEFUL
RESULT...



YESS... NOW LET'S
GET ON WITH THE
REALLY IMPORTANT
RESEARCH... HOW
LUMPS IN THE SKULL
AFFECT CRIMINAL
TENDENCIES...

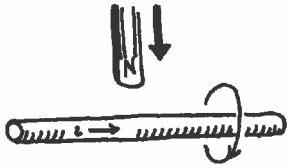


ALTHOUGH FARADAY'S DISCOVERY WAS AT FIRST RECEIVED WITH
INDIFFERENCE, TODAY ALL OUR ELECTRIC POWER IS GENERATED
BY MOVING GIANT COILS OF WIRE NEAR MAGNETS!



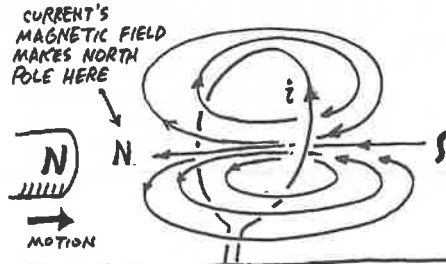
IT IS ASTONISHING THAT JUST BY ARRANGING
COPPER AND STEEL IN A HYDROELECTRIC PLANT,
FALLING WATER CAN ROTATE TURBINES WHICH
GENERATE ENOUGH ELECTRICITY TO POWER
CITIES HUNDREDS OF MILES AWAY!!

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?

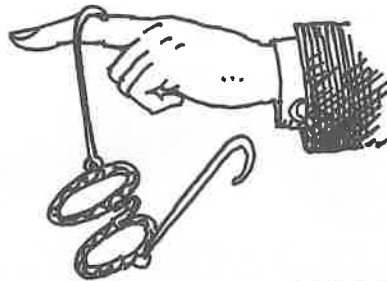


WHEN THE INDUCED CURRENT FLOWS IN THE WIRE, IT MAKES A MAGNETIC FIELD. THIS MAGNETIC FIELD MUST RESIST THE MAGNET'S MOTION, SO WORK IS DONE IN MOVING IT.

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.

