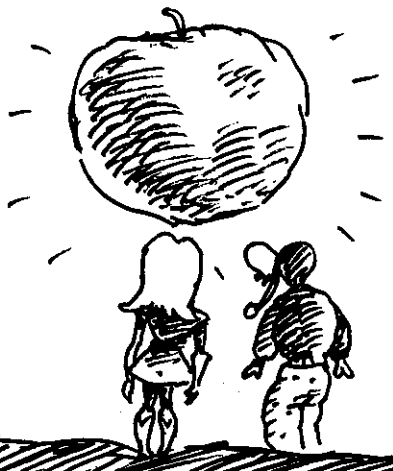
◊ CHAPTER 2 ◊

THE APPLE AND THE MOON

IN ORDER TO UNDERSTAND THE MOON'S MOTION, AND ALL THE OTHER MOTION AROUND US, WE FIRST ASK THE QUESTION: WHAT DO OBJECTS DO WHEN **NO** FORCE IS ACTING?

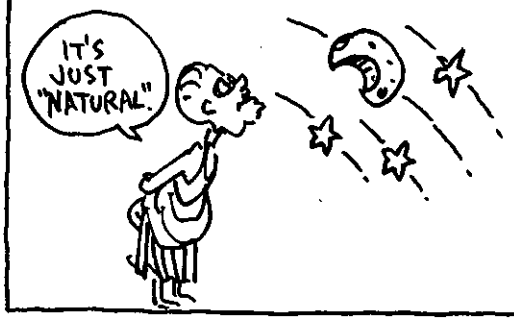


FOR CENTURIES, PHYSICS SLEPT IN THE SHADOW OF

ARISTOTLE

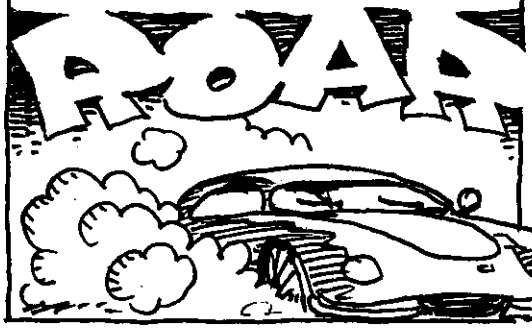
(384-322 B.C.). ARISTOTLE BELIEVED THAT THE "NATURAL" MOTION OF **CELESTIAL** OBJECTS (MOON, STARS) WAS **CIRCULAR**, WHILE **TERRESTRIAL** OBJECTS (APPLES, ROCKS, YOU) TEND "NATURALLY" TO **FALL.**

NOTICE THAT IF THE MOON NATURALLY MOVES IN A CIRCLE, WE DON'T NEED ANY GRAVITY TO EXPLAIN ITS MOTION.

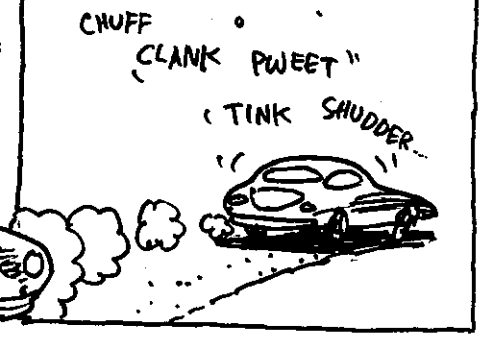


AS FOR EARTHLY OBJECTS, ARISTOTLE THOUGHT THAT AFTER FALLING, THEY COME TO REST, UNLESS SOME FORCE PUSHES THEM SIDEWAYS.

AND WE INSTINCTIVELY AGREE WITH HIM! IT DOES SEEM THAT A FORCE IS NEEDED TO MAINTAIN MOTION, LIKE A MOTOR PROPELLING A CAR.



WHEN THE ENGINE IS CUT OFF, THE CAR GRADUALLY... ROLLS... TO... A..... HALT....



IT TOOK THE GENIUS OF GALILEO TO CLAIM THAT

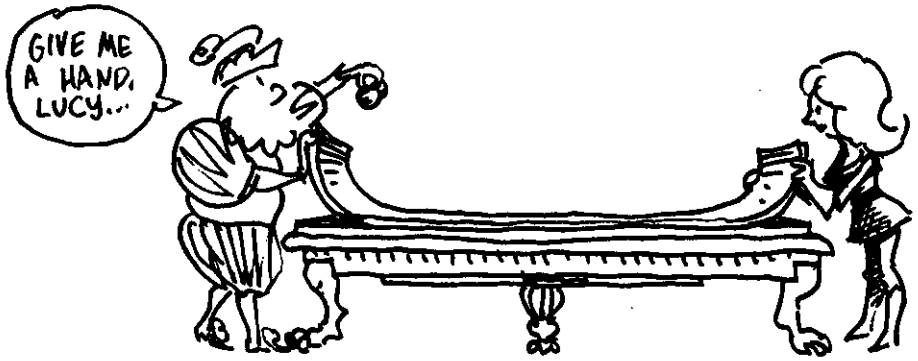
NO FORCE

IS NEEDED TO KEEP AN OBJECT IN

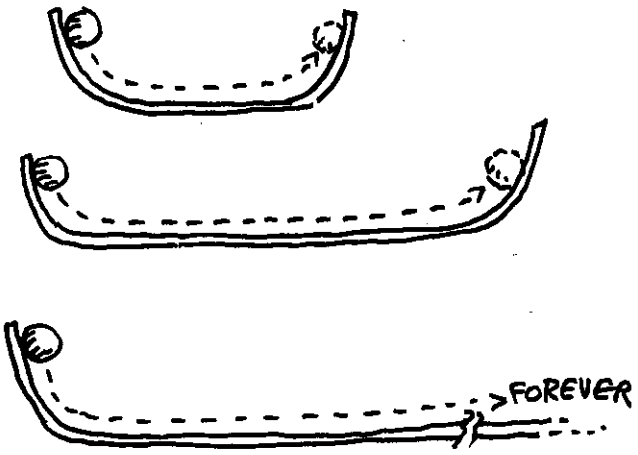
UNIFORM, STRAIGHT-LINE MOTION.

GALILEO'S BRAINSTORM WAS TO SEE THAT FORCES **CHANGE THE MOTION** OF OBJECTS. LEFT ALONE, THINGS WOULD TRAVEL IN A STRAIGHT LINE FOREVER. IT IS THE FORCE OF **FRICTION** THAT SLOWS THEM DOWN.

WE CAN CONVINCE OURSELVES OF THIS IDEA WITH A SIMPLE APPARATUS CONSISTING OF A FLEXIBLE RUBBER MAT:



A ROLLING BALL TENDS TO REACH THE SAME HEIGHT ON THE OTHER SIDE... AND IF THERE WERE NO OTHER SIDE, IT WOULD ROLL ON FOREVER, IF NOT FOR FRICTION.

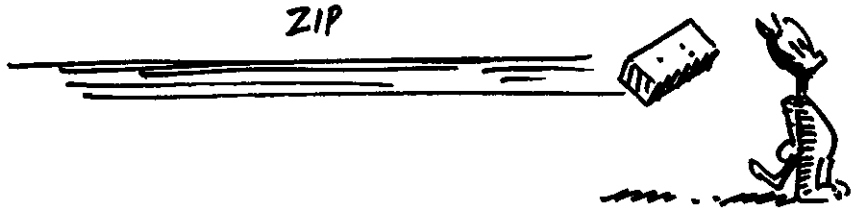


ISAAC **NEWTON** (1642-1727) SUMMARIZED GALILEO'S IDEA AS **NEWTON'S FIRST LAW:**

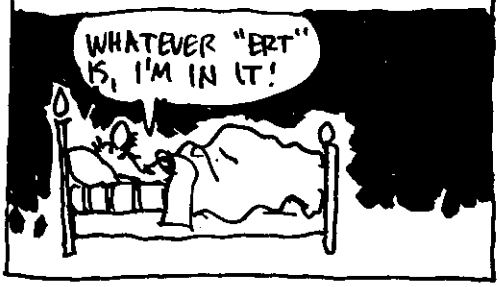
AN OBJECT AT REST TENDS TO STAY AT REST. AN OBJECT IN MOTION TENDS TO CONTINUE IN MOTION AT CONSTANT SPEED IN A STRAIGHT LINE.

(HE ALSO SAID: "IF I HAVE SEEN FAR, IT IS BECAUSE I HAVE STOOD ON THE SHOULDERS OF GIANTS," MEANING GALILEO OF COURSE...)

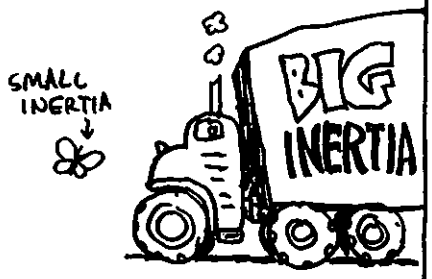
IN THE TERMINOLOGY WE DEVELOPED IN CHAPTER ONE, WE WOULD SAY THAT WHEN THERE ARE NO FORCES, OBJECTS MOVE WITH **CONSTANT VELOCITY.**



THE PROPERTY OF OBJECTS THAT MAKES THEM "TEND" TO OBEY NEWTON'S FIRST LAW, WE CALL **INERTIA**. INERTIA IS RESISTANCE TO CHANGES IN MOTION.



THE AMOUNT OF INERTIA A BODY HAS IS MEASURED BY ITS **MASS**. MASSIVE THINGS HAVE LOTS OF INERTIA, MEANING THAT A LARGE FORCE IS REQUIRED TO CHANGE THEIR MOTION.

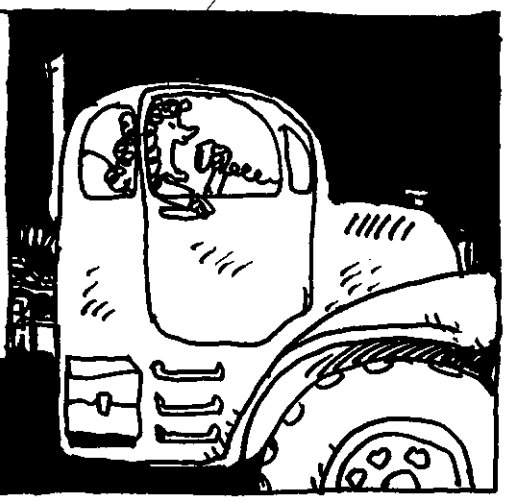


WE SAID PREVIOUSLY THAT WHEN RINGO RIDES IN A CAR THAT ACCELERATES, HE FEELS FORCES.

THESE ARE THE FORCES THE CAR HAS TO EXERT ON RINGO TO OVERCOME HIS INERTIA AND ACCELERATE HIM.

MR. NEWTON WILL SUMMARIZE:

BREAKER ONE.NINE: FORCE OVERCOMES INERTIA AND PRODUCES ACCELERATION. DO YOU READ?

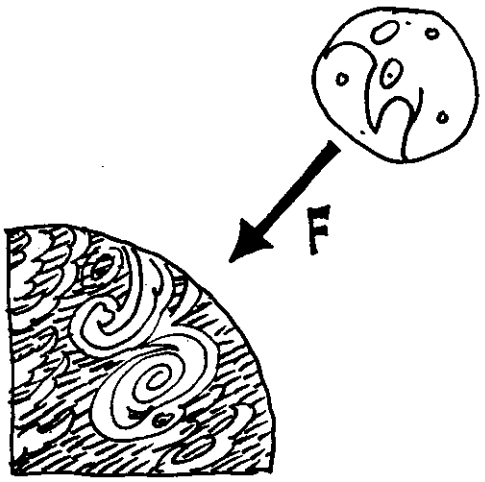


NEWTON PUT THIS RELATIONSHIP AMONG FORCE, MASS, AND ACCELERATION INTO MATHEMATICAL FORM WITH NEWTON'S **SECOND LAW:**

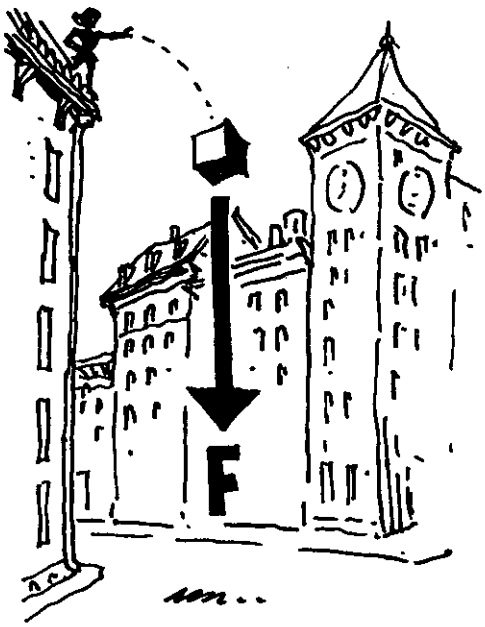
$$F = m \cdot a$$

THE MORE FORCE ON AN OBJECT, THE MORE IT ACCELERATES. BUT THE MORE MASSIVE IT IS, THE MORE IT RESISTS ACCELERATION.

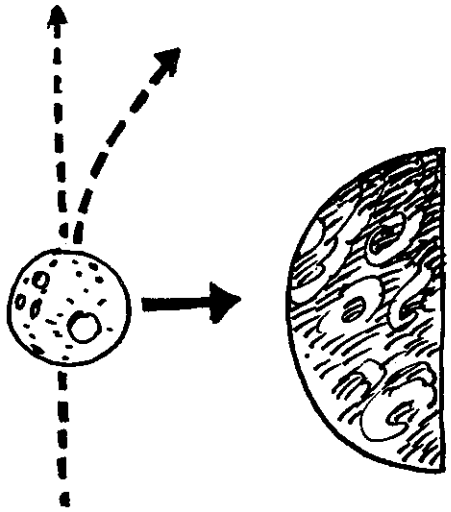
NOW LET'S LOOK AT THE MOON AGAIN. IT GOES IN A CIRCLE AROUND THE EARTH, OR NEARLY SO. AS WE HAVE SEEN, THINGS THAT MOVE IN A CIRCLE ARE ACCELERATING. THEREFORE, IT HAS A FORCE ACTING ON IT. IT MUST BE THAT **THE EARTH IS PULLING ON THE MOON.**



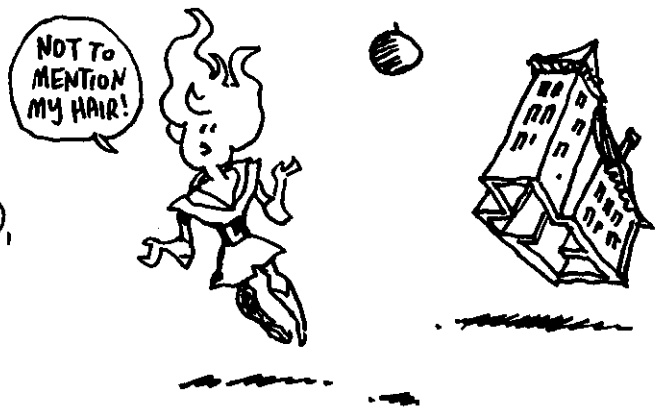
WE KNOW THAT THE EARTH PULLS ON OBJECTS NEAR ITS SURFACE, CAUSING THEM TO ACCELERATE DOWNWARD.



THE SAME FORCE, **GRAVITY**, ACTS ON THE MOON, PULLING IT AWAY FROM THE STRAIGHT LINE IT WOULD HAVE TAKEN IN THE ABSENCE OF GRAVITY.

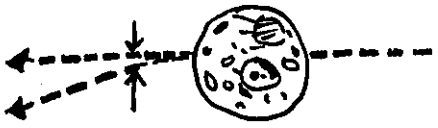


WHEN RELEASED IN MID-AIR, AN APPLE WOULD HAVE REMAINED AT REST (ITS "NATURAL" MOTION), IF NOT FOR THE EFFECT OF GRAVITY MAKING IT FALL.



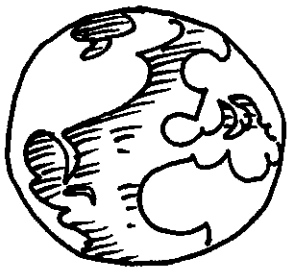
SIMILARLY, IN THE ABSENCE OF GRAVITY (OR OTHER FORCES), THE MOON WOULD CONTINUE ALONG A STRAIGHT LINE AT UNIFORM SPEED. BUT GRAVITY DOES PULL IT, ACCELERATING THE MOON TOWARD THE EARTH. **THE MOON IS FALLING** — FALLING AWAY FROM ITS NATURAL "FIRST LAW" STRAIGHT-LINE MOTION.

IN ONE SEC., THE MOON FALLS ABOUT 1 mm AWAY FROM A STRAIGHT-LINE PATH

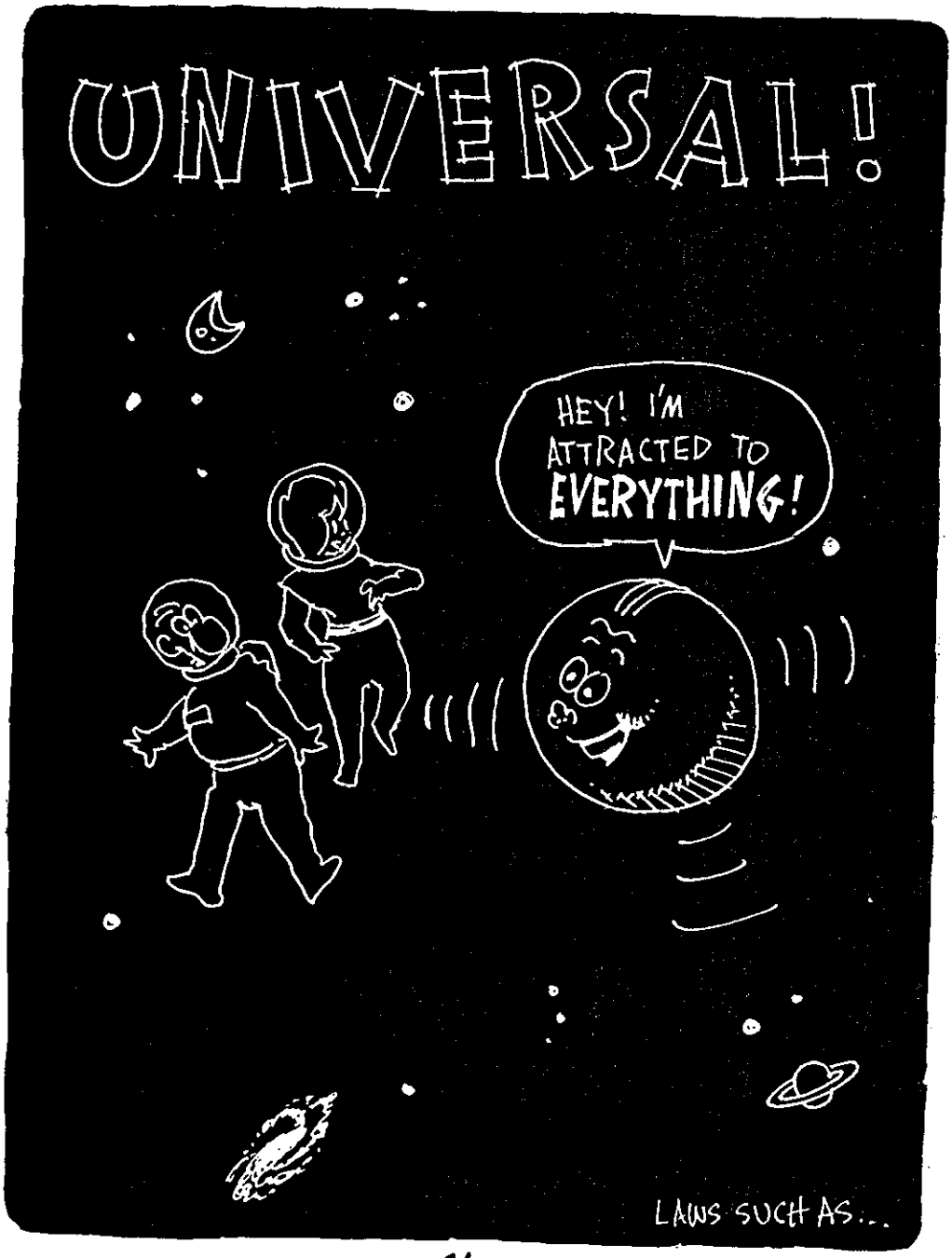


IN ONE SEC., AN APPLE FALLS 4.9 m NEAR THE EARTH'S SURFACE.

THE MOON DOESN'T FALL AS MUCH AS THE APPLE, BECAUSE THE EARTH'S GRAVITY IS WEAKER OUT THERE, FAR FROM THE EARTH.



STOP FOR A MOMENT AND CONSIDER WHAT NEWTON ACCOMPLISHED. THE MOTION OF THE APPLE AND THE MOON OBEY THE SAME LAWS. HEAVENLY BODIES BEHAVE NO DIFFERENTLY FROM EARTHLY ONES. NEWTON'S LAWS ARE—

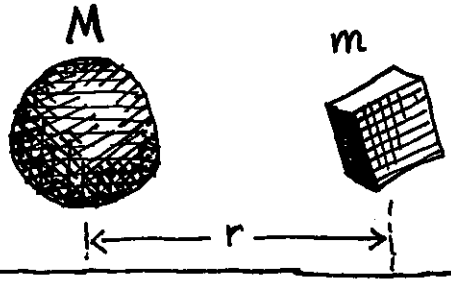


THE FAMOUS LAW OF UNIVERSAL GRAVITATION

FOR GRAVITY NEWTON'S FORMULA WAS:

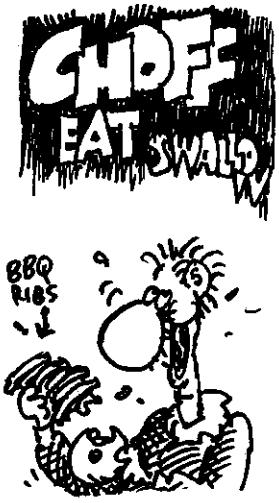
$$F = G \cdot \frac{M \cdot m}{r^2}$$

THE GRAVITATIONAL FORCE BETWEEN TWO MASSES M AND m IS PROPORTIONAL TO THE PRODUCT OF THE MASSES AND INVERSELY PROPORTIONAL TO THE SQUARE OF THE DISTANCE r BETWEEN THEM.

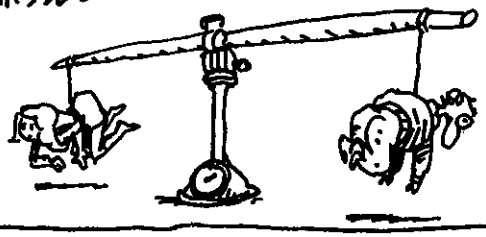


EVERYTHING IN THE UNIVERSE ATTRACTS EVERYTHING ELSE!! THE EARTH ATTRACTS THE MOON, THE MOON ATTRACTS THE EARTH, YOU ATTRACT ME...

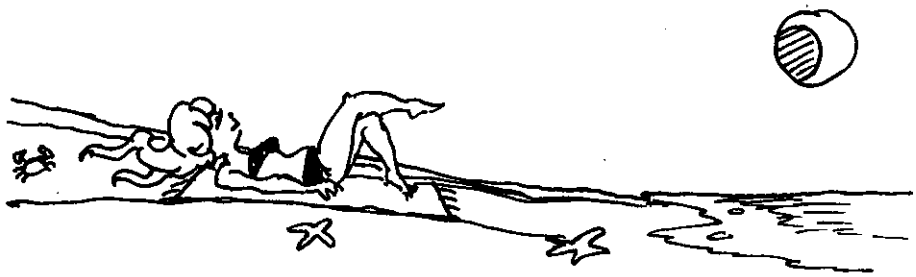
OF COURSE, IF THE MASSES ARE AS SMALL AS YOURS AND MINE, THE FORCE IS SMALL.



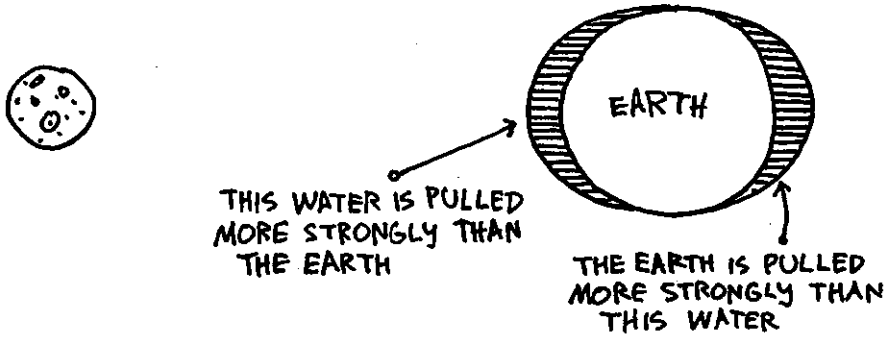
THAT NUMBER G IN THE FORMULA IS A CONSTANT OF NATURE THAT INDICATES HOW STRONG THE GRAVITATIONAL FORCE IS. TO MEASURE G, YOU WOULD HAVE TO PERFORM AN EXPERIMENT TO MEASURE THE ATTRACTION BETWEEN TWO KNOWN MASSES.

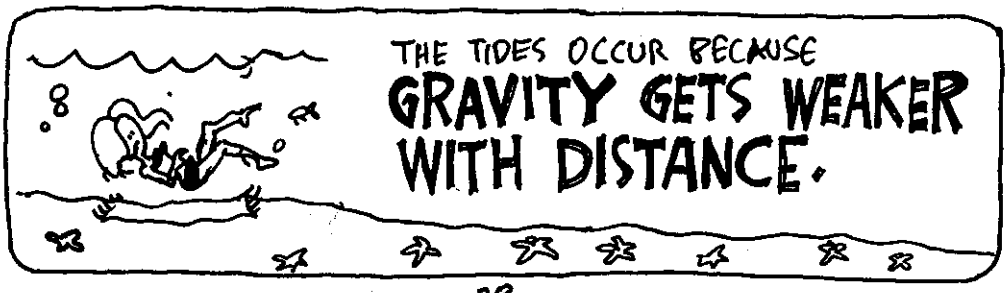


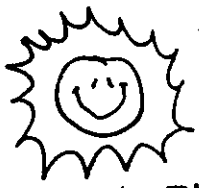
GRAVITY GETS WEAKER WITH DISTANCE: WE SAW THAT THE DISTANT MOON FALLS SLOWER THAN AN EARTHBOUND APPLE. ANOTHER EFFECT OF THIS **INVERSE-SQUARE LAW** IS THE **TIDE**, THE TWICE-DAILY RISE AND FALL OF OCEAN WATER.



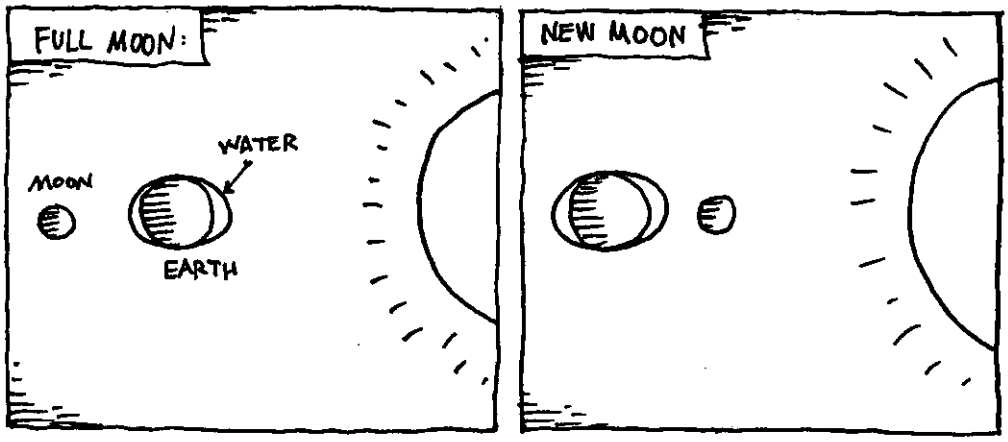
THE WATER DIRECTLY UNDER THE MOON IS CLOSER TO THE MOON THAN THE CENTER OF THE EARTH IS... SO THE MOON'S GRAVITY PULLS HARDER ON THE WATER, AND THE WATER "HEAPS UP" UNDER THE MOON. AND SINCE THE CENTER OF THE EARTH IS CLOSER TO THE MOON THAN THE WATER ON THE **OPPOSITE** SIDE OF THE EARTH, THE MOON PULLS THE EARTH AWAY FROM THAT WATER, SO IT HEAPS UP TOO!



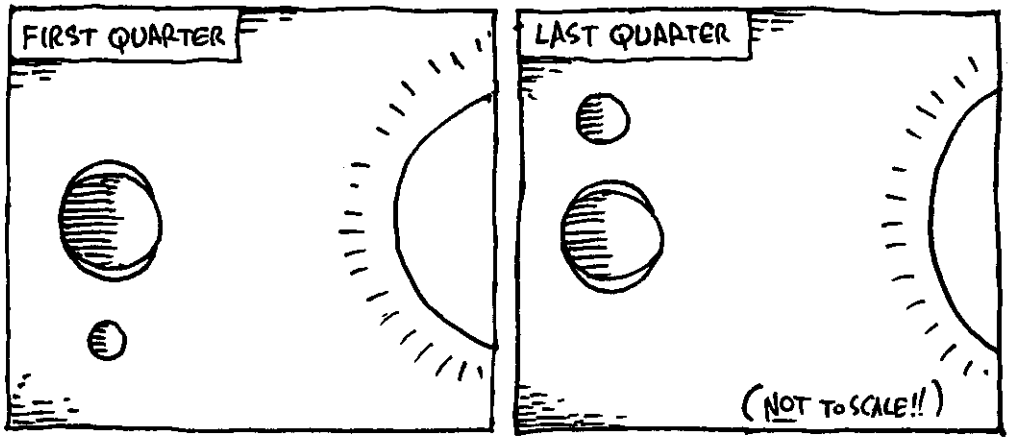




THE SUN ALSO CAUSES TIDES IN THE SAME WAY, BUT LESS SO, BECAUSE OF THE SUN'S GREATER DISTANCE. AT FULL MOON AND NEW MOON EACH MONTH, THE SUN IS IN LINE WITH THE MOON AND THE EARTH. THEN THE SUN AND MOON TOGETHER PRODUCE EXTRA-HIGH AND EXTRA-LOW TIDES. THESE ARE THE TWICE-MONTHLY **SPRING TIDES.***

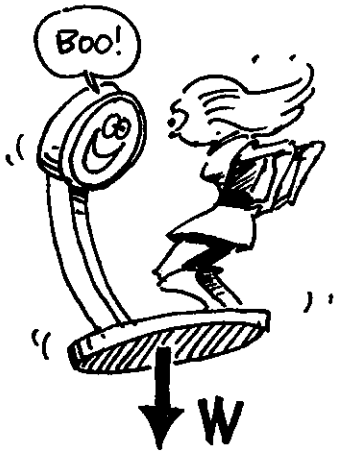


AT FIRST QUARTER AND LAST QUARTER, THE SUN AND MOON ARE AT RIGHT ANGLES. THE SUN'S TIDE IS SUBTRACTED FROM THE MOON'S, AND THE VARIATION IN TIDES IS LESS. THESE ARE THE **NEAP TIDES.**

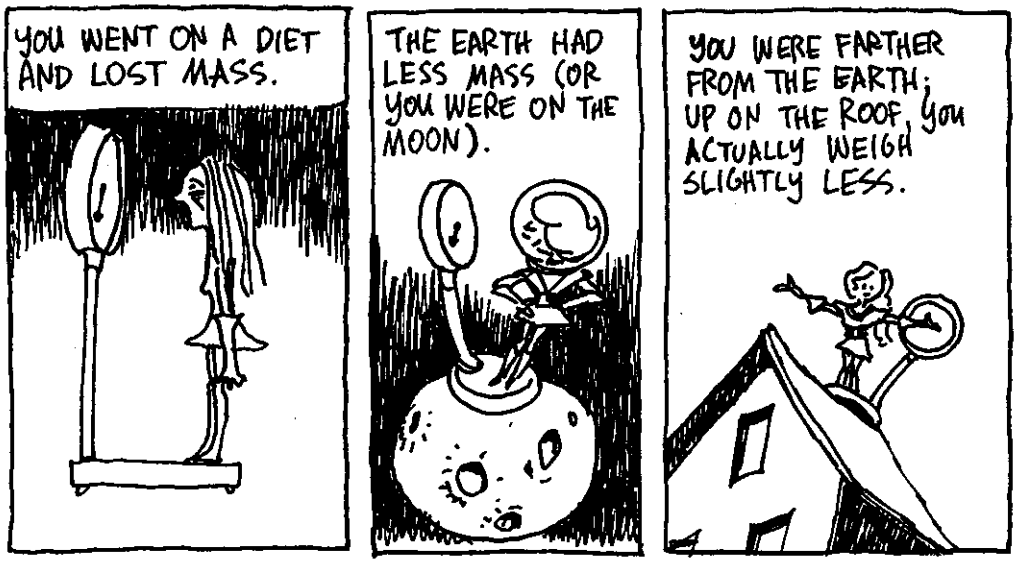


* THESE HAVE NOTHING TO DO WITH THE SPRING SEASON.

NOW LET'S THINK ABOUT GRAVITY'S EFFECTS ON THINGS NEAR THE EARTH, YOU, FOR EXAMPLE. THE GRAVITATIONAL FORCE ON YOU IS YOUR **WEIGHT.**



YOU WOULD WEIGH LESS IF:



NOW YOU JUMP OFF THE ROOF — WHAT IS YOUR ACCELERATION? NOTE THAT WE NOW HAVE TWO WAYS TO EXPRESS THE GRAVITATIONAL FORCE ON YOU:

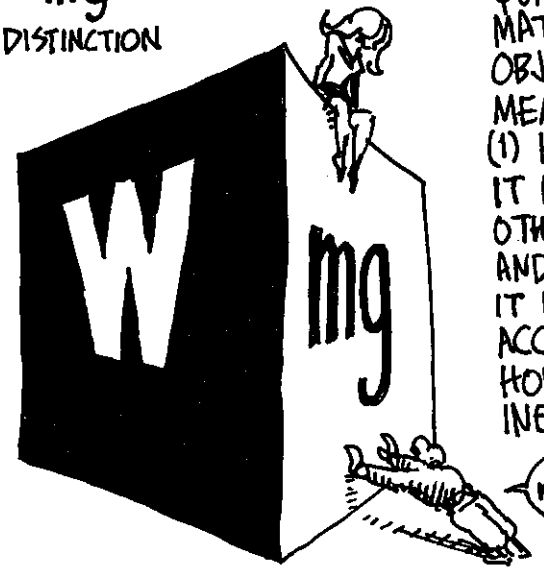
FROM NEWTON'S SECOND LAW:	FROM UNIVERSAL GRAVITATION:
$F = mg$	$F = G\frac{Mm}{r^2}$

SETTING THESE EQUAL, WE FIND:

$mg = G\frac{Mm}{r^2}$, so $g = G\frac{M}{r^2}$

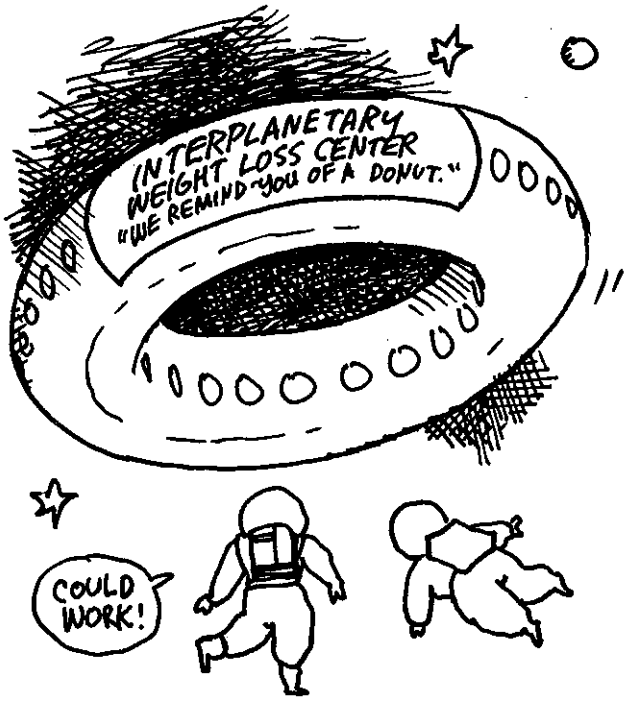
THIS LAST FORMULA SHOWS HOW g IS RELATED TO THE FUNDAMENTAL CONSTANT G AND THE EARTH'S MASS AND RADIUS. NOTE THAT m, YOUR MASS, CANCELS OUT. g DOESN'T DEPEND ON YOUR MASS!

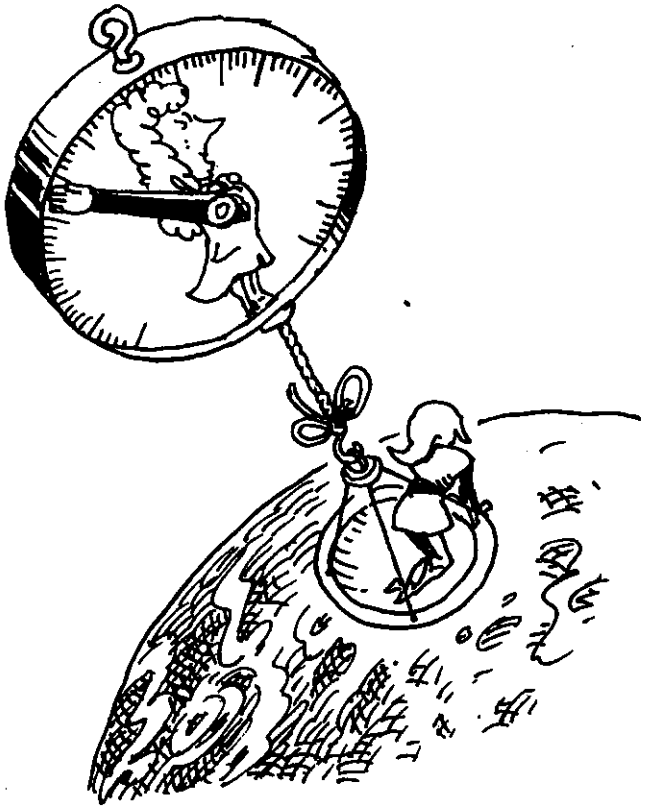
THE FORCE THE EARTH EXERTS ON YOU **W = mg** SHOWS THE DISTINCTION BETWEEN **WEIGHT** AND **MASS.**



MASS, **m**, IS THE QUANTITY OF MATTER IN AN OBJECT. MASS MEASURES (1) HOW MUCH GRAVITY IT EXERTS ON OTHER OBJECTS AND (2) HOW MUCH IT RESISTS ACCELERATION, HOW MUCH INERTIA IT HAS.

WEIGHT, **W**, IS THE AMOUNT OF GRAVITATIONAL PULL ON THE OBJECT. WEIGHT VARIES ACCORDING TO WHERE YOU ARE: IN DEEP SPACE, YOUR WEIGHT MIGHT BE ZERO, BUT YOUR MASS IS THE SAME WHEREVER YOU GO!





WE EVEN MEASURE WEIGHT AND MASS IN DIFFERENT UNITS. IN THE METRIC SYSTEM, THE **KILOGRAM** IS THE UNIT OF MASS, WHILE THE **NEWTON** IS THE UNIT OF WEIGHT. A PERSON "MASSING" 50 kg HAS A WEIGHT

$$W = mg$$
$$= (50\ \text{kg})(9.8\ \text{m/s}^2)$$
$$= 490\ \text{NEWTONS}$$

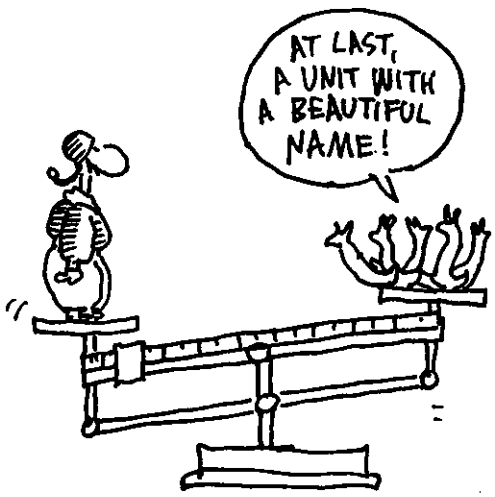
IT IS TECHNICALLY INCORRECT TO SAY THAT SOMETHING "WEIGHS" 50 kg. WEIGHT IS STATED IN UNITS OF FORCE, NEWTONS.

CONFUSING? LISTEN TO THIS: IN THE ENGLISH SYSTEM, THE UNIT OF FORCE IS THE **POUND**, WHILE THE UNIT OF MASS IS THE **SLUG**.

A PERSON WEIGHING 160 POUNDS HAS A MASS

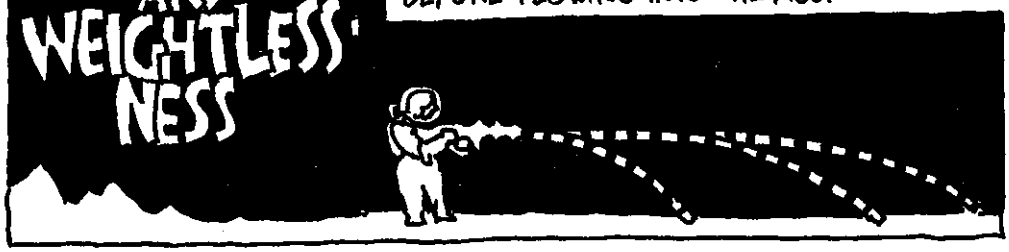
$$m = \frac{W}{g} = \frac{160\ \text{POUNDS}}{32\ \text{ft/sec}^2}$$

$$= 5\ \text{SLUGS}.$$

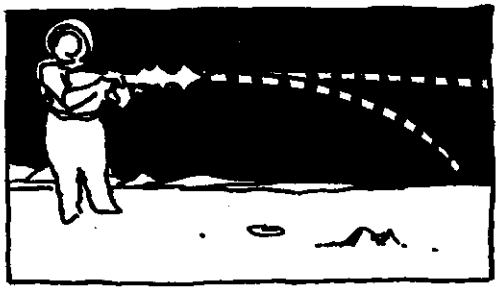


· CHAPTER 4 ·
SATELLITE MOTION AND WEIGHTLESSNESS

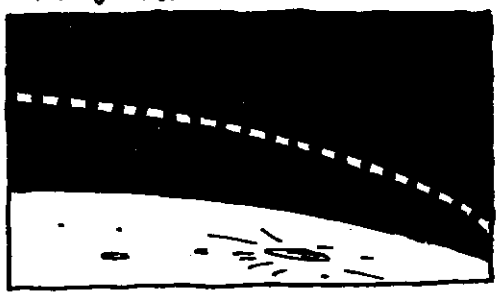
NOW WE'RE ON THE MOON, WHERE THERE'S NO AIR RESISTANCE. WATCH AS I FIRE BULLETS HORIZONTALLY WITH GREATER AND GREATER SPEED. EACH BULLET FALLS TO THE GROUND IN THE SAME TIME — THE HORIZONTAL MOTION DOESN'T AFFECT THE FALLING RATE — BUT THE FASTER BULLETS GO FARTHER BEFORE PLOWING INTO THE MOON.



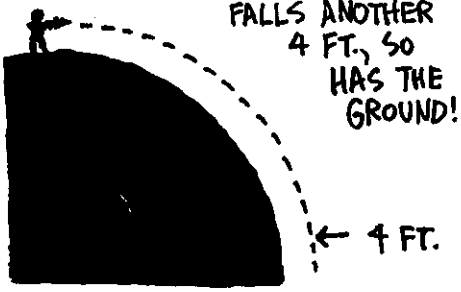
THE GUN IS 4 FEET OFF THE GROUND. ON EARTH, THE BULLET FALLS IN $\frac{1}{2}$ SEC., BUT HERE, WHERE GRAVITY IS WEAKER, IT TAKES 1.2 SEC. (AS LONG AS THE GROUND IS LEVEL).



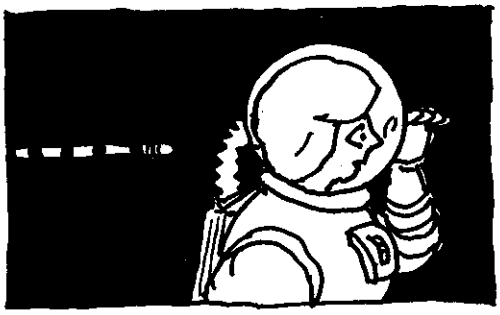
BUT AS THE BULLETS GO FARTHER, SOMETHING NEW HAPPENS: THE MOON ISN'T FLAT, IT'S ROUND!! THE GROUND STARTS CURVING DOWN UNDER THE BULLET AND AWAY FROM IT.



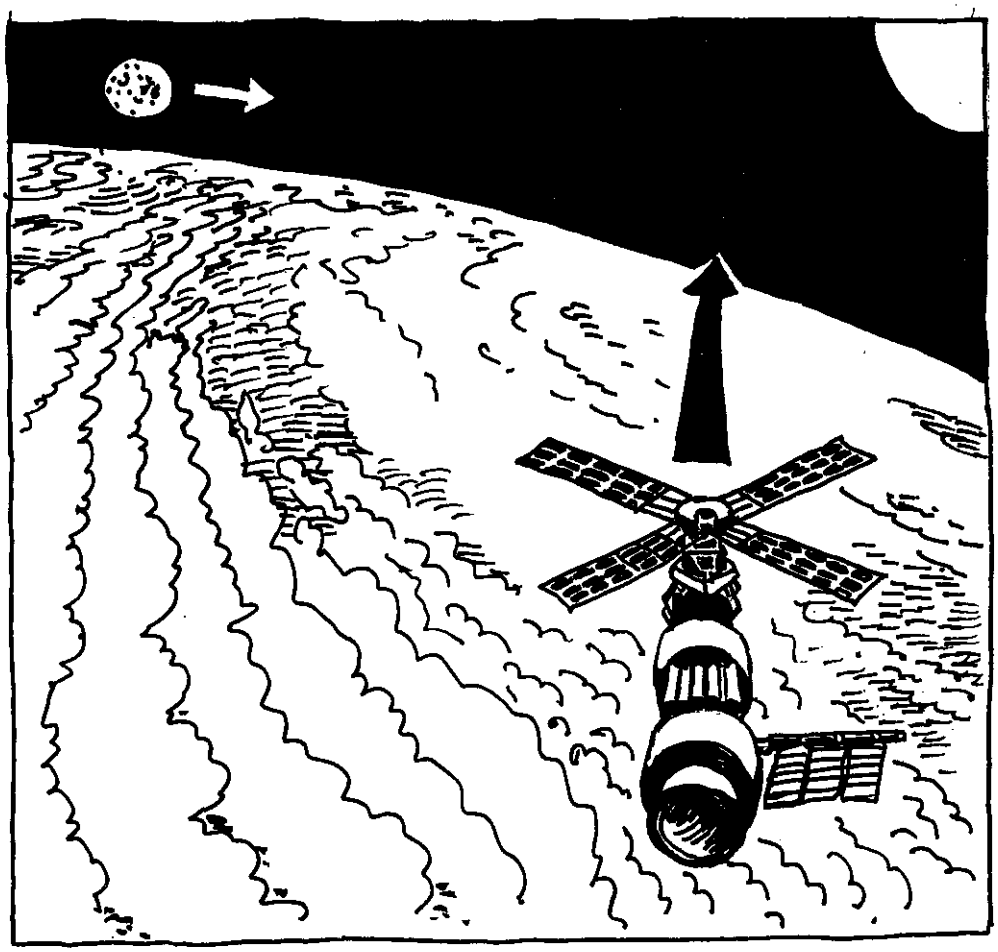
EVENTUALLY, AS I FIRE FASTER AND FASTER, BY THE TIME THE BULLET HAS FALLEN 4 FT., THE GROUND HAS CURVED 4 FT. DOWN AND THE BULLET IS **STILL** 4 FT. HIGH! BY THE TIME IT FALLS ANOTHER 4 FT., SO HAS THE GROUND!



THE BULLET IS NOW IN A 4-FOOT-HIGH **ORBIT** AROUND THE MOON. IT IS FALLING CONTINUALLY, BUT THE GROUND IS STEADILY CURVING AWAY BENEATH IT.

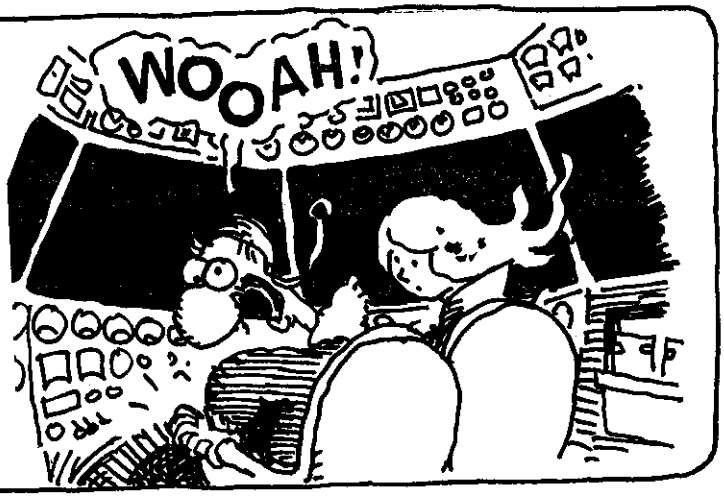


OF COURSE, THIS WORKS ONLY WHEN THERE IS NO AIR RESISTANCE (AND NO 4-FT-HIGH OBSTACLES!) TO SLOW THE BULLET, BUT THE EXPERIMENT ILLUSTRATES THE PRINCIPLE OF SATELLITE MOTION. FROM EARTH WE LAUNCH SATELLITES ABOVE THE ATMOSPHERE WITH ROCKETS, THEN TILT THEM OVER AND GIVE THEM ENOUGH **HORIZONTAL** SPEED SO THAT THE EARTH CURVES AWAY FROM THEM AS THEY FALL.

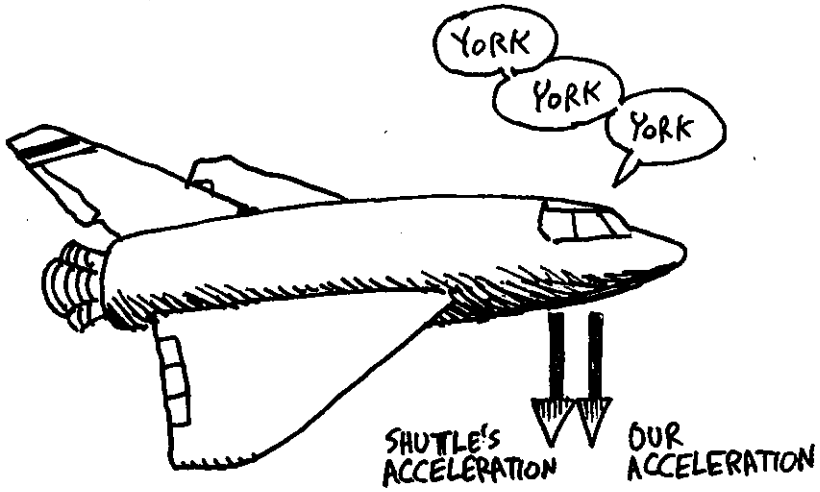


SIMILARLY, OUR NATURAL SATELLITE, THE MOON, FALLS CONTINUALLY, BUT ITS FORWARD MOTION CARRIES IT ALONG SO IT REMAINS THE SAME HEIGHT ABOVE EARTH. (THE MOON'S ORBIT IS CIRCULAR, OR NEARLY SO.)

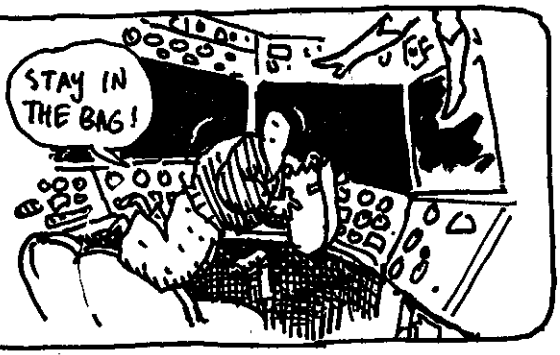
NOW LET'S GO UP IN THE SPACE SHUTTLE. AS WE REACH ORBITAL SPEED AND I CUT OFF THE ENGINES, THE ONLY FORCE ON US IS **GRAVITY**, AND WE FALL TOWARD EARTH.



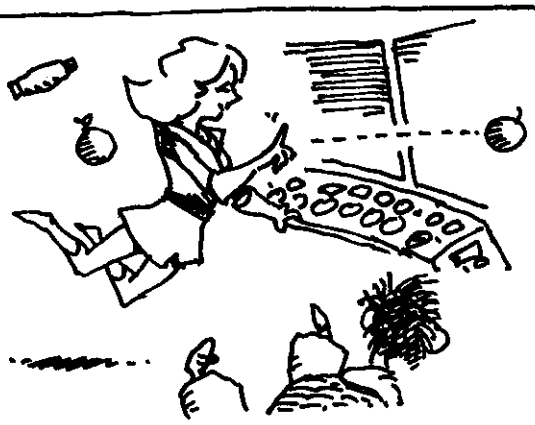
BUT THE SAME IS TRUE OF THE SHUTTLE ITSELF. IT'S ALSO FALLING, AND WITH THE SAME ACCELERATION



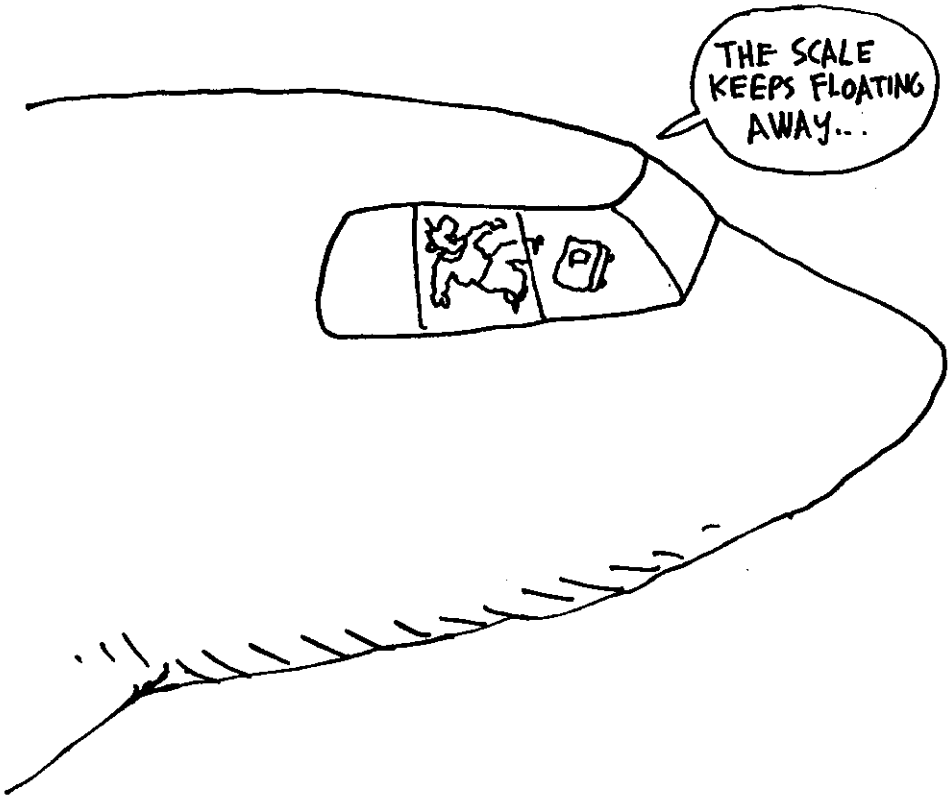
SO THERE IS NO NO RELATIVE MOTION BETWEEN US AND THE SHIP, AND WE FLOAT FREELY INSIDE, WEIGHTLESS!!

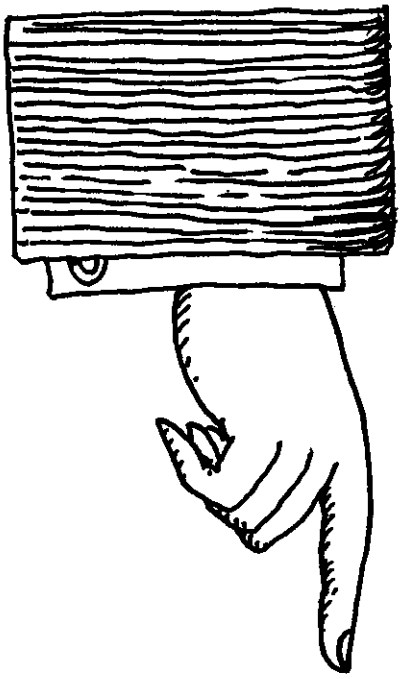


IF YOU RELEASE AN APPLE IN THE FALLING SHUTTLE, IT HANGS IN MID-AIR. GIVE IT A NUDGE AND IT TRAVELS IN A STRAIGHT LINE. IT OBEYS NEWTON'S FIRST LAW!



WHENEVER THE ONLY FORCE ON THE CRAFT IS GRAVITY, WHETHER IT'S COASTING UP, FALLING DOWN, OR IN ORBIT, OBJECTS INSIDE ARE **WEIGHTLESS**.

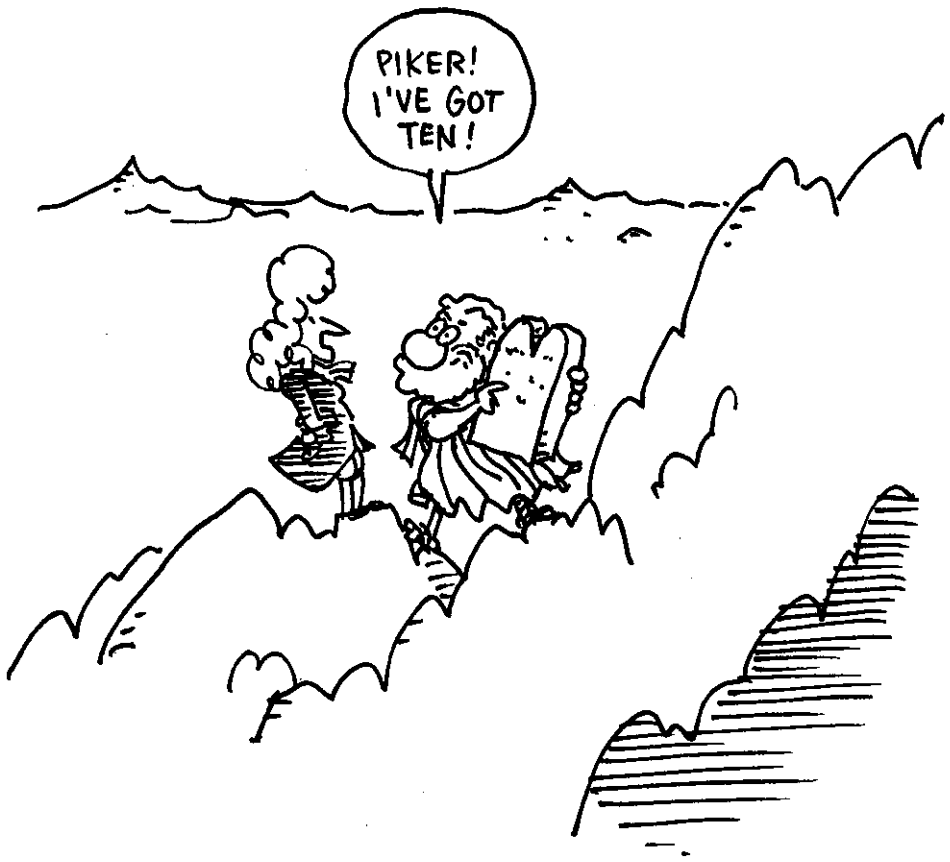




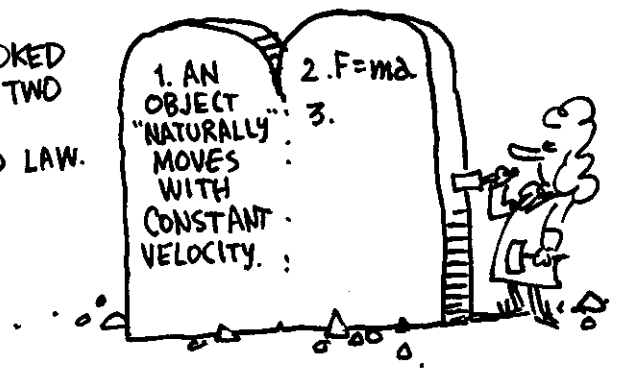
THUS, ALTHOUGH GRAVITY PRODUCES ACCELERATION, NO **ACCELERATION FORCES** ARE FELT WITHIN THE FALLING SYSTEM.

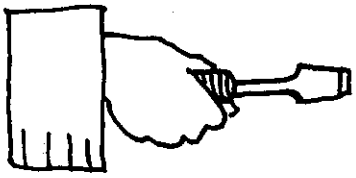
THIS WAS ANOTHER HINT TO EINSTEIN THAT GRAVITY IS A PROPERTY OF SPACE, RATHER THAN OBJECTS.

◊CHAPTER 6◊
NEWTON'S THIRD LAW



SO FAR, WE HAVE LOOKED AT NEWTON'S FIRST TWO LAWS: NOW LET'S LOOK AT HIS THIRD LAW. IT IS:



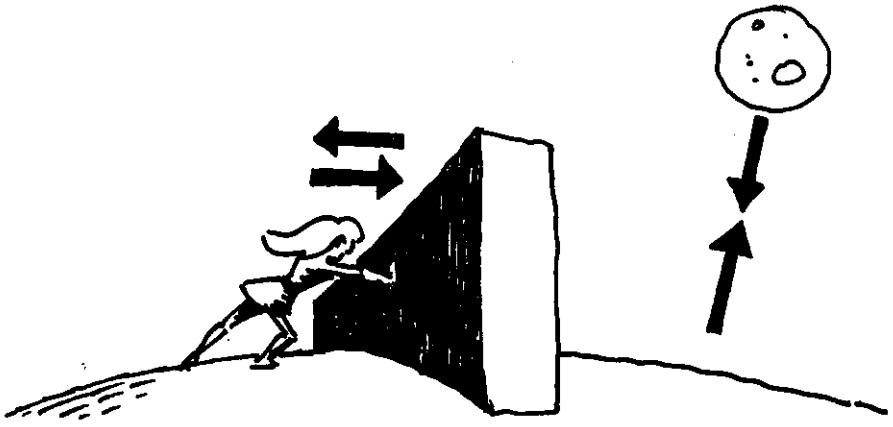


NEWTON'S THIRD LAW: WHEN ONE OBJECT EXERTS A FORCE ON A SECOND OBJECT, THE SECOND OBJECT EXERTS AN EQUAL BUT OPPOSITE FORCE ON THE FIRST.

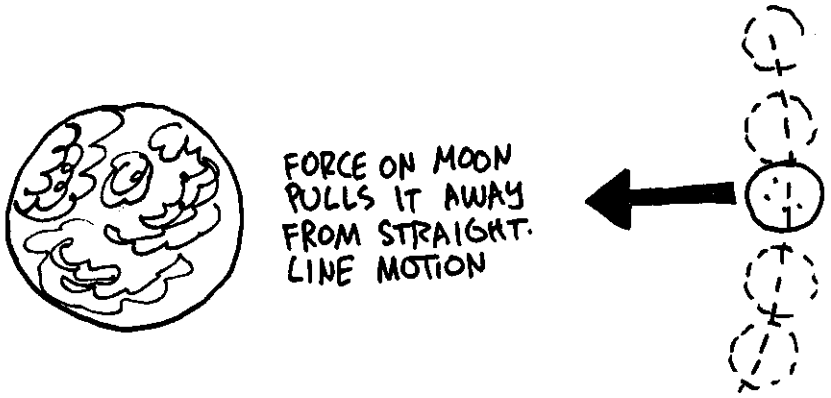
IN OTHER WORDS,

ACTION EQUALS REACTION.

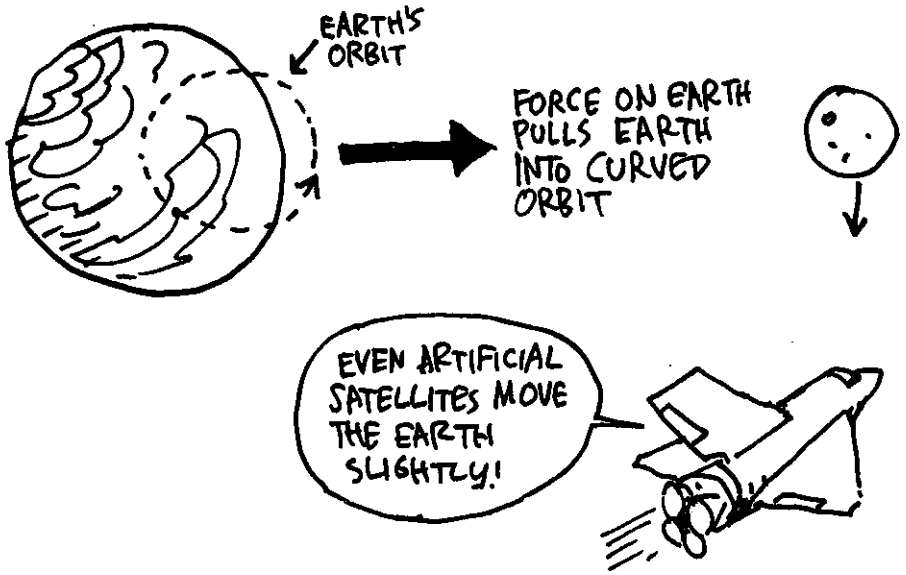
FOR EXAMPLE, WHEN I PUSH ON A WALL, THE WALL PUSHES BACK WITH EQUAL FORCE. THE EARTH'S GRAVITATIONAL PULL ON THE MOON EQUALS THE MOON'S PULL ON THE EARTH.



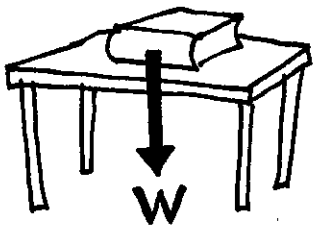
THE EARTH'S PULL ON THE MOON KEEPS THE MOON IN A (NEARLY) CIRCULAR ORBIT. BUT WHAT ABOUT THE MOON'S PULL ON THE EARTH?



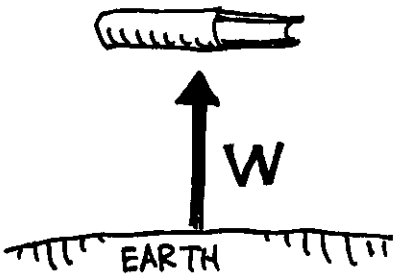
IN FACT, THE MOON PULLING BACK WITH EQUAL FORCE DOES CAUSE THE EARTH TO EXECUTE A SMALL ORBIT! THE EARTH MOVES LESS THAN THE MOON—ACCELERATES LESS- BECAUSE IT IS MUCH MORE MASSIVE.



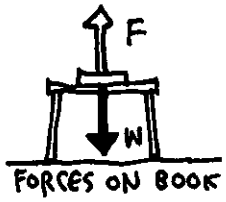
HERE IS A BOOK ON A TABLE. WHAT IS THE FORCE OPPOSITE TO THE BOOK'S WEIGHT **W**? **NOT** THE SUPPORT FORCE FROM THE TABLE!



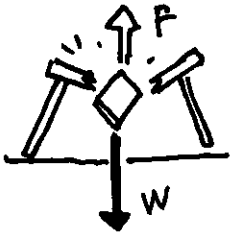
THE SECOND BODY CAUSING THE FORCE **W** ON THE BOOK IS — **The EARTH!** THE EARTH PULLS THE BOOK WITH FORCE **W**, SO THE BOOK PULLS UP ON THE ENTIRE EARTH WITH FORCE **W**!



BUT DOESN'T THE TABLE PUSH UP ON THE BOOK? YES, IN THIS CASE. THE BOOK IS NOT ACCELERATING, SO, BY NEWTON'S SECOND LAW, THE TOTAL FORCE ON IT IS ZERO. SINCE THE EARTH PULLS DOWN ON THE BOOK, SOMETHING ELSE MUST BE PUSHING IT UP — NAMELY THE TABLE, AND **F = W**. BUT THIS IS A SPECIAL CASE! IF THE TABLE WASN'T STRONG ENOUGH TO SUPPORT THE BOOK, THE UP-PUSH WOULD BE LESS THAN **W**, AND THE BOOK WOULD BREAK THE TABLE AND FALL!

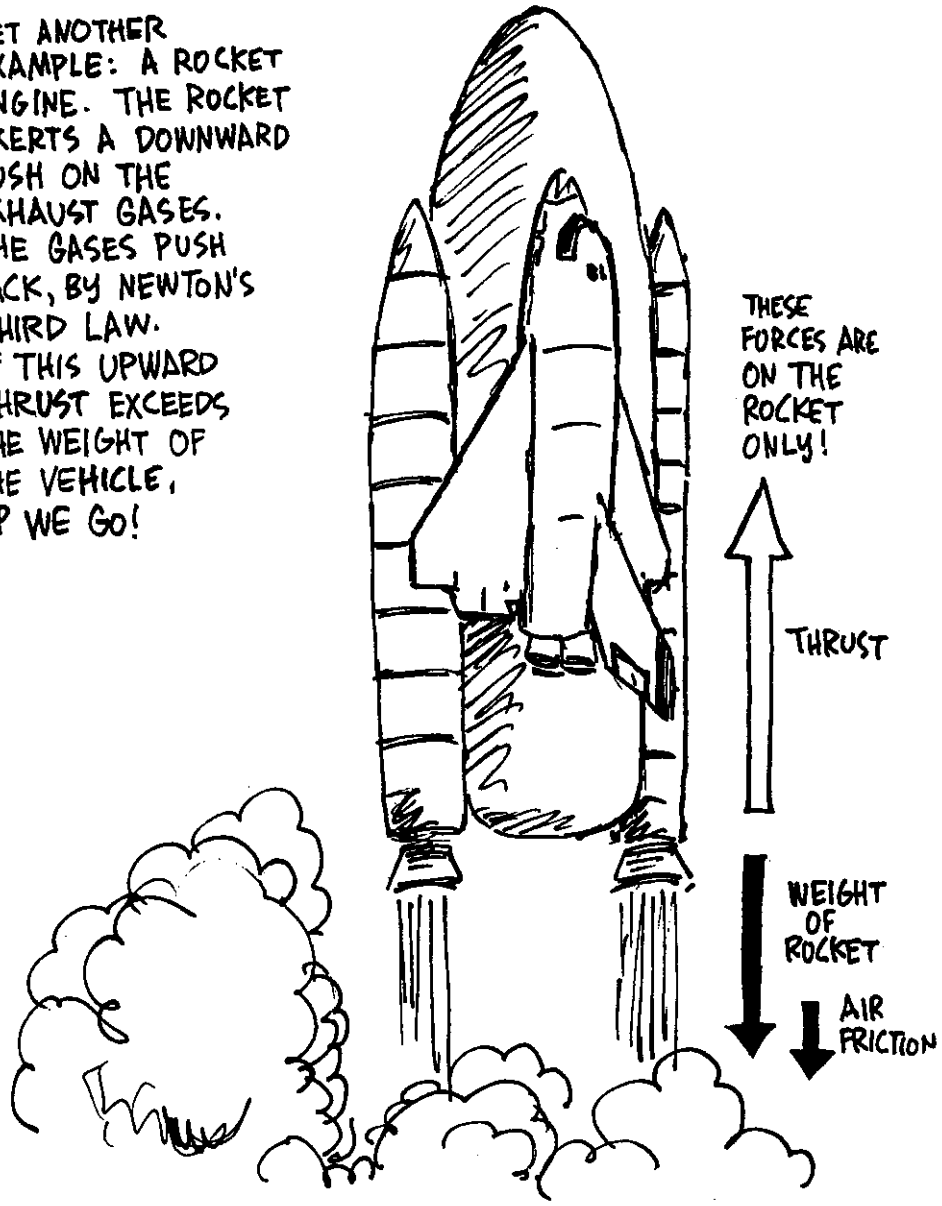


F = W

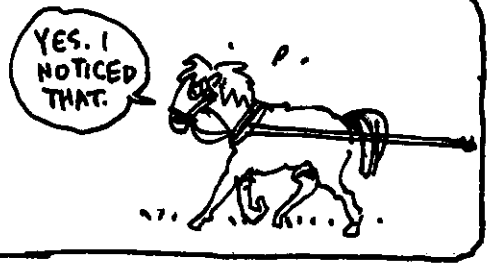


F < W

YET ANOTHER EXAMPLE: A ROCKET ENGINE. THE ROCKET EXERTS A DOWNWARD PUSH ON THE EXHAUST GASES. THE GASES PUSH BACK, BY NEWTON'S THIRD LAW. IF THIS UPWARD THRUST EXCEEDS THE WEIGHT OF THE VEHICLE, UP WE GO!

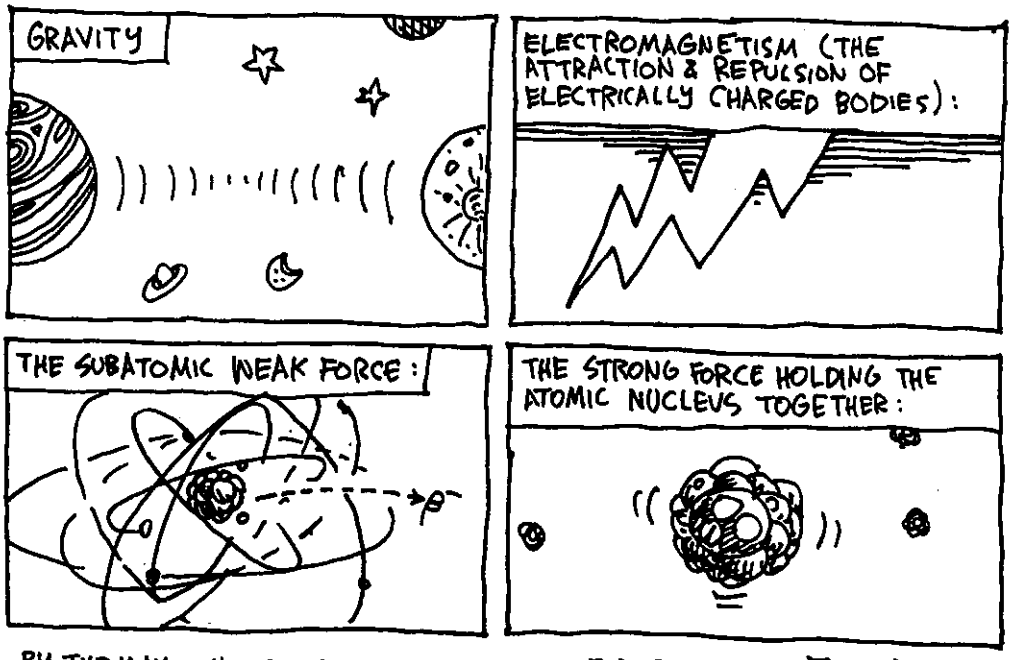


NOTE: IT IS NOT NECESSARY FOR THE ESCAPING GASES TO PUSH AGAINST AIR. IN FACT, AIR JUST ACTS AS A FRICTIONAL DRAG ON THE ROCKET.



WE SEE SUCH A VARIETY OF FORCES, THAT IT MAY SEEM HOPELESS TO TRY AND ORGANIZE THEM. NEVERTHELESS, PHYSICISTS HAVE BEEN ABLE TO SHOW THAT ALL THE KNOWN EFFECTS IN THE UNIVERSE ARE THE RESULT OF THESE

4 BASIC FORCES:



BY THE WAY, THE ONLY ONE OF THE BASIC FORCES YOU'VE EVER FELT IS ELECTROMAGNETISM!! WHEN YOU PUSH THE WALL (AND IT PUSHES BACK), YOU'RE FEELING ELECTRIC REPULSION BETWEEN ATOMS. YOU HAVE NEVER FELT GRAVITY — ONLY THE ELECTRIC FORCES OF THE FLOOR THAT SUPPORT YOU AGAINST GRAVITY.