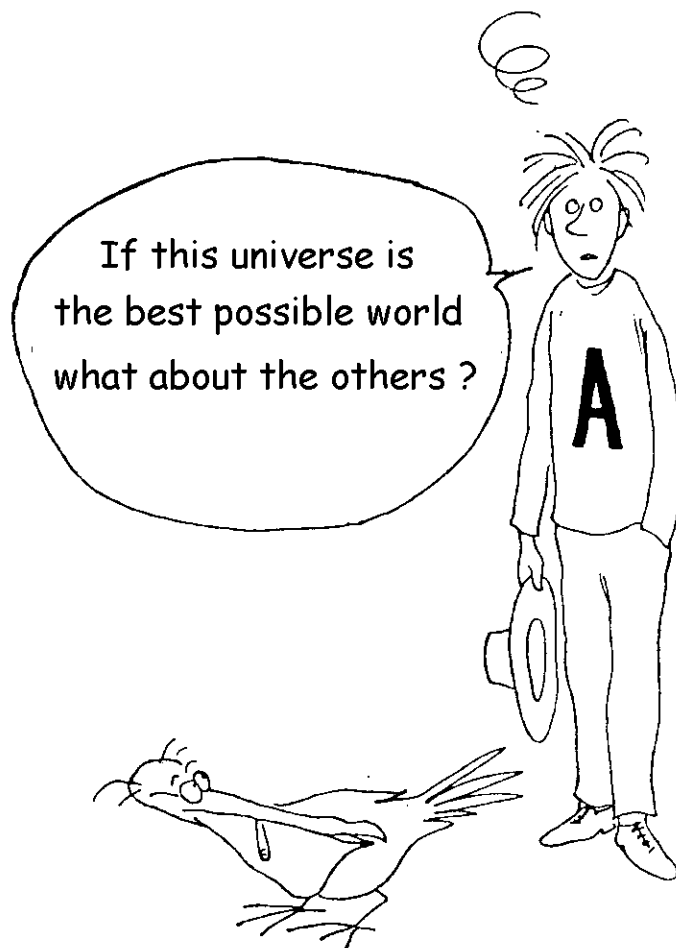


Jean-Pierre Petit

# BLACK HOLE



The Association Knowledge without Borders, founded and chaired by Professor Jean-Pierre Petit, astrophysicist, aims at spreading scientific and technical knowledge in as many countries as possible and in as many languages as possible. To this end, all his popular scientific works, which cover a period of thirty years, and more particularly the illustrated albums he has created, are now freely accessible. Anyone is now free to duplicate the present file, either in digital form or in the form of printed copies and circulate these copies to libraries, within the context of schools or universities or associations whose aims would be the same as the association, provided that they do not derive any profit from this circulation and that they do not have any political, sectarian or confessional connotations. These pdf files may also be put on line in the computer networks of school and university libraries.



Jean-Pierre Petit intends to create numerous other works which will be accessible to a larger audience. Even illiterate people will be able to read them because the written parts will “speak” when the readers click on them. Thus it will be possible to use these works to support literacy schemes. Other albums will be “bilingual” in so far as it will be possible to switch from one language to another selected language with a mere click. Hence another tool made available to develop language skills.

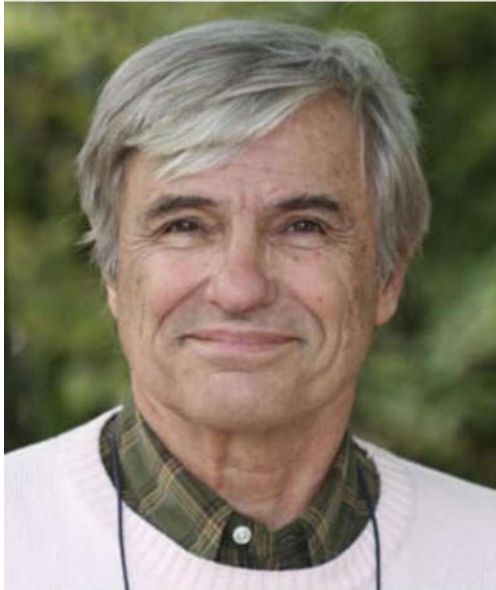
Jean-Pierre Petit was born in 1937. He made his career in French research. He worked as a plasma physicist, he directed a computer science centre, he has created softwares, he has published hundreds of articles in scientific magazines, dealing with subjects ranging from fluid mechanics to theoretical cosmology. He has published about thirty books which have been translated in numerous languages.

The association can be contacted on the following internet site:

**<http://savoir-sans-frontieres.com>**

# Knowledge without Borders

**Non-profit-making association created in 2005 and managed by two French scientists. Aim: to disseminate scientific knowledge using the band drawn through free downloadable PDFs. In 2020: 565 translations in 40 languages had thus been achieved. With more than 500,000 downloads.**



**Jean-Pierre Petit**




**Gilles d'Agostini**

**The association is totally voluntary. The money donated entirely to the translators.**

**To make a donation, use the PayPal button on the home page:**

<http://www.savoir-sans-frontieres.com>



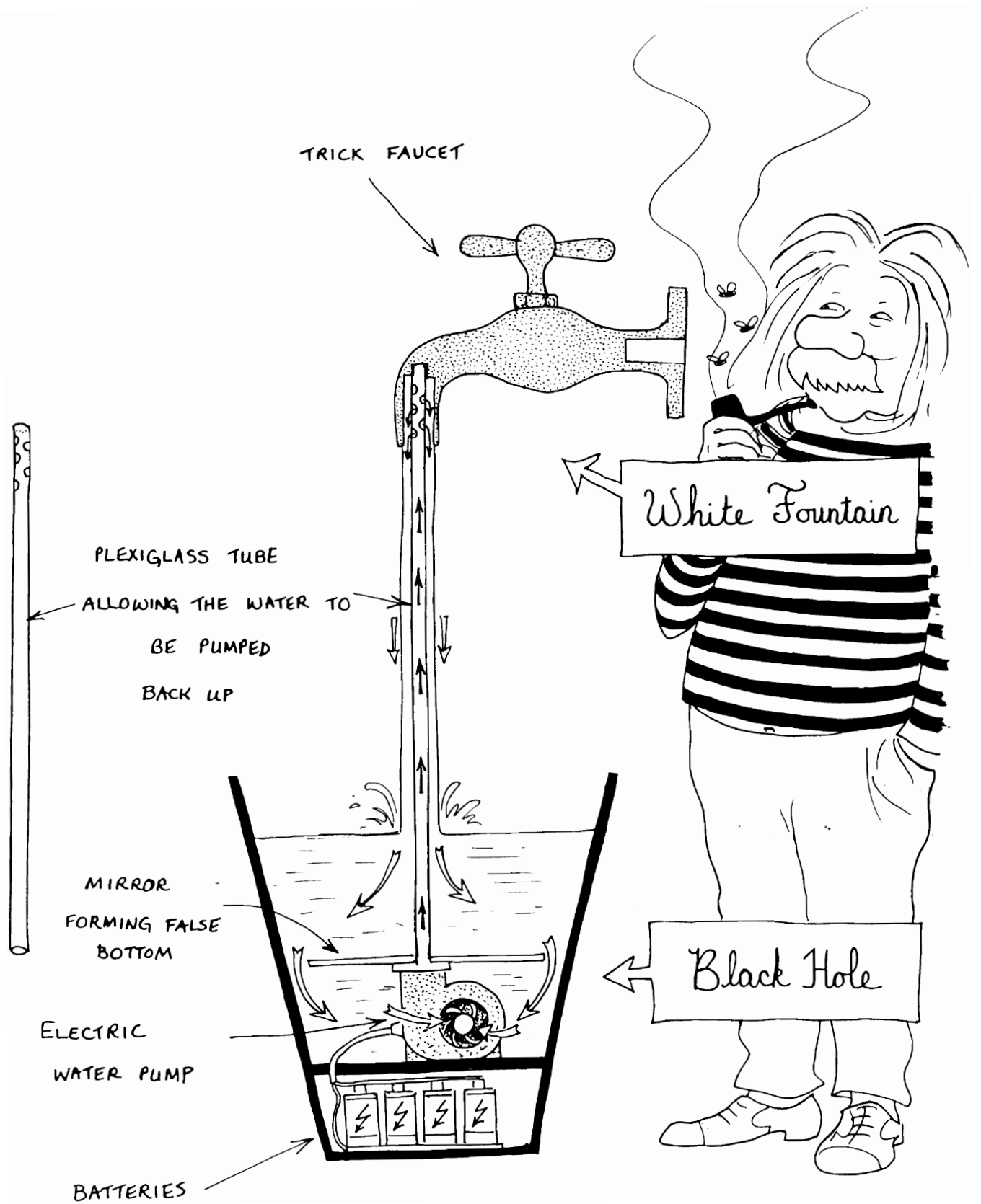


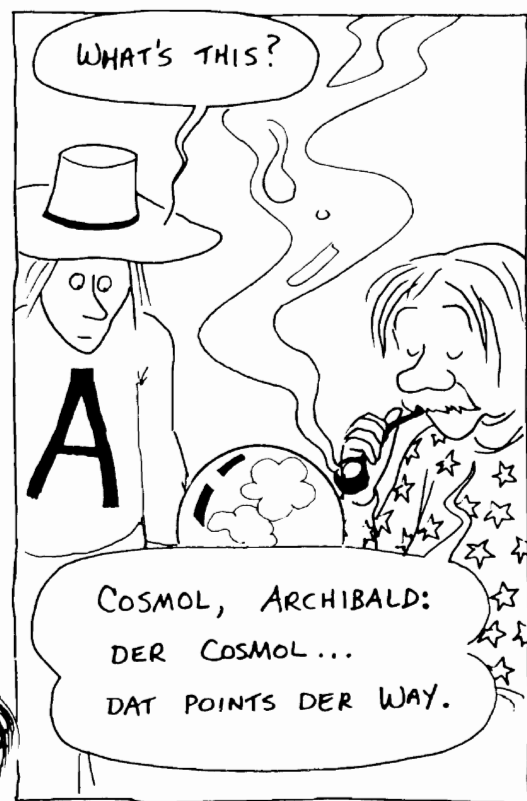
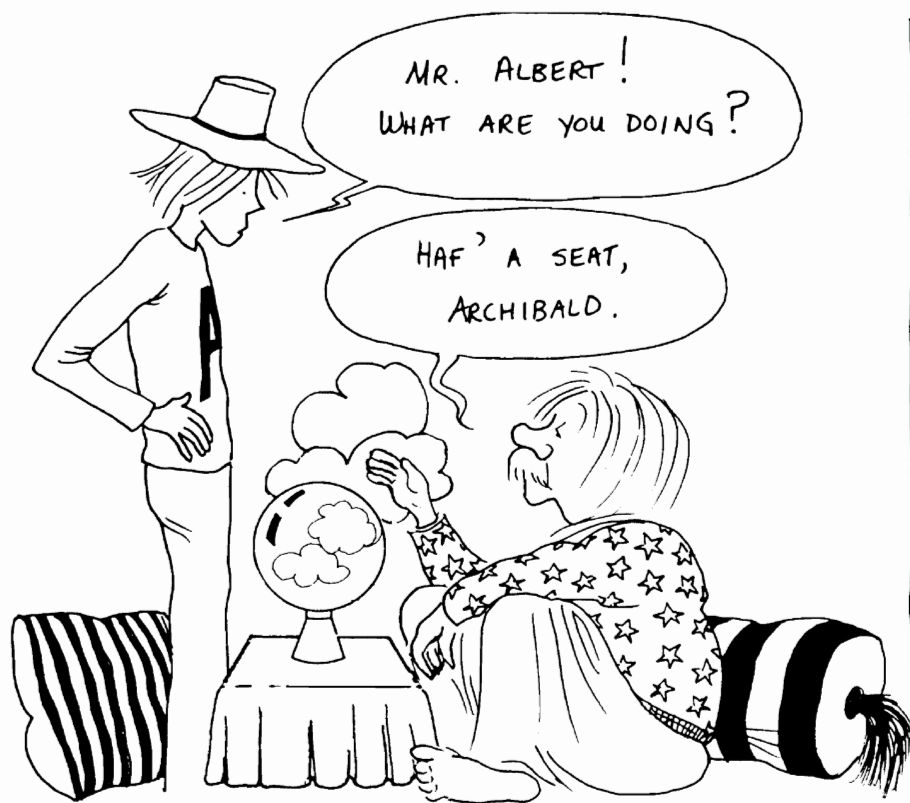
THE FAUCET'S FLOATING IN  
MID-AIR — SO WHERE DOES THE  
WATER COME FROM?

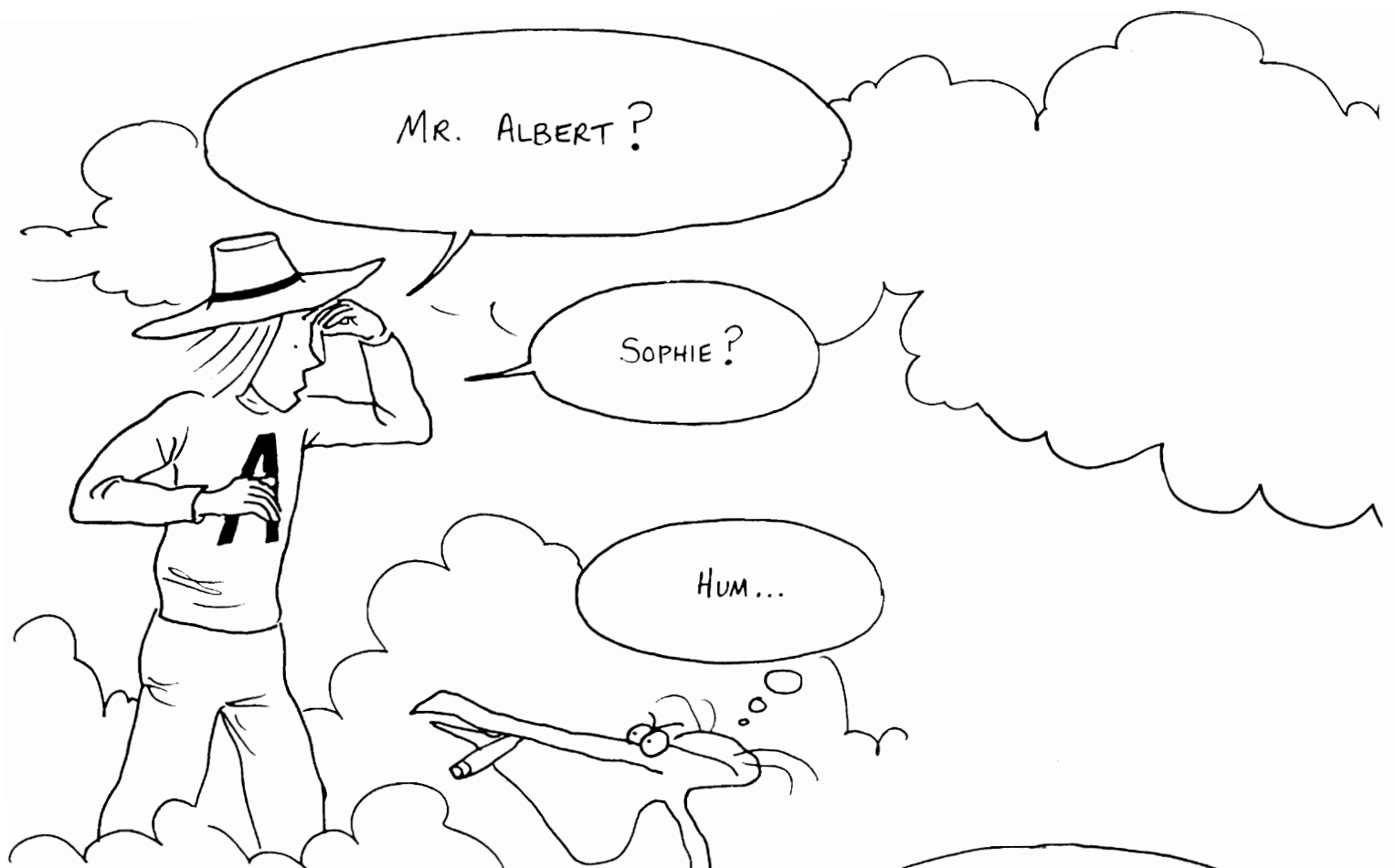
HMMM...

FOR THAT MATTER —  
WHERE DOES IT GO TO?  
THE LEVEL IN THE BUCKET  
NEVER CHANGES.

IT KEEPS FLOWING,  
ALL THE SAME.

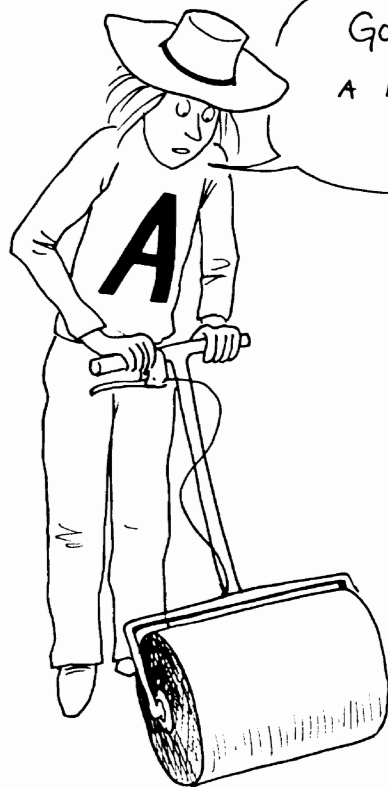




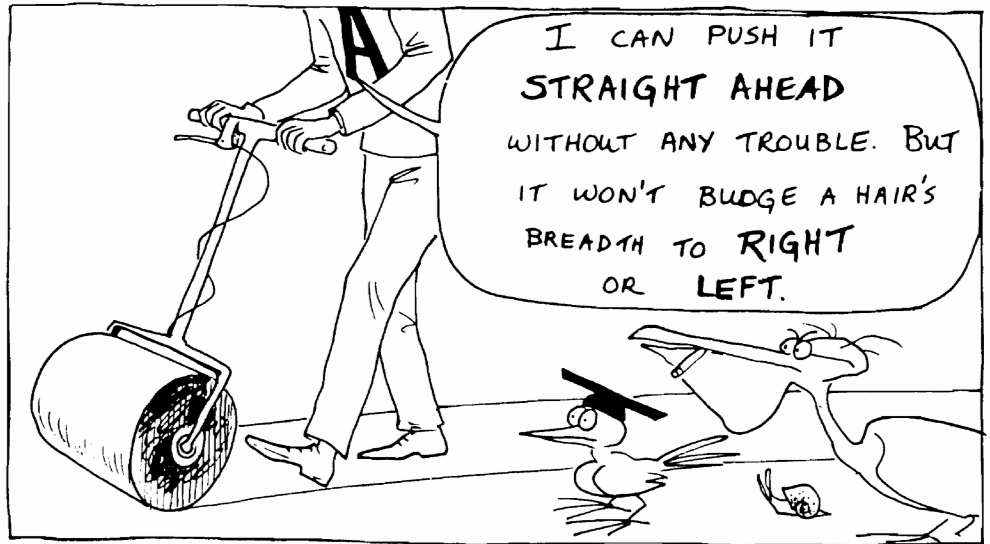


ONCE MORE, ARCHIE  
SETS OUT TO EXPLORE  
THE WORLD OF MISTS.

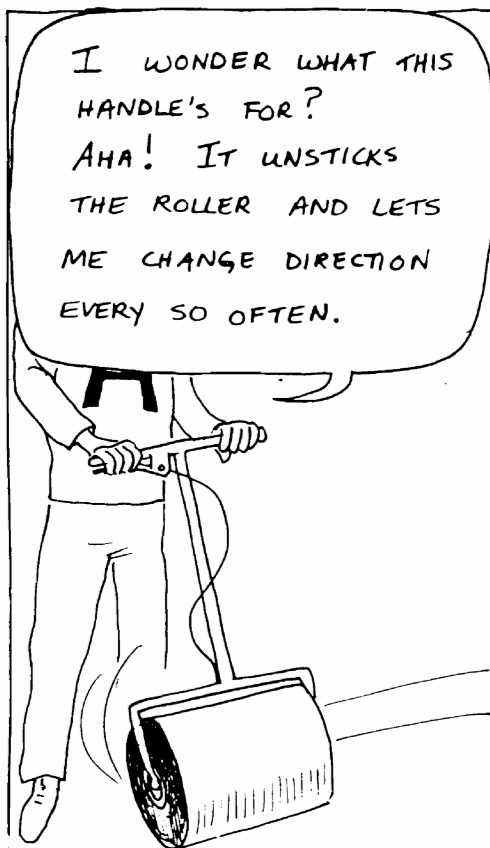




GOSH, WHAT'S THIS GADGET? IT LOOKS LIKE A ROLLER FOR A TENNIS COURT... OR MAYBE FOR PAINTING THINGS.

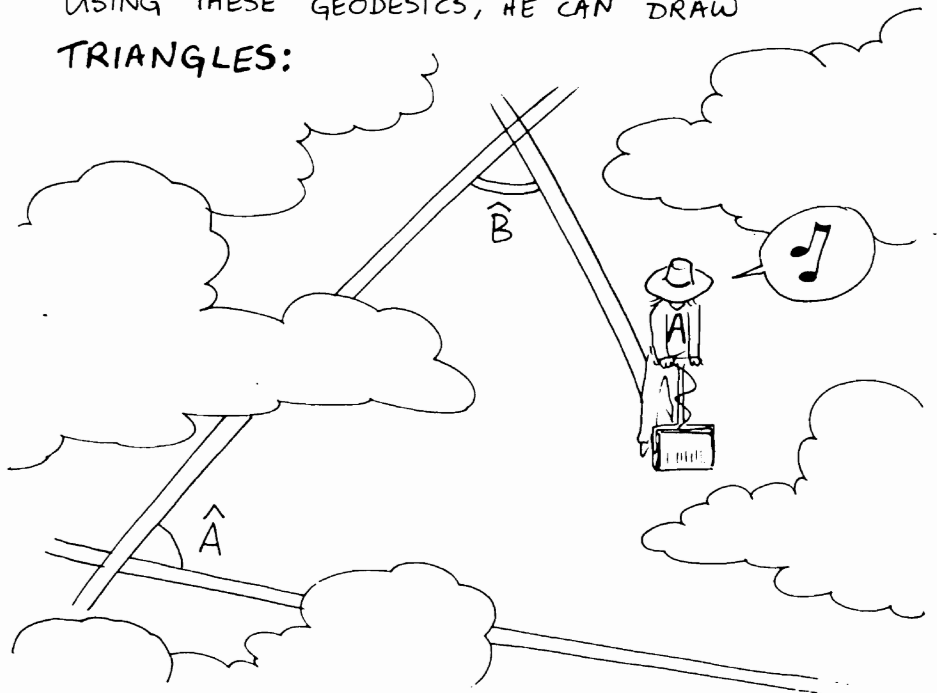


I CAN PUSH IT STRAIGHT AHEAD WITHOUT ANY TROUBLE. BUT IT WON'T BUDGE A HAIR'S BREADTH TO RIGHT OR LEFT.



I WONDER WHAT THIS HANDLE'S FOR? AHA! IT UNSTICKS THE ROLLER AND LETS ME CHANGE DIRECTION EVERY SO OFTEN.

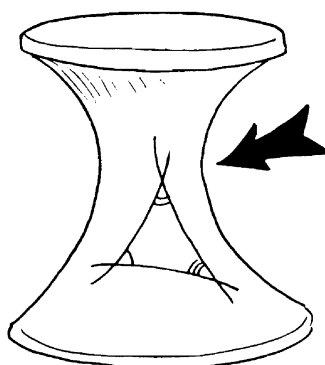
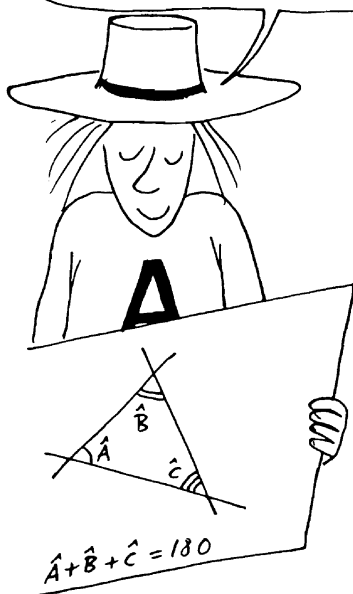
WITH THE AID OF THIS STRANGE DEVICE, ARCHIE CAN DRAW GEODESICS ON A SURFACE. USING THESE GEODESICS, HE CAN DRAW TRIANGLES:



A SURFACE IS A 2-DIMENSIONAL SPACE. THAT IS, YOU NEED TWO NUMBERS—TWO COORDINATES—TO SPECIFY THE POSITION OF A POINT.

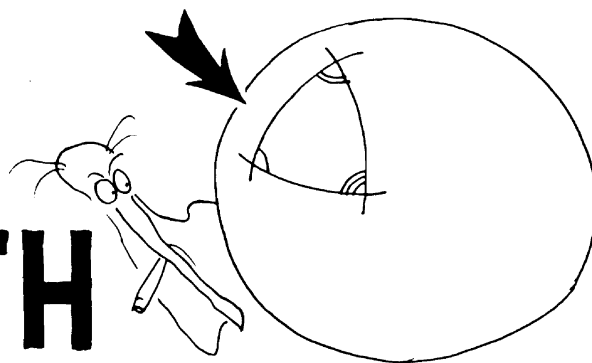


LESSEE ... IF THE SPACE IS EUCLIDEAN, THEN THE SUM OF THE ANGLES OF A TRIANGLE IS  $180^\circ$ .\*

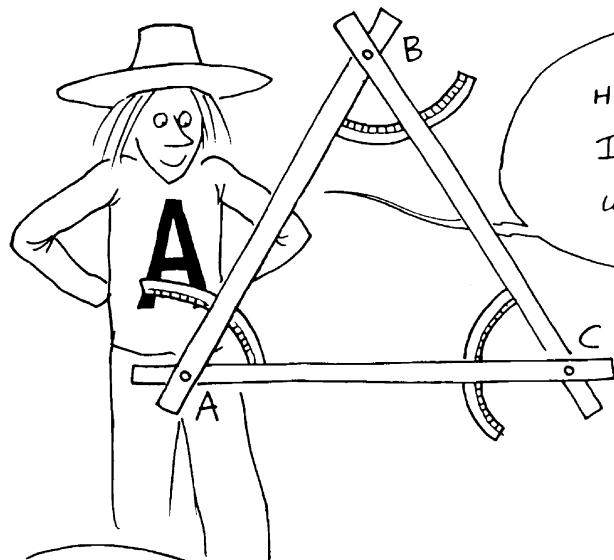


WHEN THE SPACE HAS NEGATIVE CURVATURE, THE SUM IS LESS THAN  $180^\circ$ .

IN A SPACE OF POSITIVE CURVATURE, IT'S GREATER THAN  $180^\circ$ .



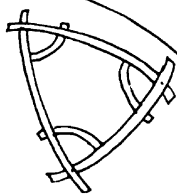
# SPACES WITH VARIABLE CURVATURE



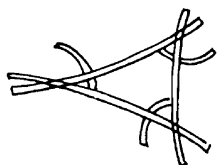
HERE'S THE CUNNING INVENTOR WITH HIS NEW BRAINCHILD, THE CURVIMETER. IT'S MADE FROM THREE FLEXIBLE STRIPS WHICH CAN TURN FREELY ABOUT THREE RIVETS A, B, AND C.



TO FIND THE LOCAL CURVATURE IT SUFFICES TO LAY THE CURVIMETER ON THE SURFACE AND MEASURE THE ANGLES WITH THE BUILT-IN PROTRACTORS.



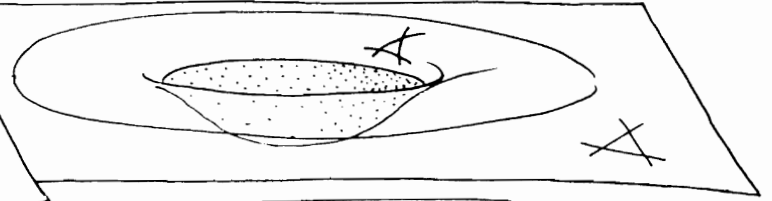
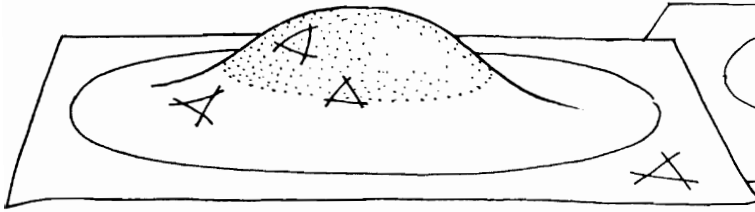
POSITIVE CURVATURE



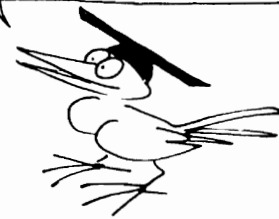
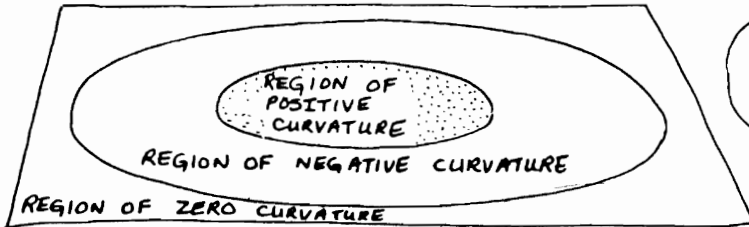
NEGATIVE CURVATURE

(\*) FOR FURTHER DETAILS, SEE HERE'S LOOKING AT EUCLID IN THE SAME SERIES.

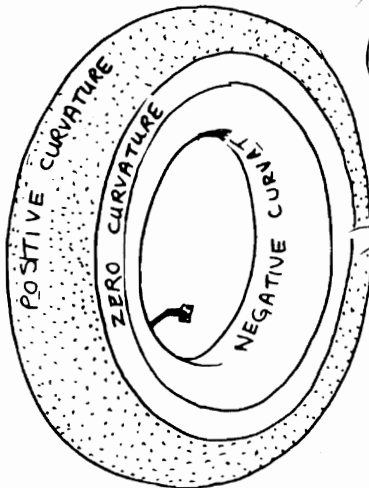
THIS BUMP IN THE PLANE IS MADE FROM A CENTRAL REGION OF POSITIVE CURVATURE, SURROUNDED BY A REGION OF NEGATIVE CURVATURE.



FROM THE POINT OF VIEW OF CURVATURE, A DENT IS JUST LIKE A BUMP.

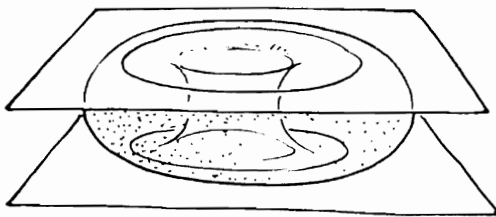


CRUIKEY, IF I AIN'T MISTAKEN, H'IT'S A BLINKIN' TORUS.



I'M A VIRGO MYSELF...  
OH, I SEE. YES, THERE'S A BAND OF POSITIVE CURVATURE AND A BAND OF NEGATIVE CURVATURE, SEPARATED BY A FRONTIER HAVING ZERO CURVATURE.

TO FIND THE FRONTIER, MAKE A TORUSBURGER USING TWO PLANES FOR BUNS.



TIRESIAS, OLD FRUIT, 'AS IT EVER STRUCK YER THAT YER SHELL IS JUST A TWO-DIMENSIONAL SPACE WIV VARIABLE CURVYTURE?

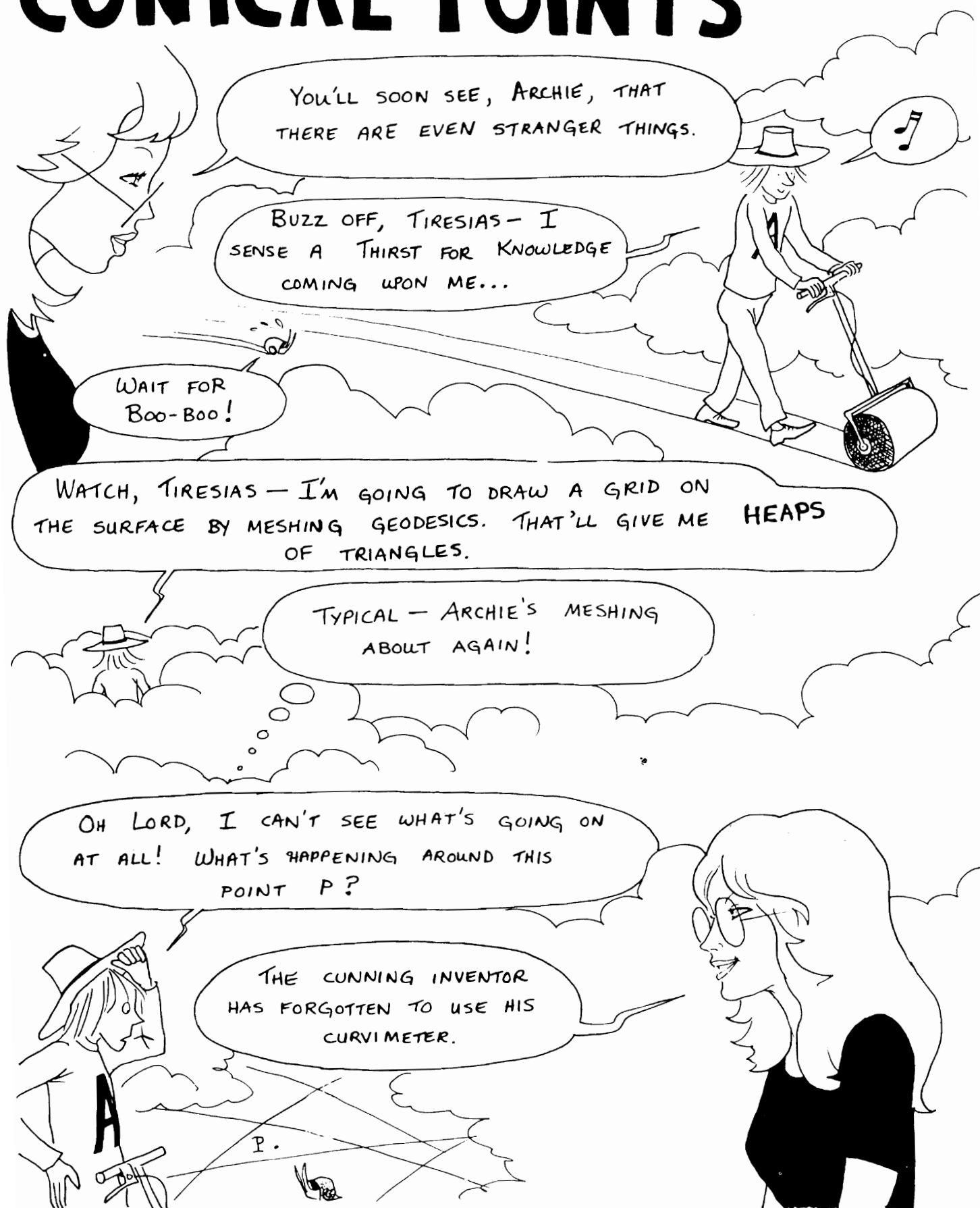
LENNY, STOP BUGGING TIRESIAS!



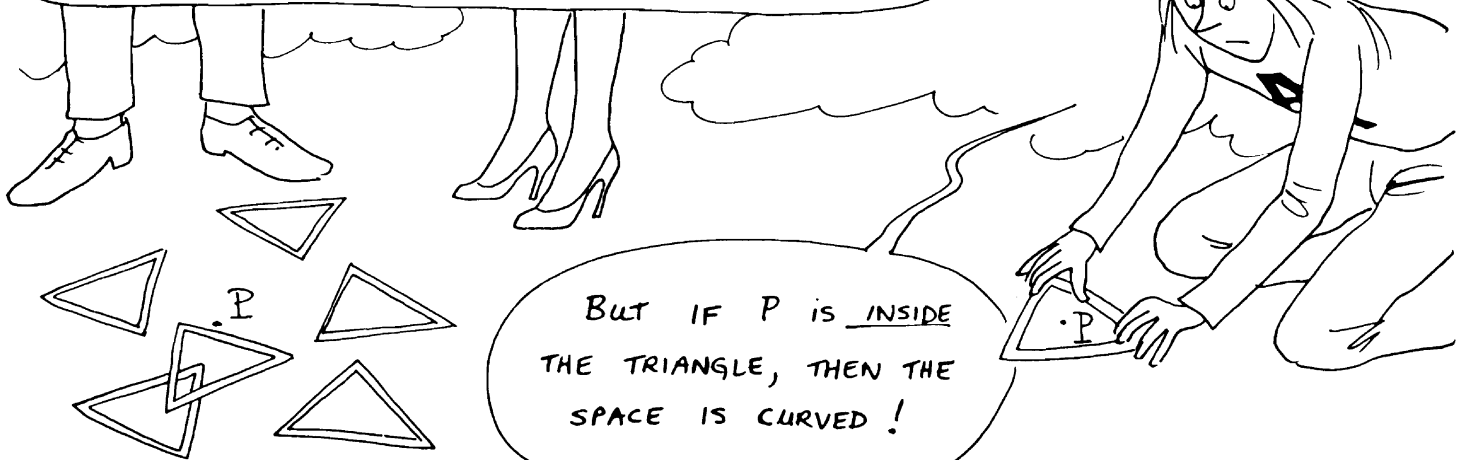
EEEP!



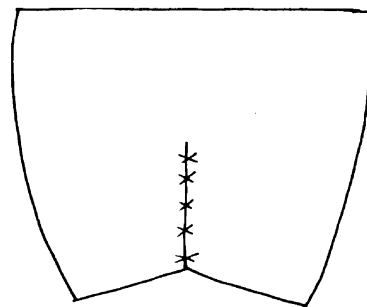
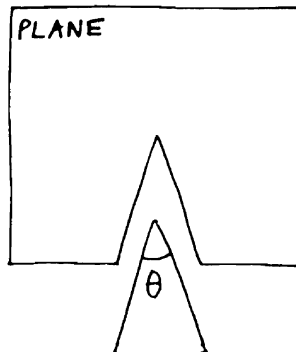
# CONICAL POINTS



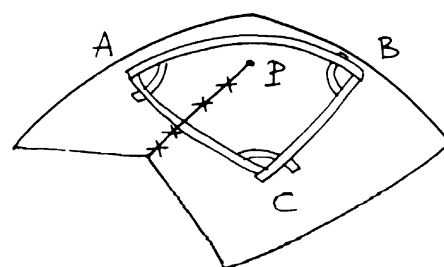
HEY, SOPHIE - WHAT'S GOING ON? IF THE CURVIMETER'S TRIANGLE DOESN'T CONTAIN THE POINT P, IT SAYS THE CURVATURE IS ZERO.



IT'S A CONICAL POINT. LOOK - SUPPOSE I TAKE A PLANE, CUT OUT A SECTOR WITH ANGLE  $\theta$ , AND JOIN IT UP AGAIN.



I GET A KIND OF CONE, WHICH WE'LL CALL A POSICONE.

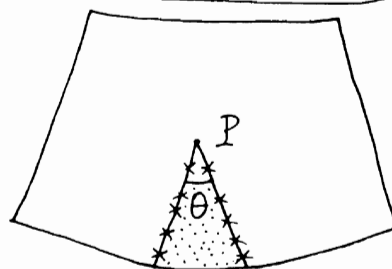
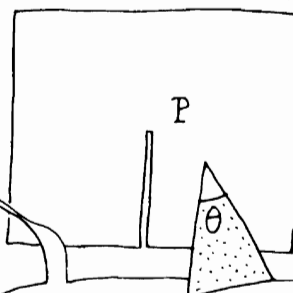


$$\hat{A} + \hat{B} + \hat{C} = 180^\circ + \theta$$

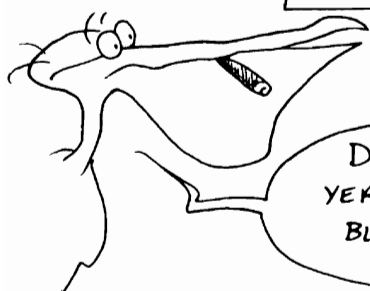


YOU CAN TEST IT OUT WITH A PIECE OF CARDBOARD. A ROLL OF STICKY TAPE WILL HELP YOU FIND GEODESICS EASILY.

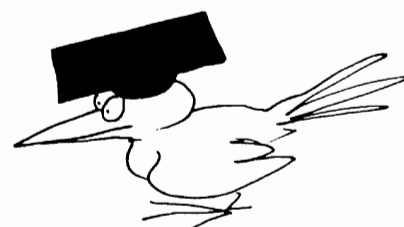
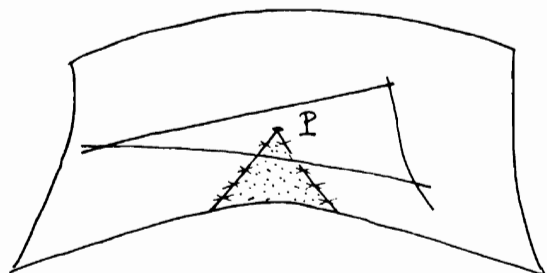
OH, I SEE! IF MY TRIANGLE CONTAINS THE TIP OF A CONE THEN THE SUM OF THE ANGLES IS ALWAYS GREATER THAN  $180^\circ$ .



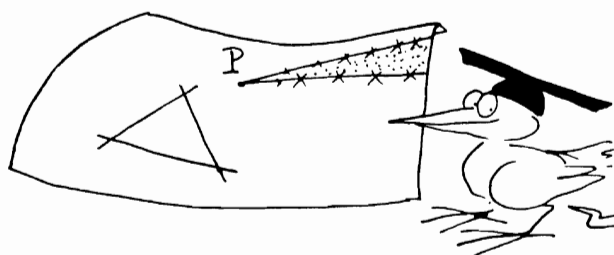
HOLD YOUR HORSES! IT'S NOT THAT SIMPLE! SUPPOSE INSTEAD I SLIT THE PLANE AND ADD A SECTOR WITH ANGLE  $\theta$ .



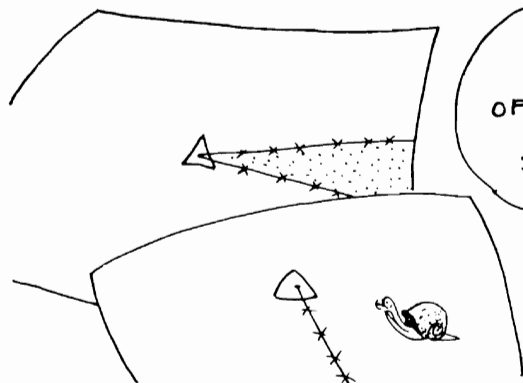
DON' TELL ME—  
YER GETS A  
BLINKIN' **NEGACONE**.



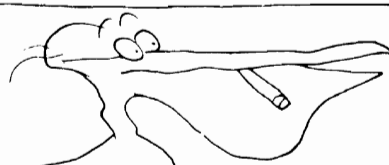
THIS TIME, IF THE TRIANGLE CONTAINS THE POINT P, THE ANGLE-SUM WILL BE  $180^\circ - \theta$ , SMALLER THAN  $180^\circ$ .

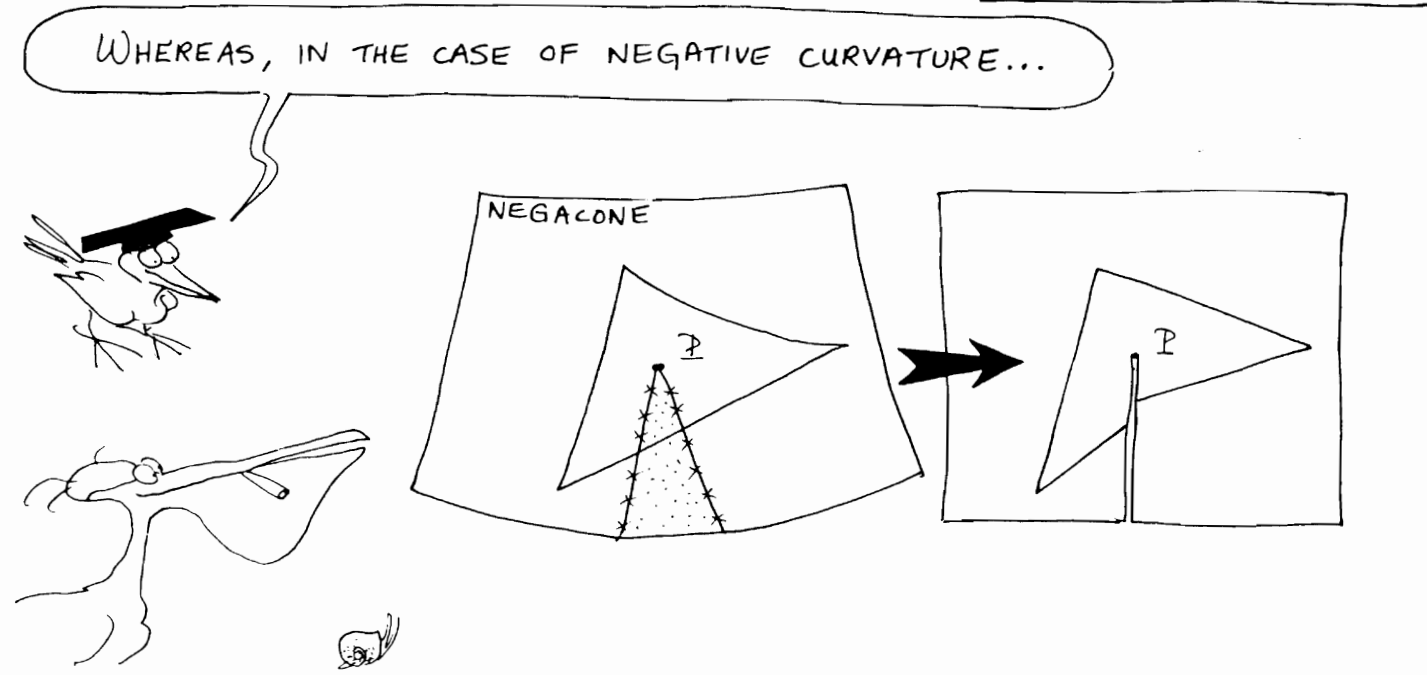
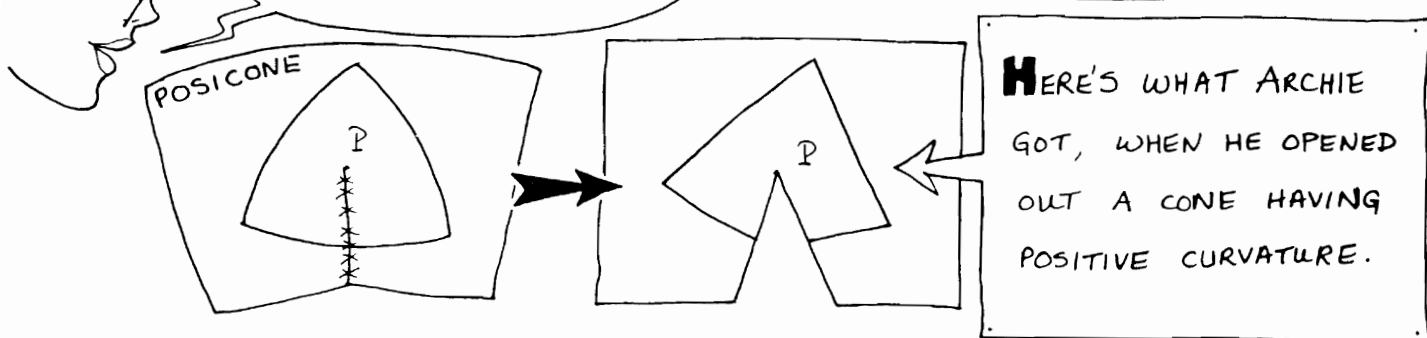
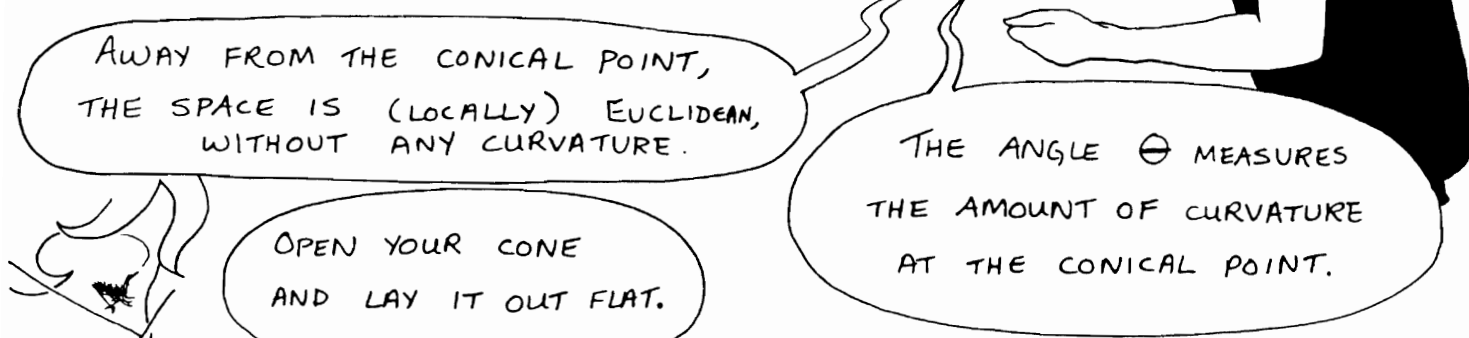
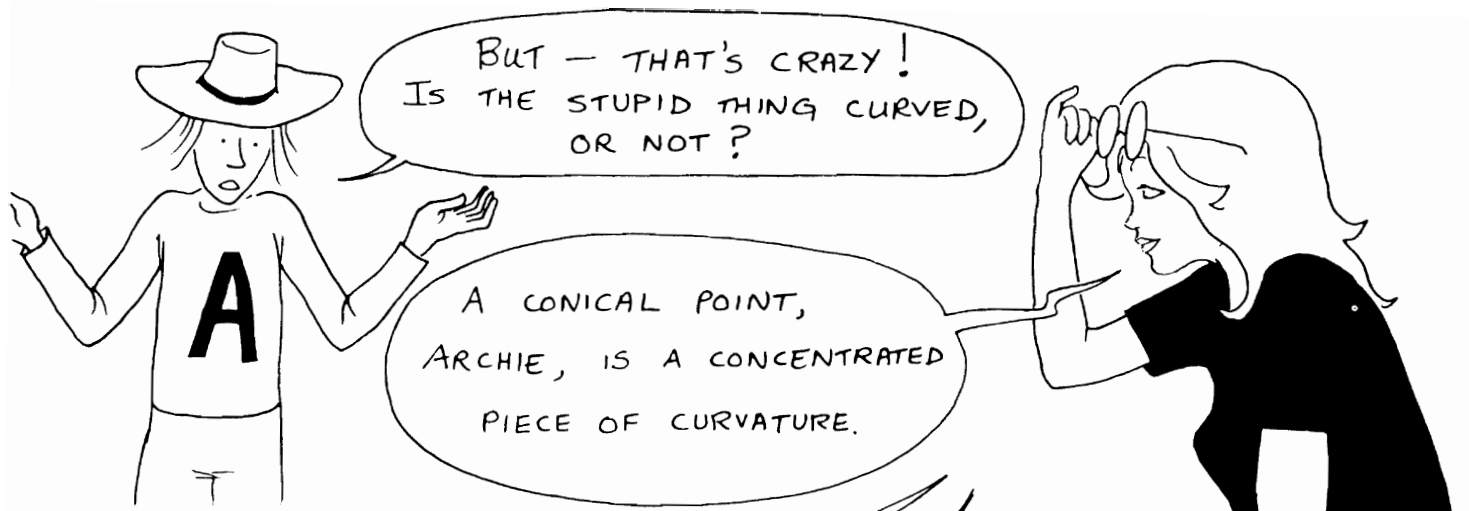


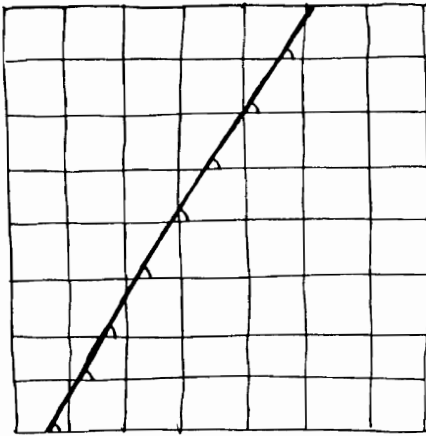
BUT IF THE POINT IS OUTSIDE THE TRIANGLE, THE SUM IS  $180^\circ$  AGAIN.



THIS PROPERTY OF CONES IS INDEPENDENT OF THE SIZE OF THE TRIANGLE: YOU GET THE SAME RESULT WHETHER IT'S LARGE OR SMALL.





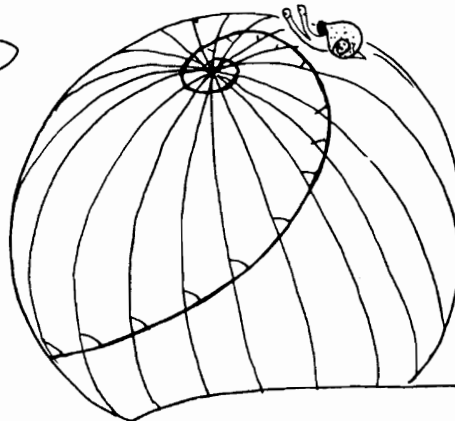


TAKE A **PLANE** SURFACE AND RULE IT WITH GEODESICS TO FORM A REGULAR SQUARE GRID. WE SAY THAT THE SURFACE HAS BEEN TILED WITH IDENTICAL SQUARES. IF WE FOLLOW A PATH, OR **TRAJECTORY**, THAT CUTS EACH SUCCESSIVE SQUARE AT THE SAME ANGLE, THEN THIS PATH WILL ALWAYS BE A GEODESIC ON THE SURFACE.

*The Boss*

SO WHAT STOPS ME FROM DOING THE SAME ON A SPHERE?

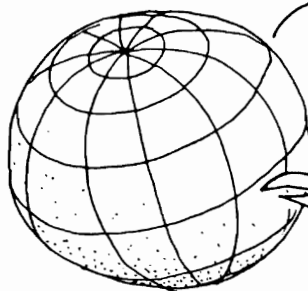
WELL, YOU MIGHT START BY TRYING TO TILE A SPHERE NEATLY WITH SQUARES. THAT WOULD BE NOVEL.



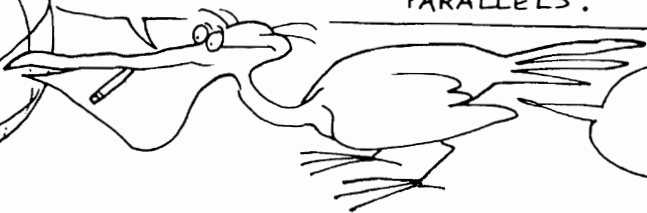
THE MERIDIANS OF A SPHERE ARE ITS GEODESICS. A PATH CUTTING THE MERIDIANS AT A CONSTANT ANGLE, OTHER THAN  $90^\circ$ , WILL INVARIABLY WIND TOWARDS ONE OF THE **POLES!**

NAVIGATION ON A FIXED HEADING LEADS TO... THE POLE!

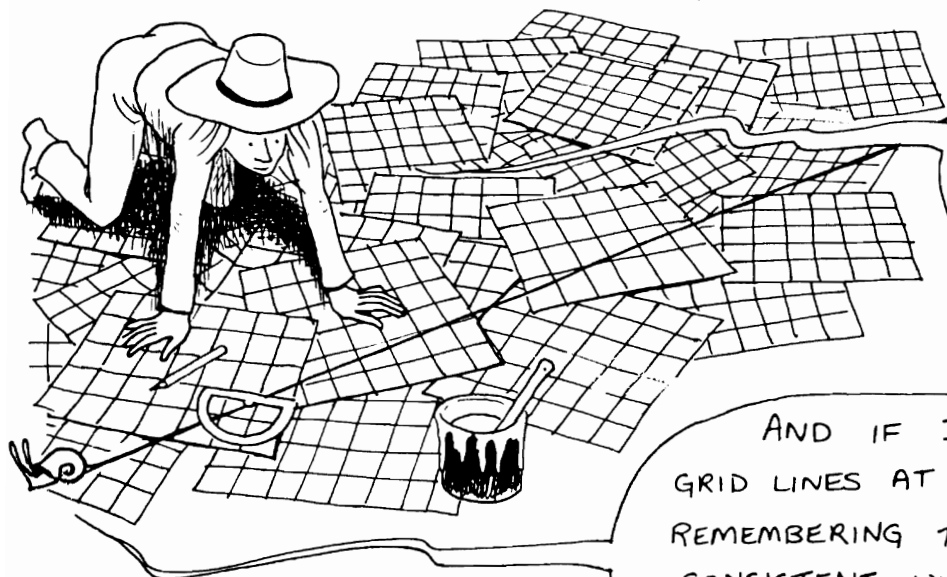




IF I CUTS THE MERIDDYUNS OF A SPHERE  
AT  $90^\circ$ , I GO ALONG ONE O' THE  
PARALLELS.

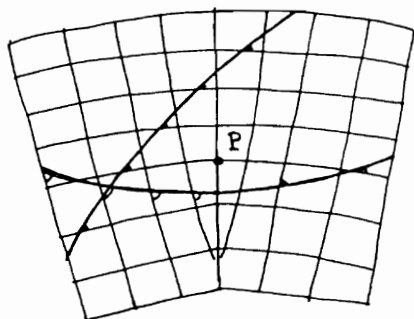


BUT PARALLELS AIN'T  
GEO-DEESICKS. GOTIT! (\*)

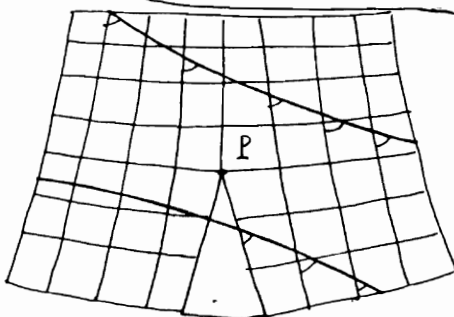


I CAN GET A  
PLANE EUCLIDEAN  
SURFACE BY FITTING  
TOGETHER A LOT OF  
FLAT GRIDS.

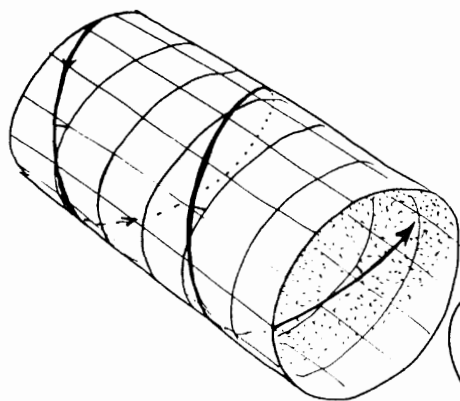
AND IF I MOVE BY CUTTING THE  
GRID LINES AT A FIXED ANGLE,  
REMEMBERING TO KEEP EVERYTHING  
CONSISTENT WHEN I SWITCH GRIDS,  
THEN I'LL GET A GEODESIC.



POSICONE



NEGACONE

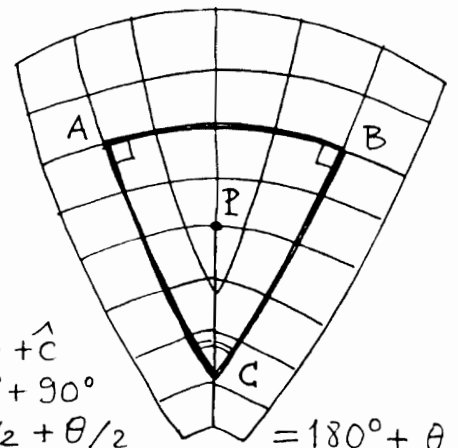
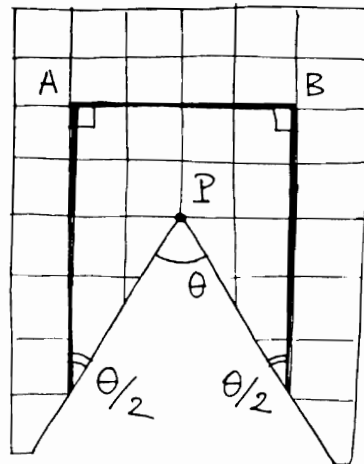
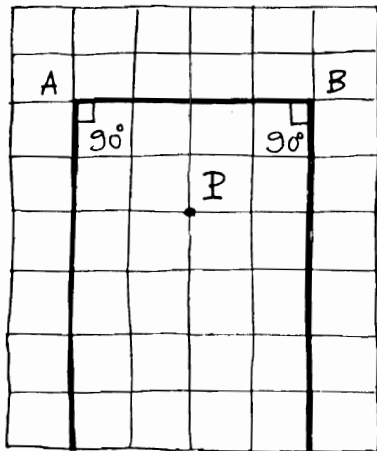


YOU CAN DO THE SAME THING ON A  
CYLINDER - JUST LIKE A SALAMI IN A  
STRING BAG.

(\*) YOU CAN'T DRAW A PARALLEL ON A SPHERE WITH STICKY TAPE, EXCEPT  
AT THE EQUATOR. TRY IT ON A BASKETBALL.



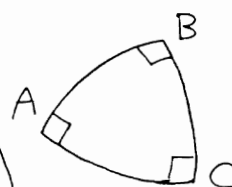
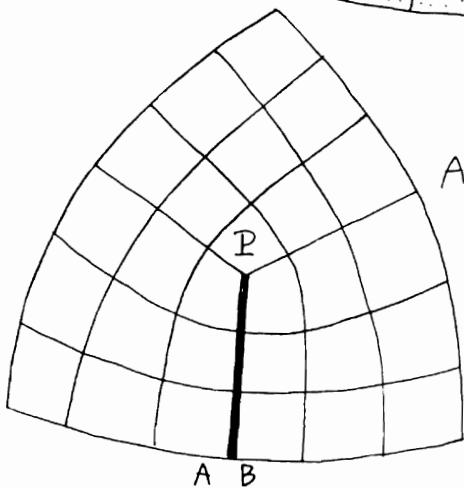
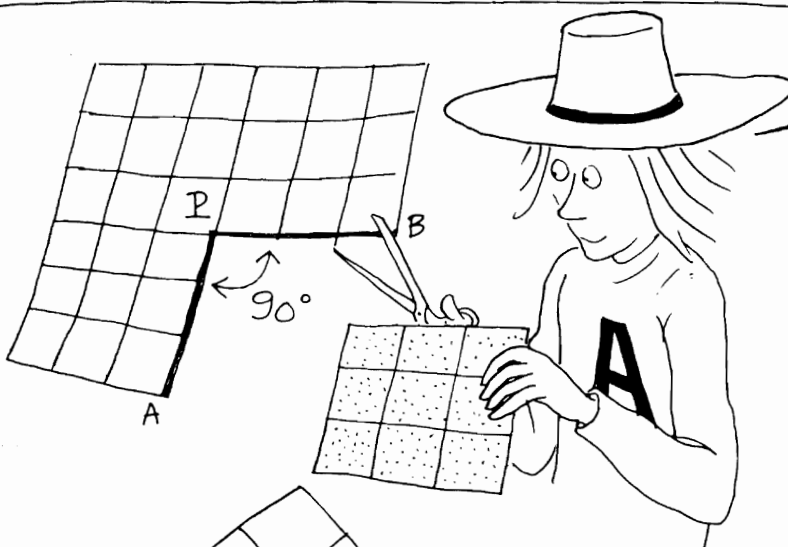
HERE'S WHY THE ANGLE-SUM OF A TRIANGLE, ON A POSICONE, IS INCREASED BY THE ANGLE  $\theta$  OF THE CUT.



$$\begin{aligned} \hat{A} + \hat{B} + \hat{C} &= 90^\circ + 90^\circ \\ &+ \theta/2 + \theta/2 = 180^\circ + \theta \end{aligned}$$

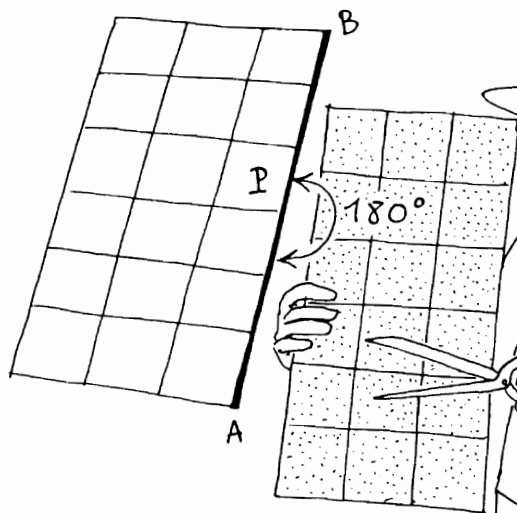
ARCHIBALD HIGGINS WILL NOW CONSTRUCT SPECIAL CONES, WHICH KEEP THE TILING REGULAR.

*The Boss*

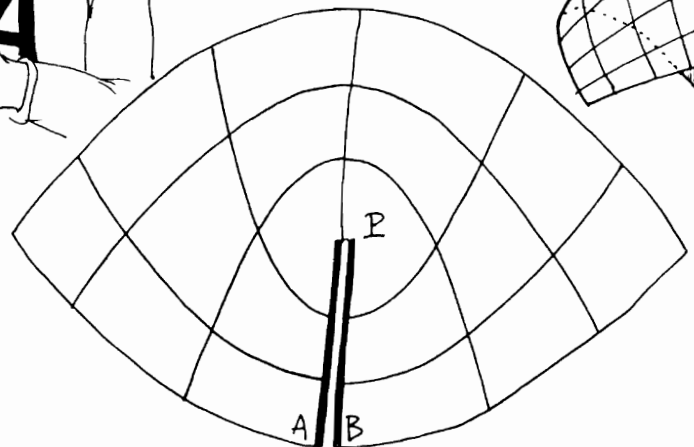
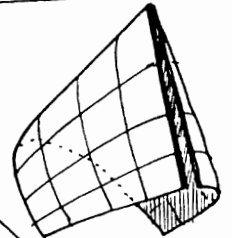


$$\begin{aligned} \hat{A} + \hat{B} + \hat{C} &= 180^\circ + 90^\circ \\ &= 270^\circ \end{aligned}$$

ON THIS CONE YOU CAN DRAW RIGHT-ANGLED EQUILATERAL TRIANGLES.



NOW I EXCISE  
A SECTOR OF  $180^\circ$



ON THIS CONE, YER  
GITS A H'ANGLE-SUM OF  
 $360^\circ$ .



WHICH IMPLIES THAT YOU CAN DRAW ON IT,  
USING GEODESICS, A TRIANGLE HAVING THREE  
ANGLES OF  $120^\circ$ — THAT IS, **OBTUSE**.

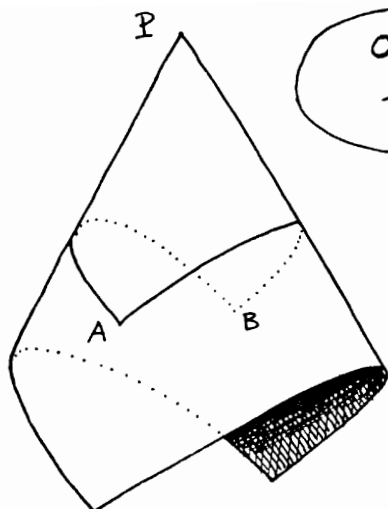
AND IT STILL CLOSES UP? THAT'S WEIRD.

$120^\circ$

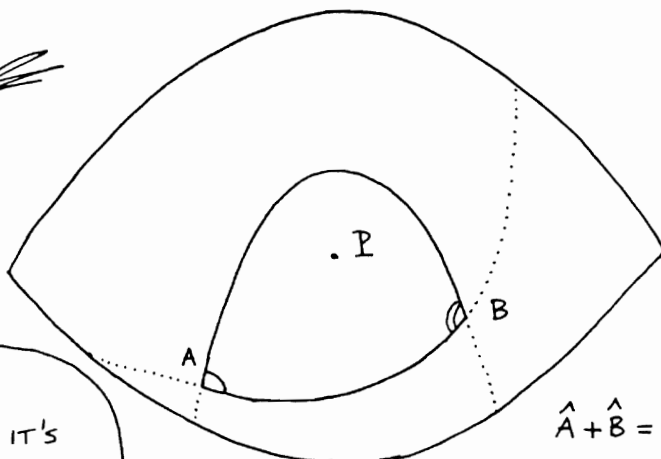
HUM...

SEEMS TER ME,  
TIRESIAS, THAT **YOU'RE** THE  
ONE WOT'S H'OBTUSE!

ME?

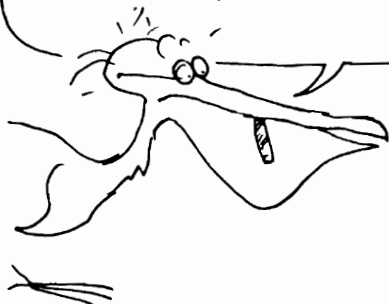


ON THIS CONE YOU CAN DRAW **BIANGLES**.  
THE ANGLE-SUM IS  $180^\circ$ .

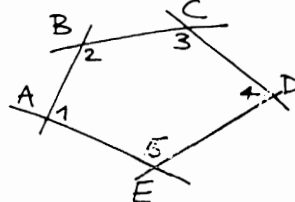
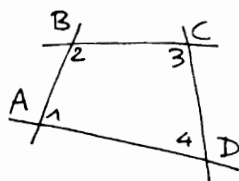
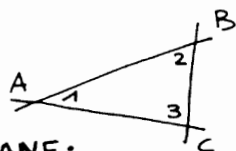


THE CONE,  
VIEWED FROM ABOVE

'OLD IT! NAR YER LORST ME...  
FIRST IT WUZ **TRIANGLES**. NAR IT'S  
BLINKIN' **BIANGLES**. WOZZIT GONNA BE  
NEXT? **MONOANGLES?**



IT'S OK; THEY'RE  
ALL **POLYGONS**.



Etc...

IN THE PLANE:

THE ANGLE-SUM OF A

- **TRIANGLE** IS  $180^\circ$
- **QUADRILATERAL** IS  $180^\circ + 180^\circ = 360^\circ$
- **PENTAGON** IS  $180^\circ + 180^\circ + 180^\circ = 540^\circ$

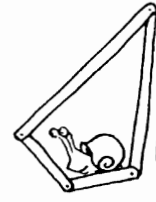
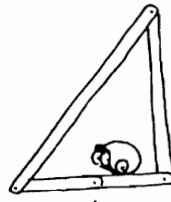
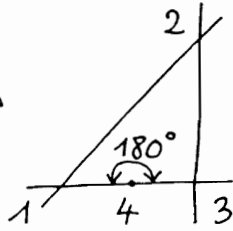
AND FOR A **BIANGLE**, WHICH REDUCES  
TO A LINE SEGMENT, THE SUM IS ZERO.



I'M GOIN'  
BONKERS...



WHY THE H'EXTRA  $180^\circ$  EVERY TIME YER ADDS A CORNER?

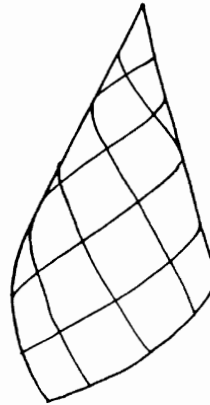
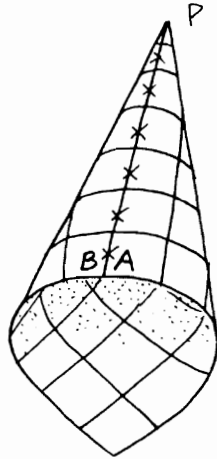


HA!

A SIMPLE KARATE CHOP  
WILL MAKE IT CLEAR...

ALL RIGHT, YOU  
TWO, LET'S GET ON  
WITH IT.

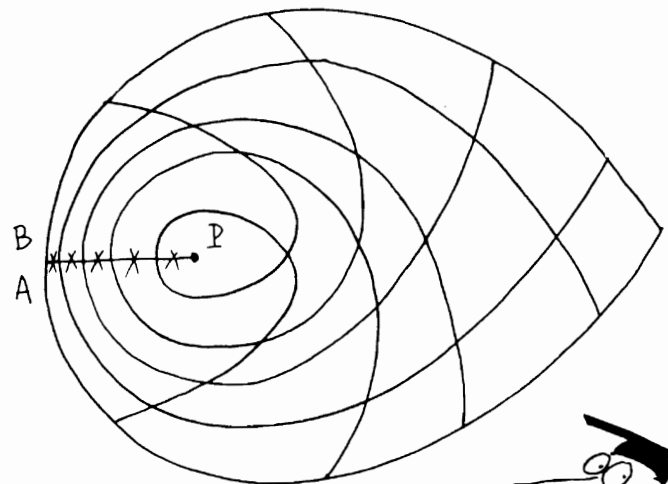
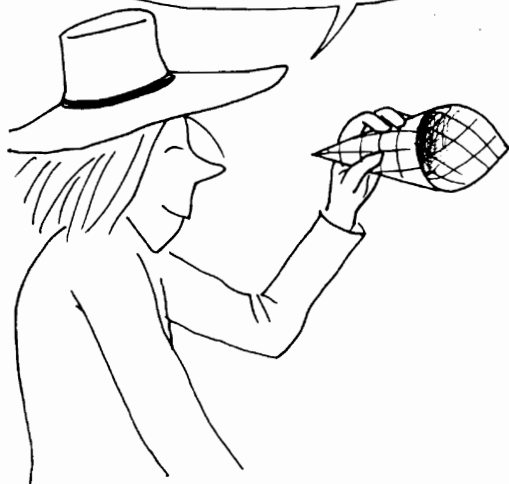
NOW I CUT OUT THREE  
QUARTERS OF THE PLANE.



YOU MIGHT CALL  
THAT A NAPKONE.

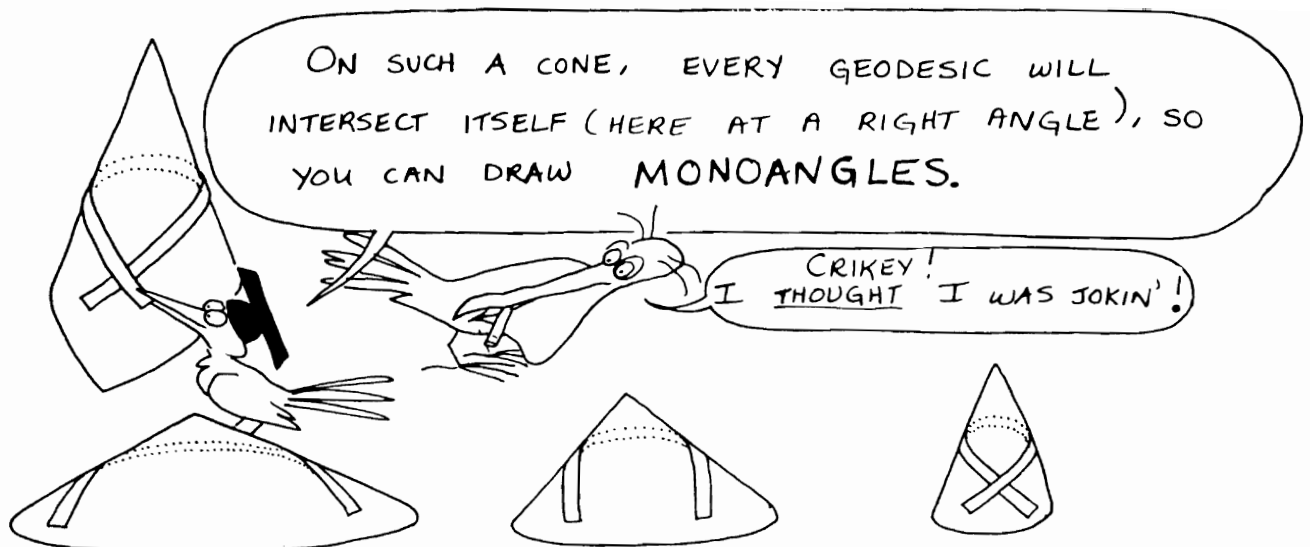


AND WHEN I LOOK  
AT THE END...

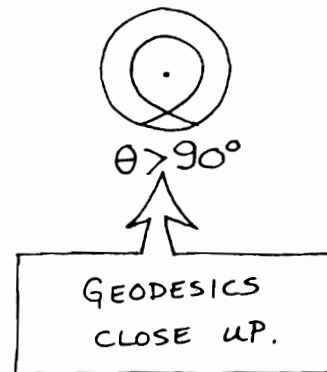
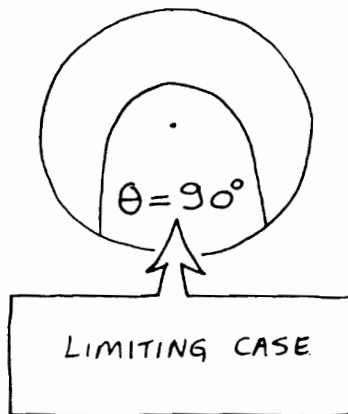
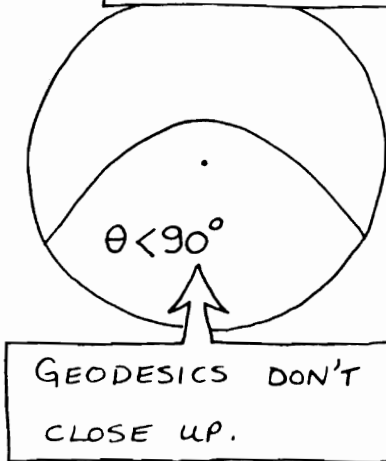


ARCHIE SEES THIS

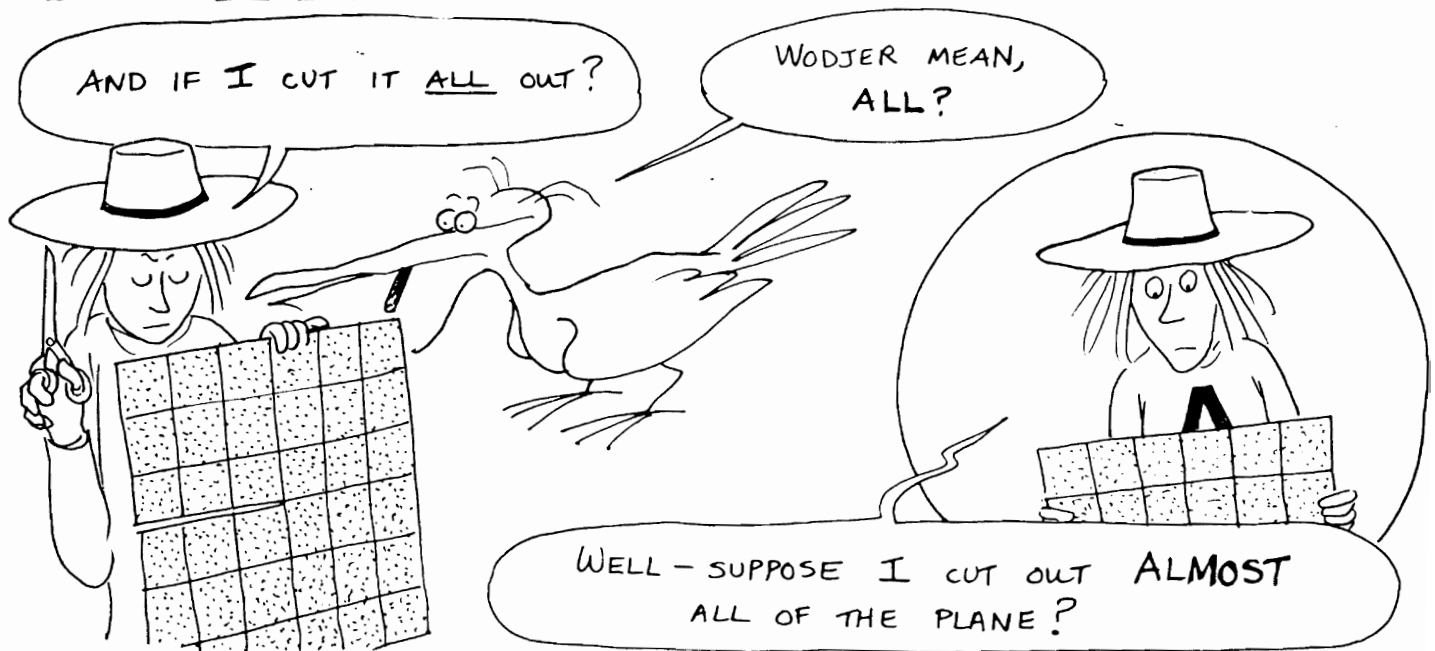


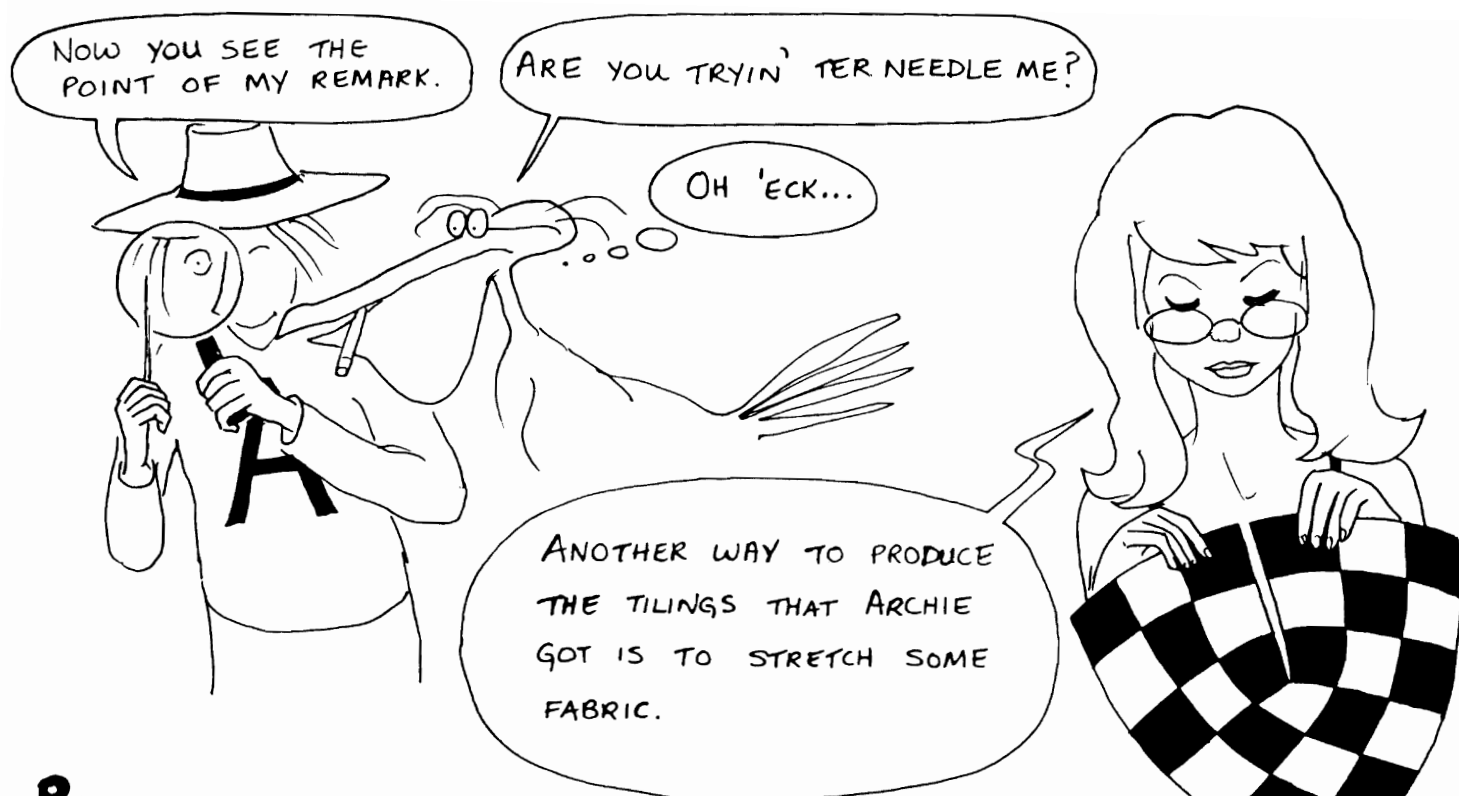


• IT ALL DEPENDS ON THE ANGLE  $\theta$  OF THE CONE. •

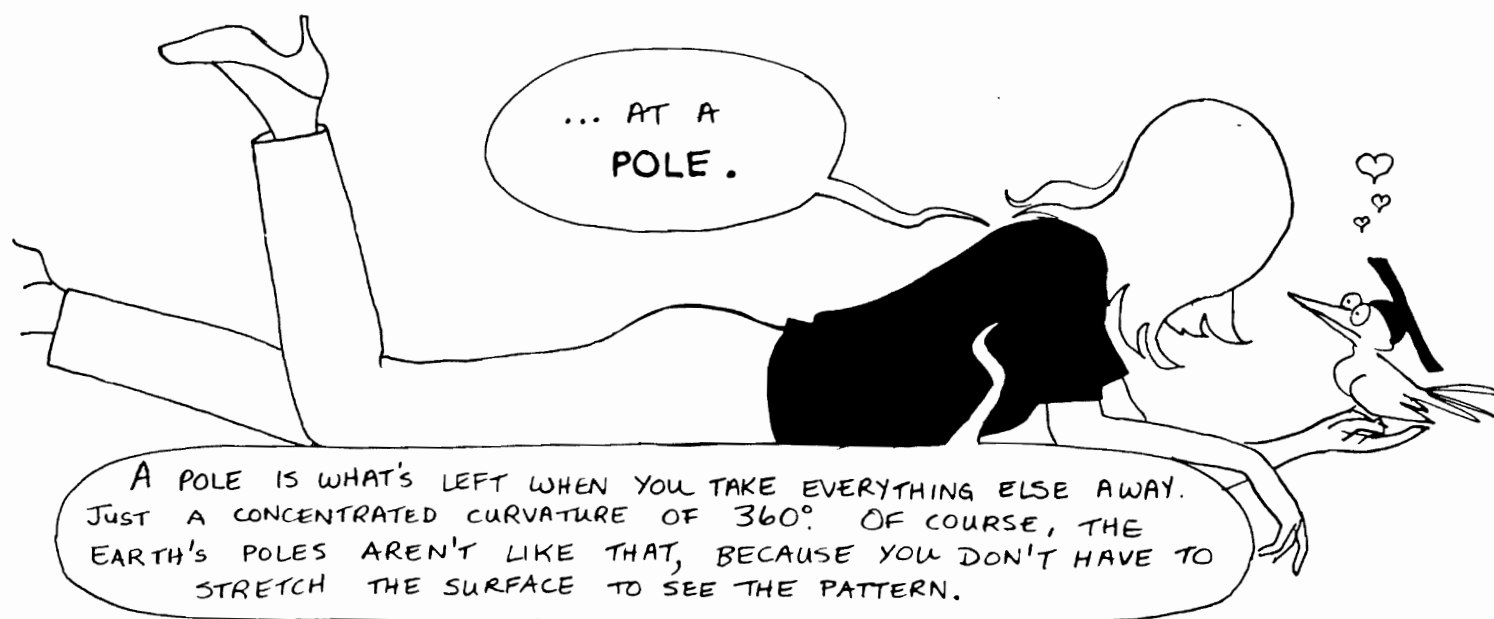
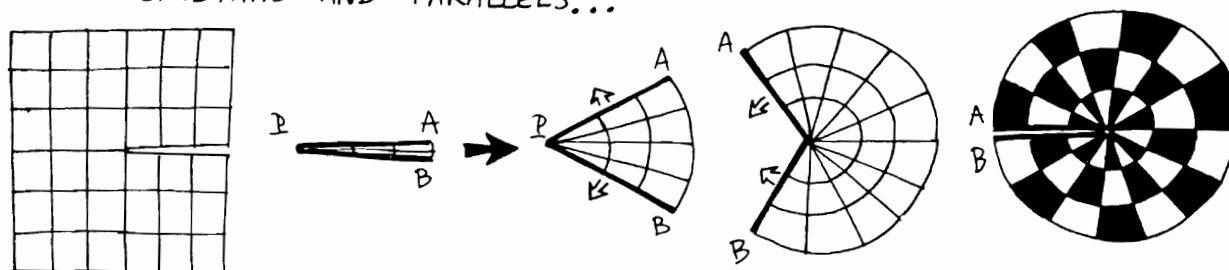


# POLES

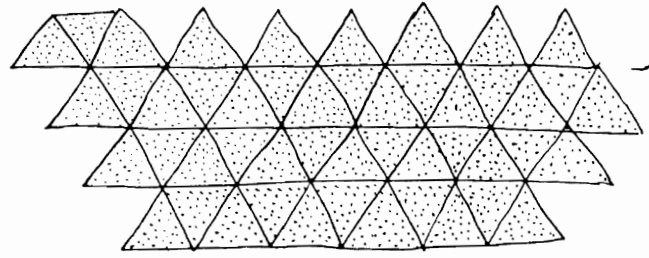




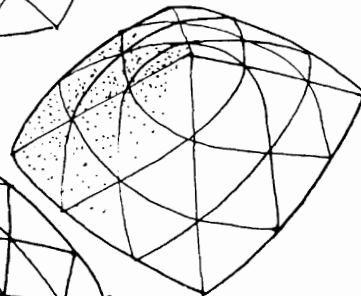
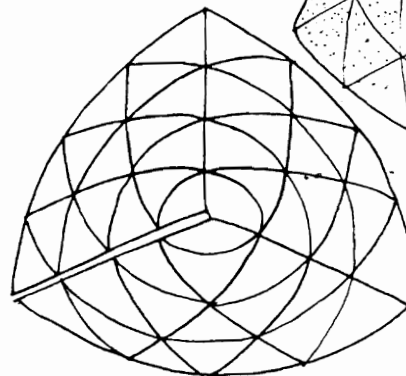
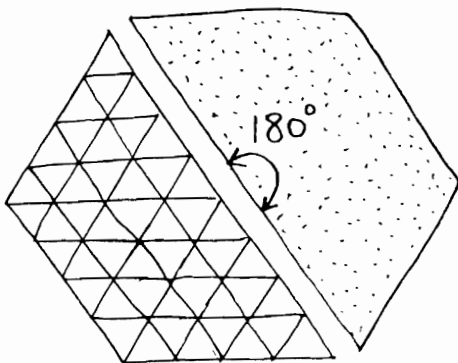
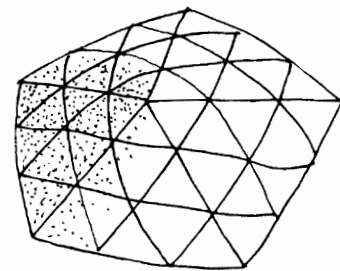
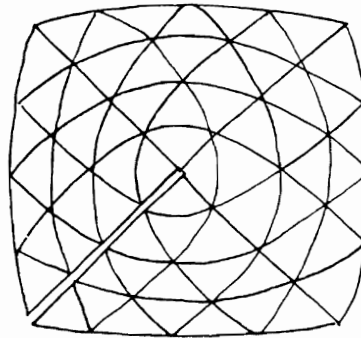
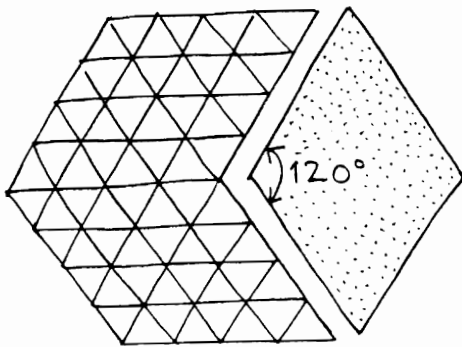
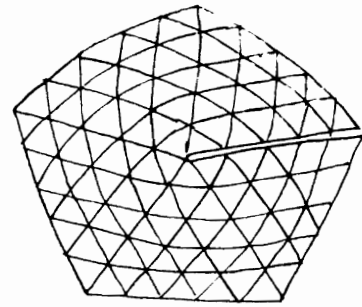
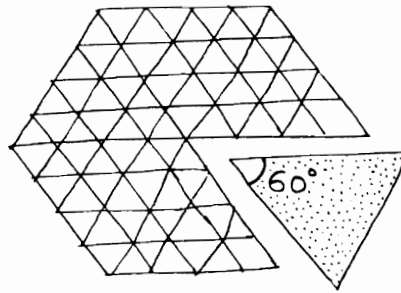
**R**EMOVING ALMOST ALL OF THE PLANE AND APPLYING THIS PROCEDURE IN REVERSE, YOU GET THIS: A PATTERN LIKE MERIDIANS AND PARALLELS...



A WHILE AGO I TILED MY TWO-DIMENSIONAL SPACES (SURFACES) WITH SQUARES. BUT I COULD HAVE DONE IT EQUALLY WELL WITH TRIANGLES...

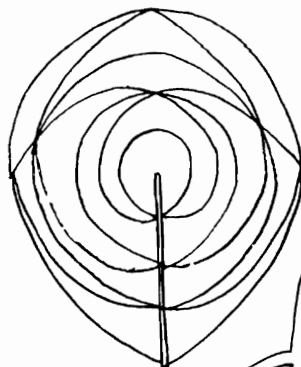
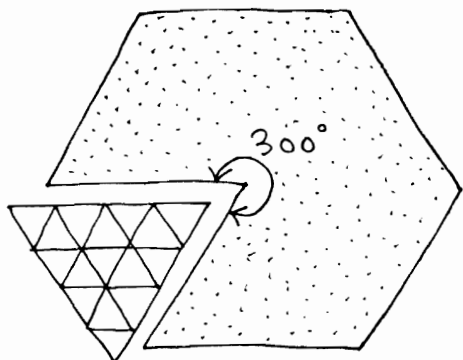
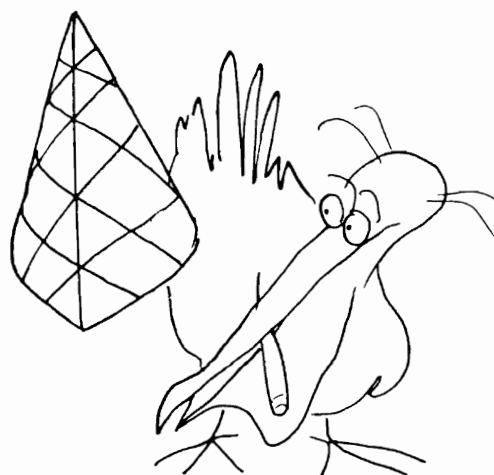
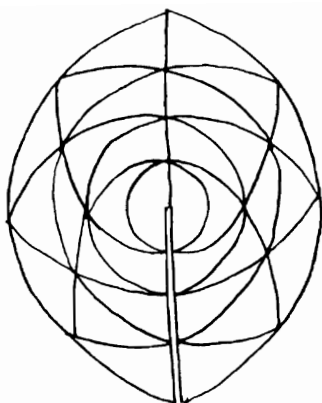
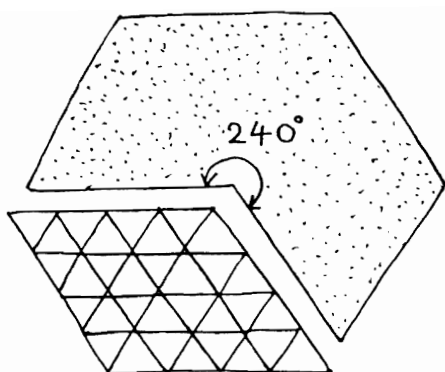


... OR  
HEXAGONS.

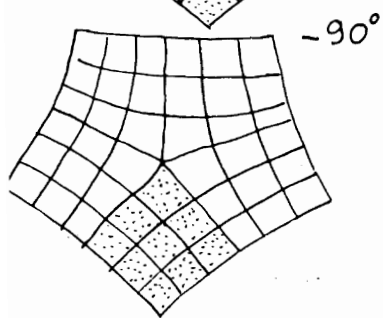
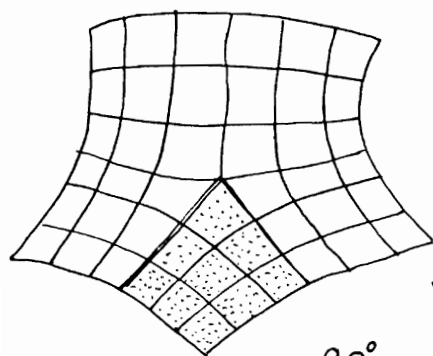


TRIANGULAR TILINGS LET US MAKE CONES  
WITH ANGLES OF  $60^\circ$ ,  $120^\circ$ ,  $180^\circ$ ,  $240^\circ$ ,  
AND  $300^\circ$ .

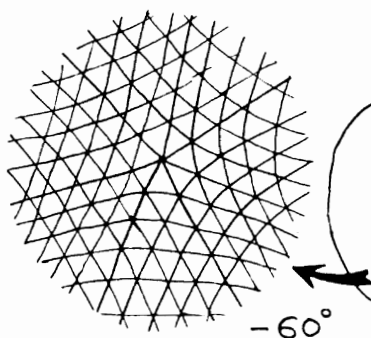
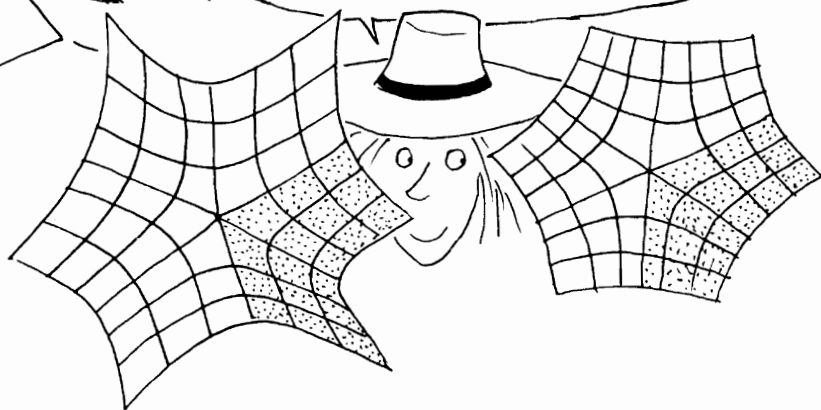




ON THE OTHER HAND,  
BY INSERTING A SECTOR WITH  
ANGLE  $\theta$ , I CAN CREATE  
A POINT OF NEGATIVE  
CURVATURE, CONCENTRATED AT  
THE TIP OF THIS NEGAONE.



CONCENTRATED  
CURVATURE OF  $-180^\circ$ , ETC...



YOU CAN MAKE SOME  
PRETTY NEGAONES  
USING TRIANGULAR  
TILINGS, TOO.

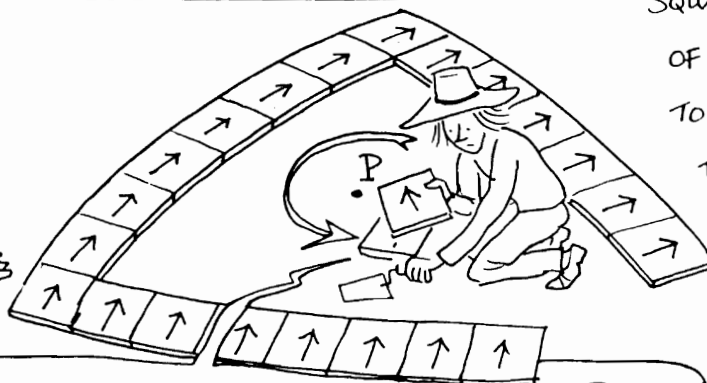




# MEASURING CURVATURE



ARCHIE SEEMS TO BE  
PLAYING A CROSS BETWEEN  
DOMINOS AND HOPSCOTCH.

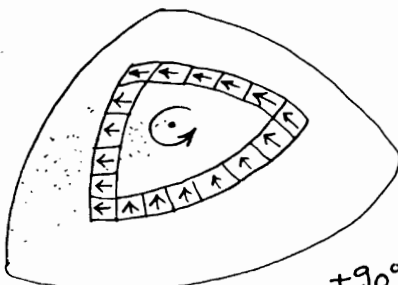
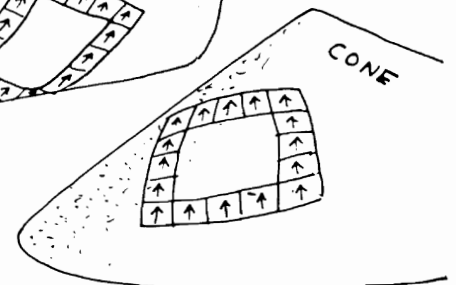
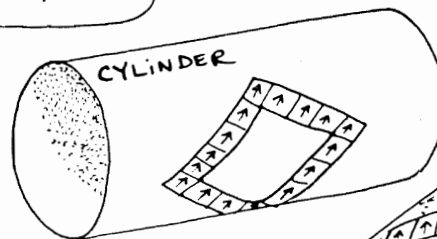
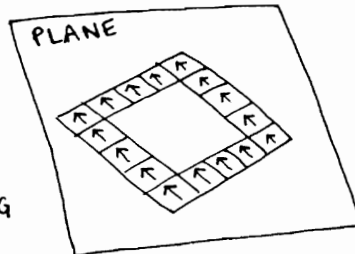


HMMM... PENNSYLVANIA AVENUE?

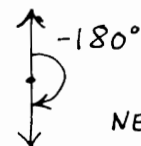
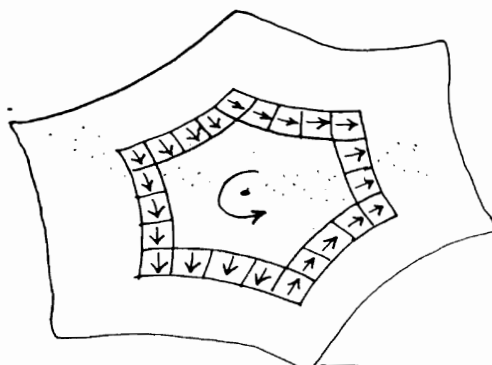
THE OBJECT OF THE GAME IS TO COMPLETELY SURROUND A POINT OF CONCENTRATED CURVATURE WITH SQUARES, KEEPING THE DIRECTION OF THE ARROW THE SAME FROM ONE TO THE NEXT. WHEN YOU GO ALL THE WAY ROUND P, THE ANGLE THROUGH WHICH THE ARROW HAS TURNED GIVES A DIRECT MEASURE OF THE CURVATURE  $\theta$ .

SOME EXAMPLES:

PLANE, CYLINDER,  
CONE (NOT SURROUNDING  
THE TIP) -  
CURVATURE ZERO.



Posicone +90°

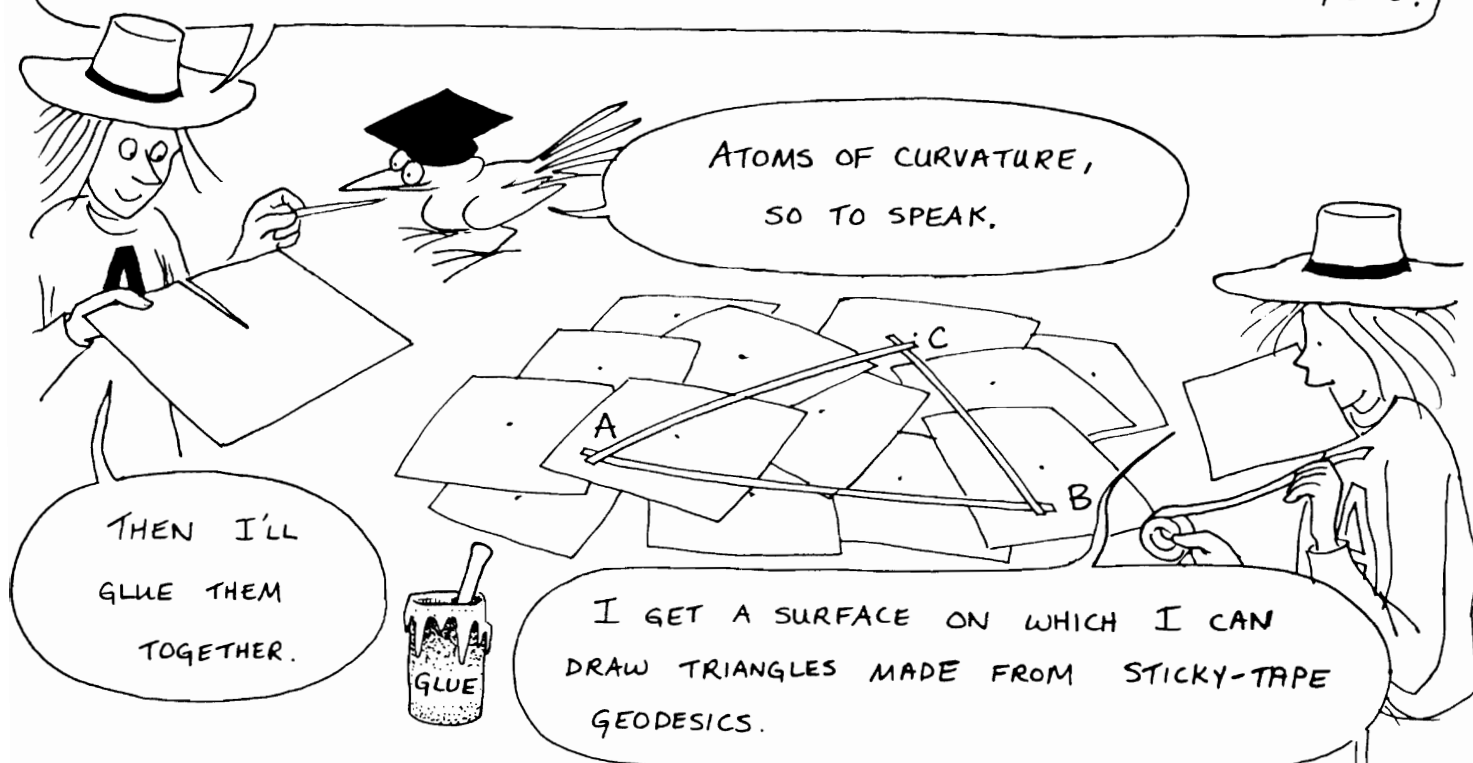


NEGACONE -180°



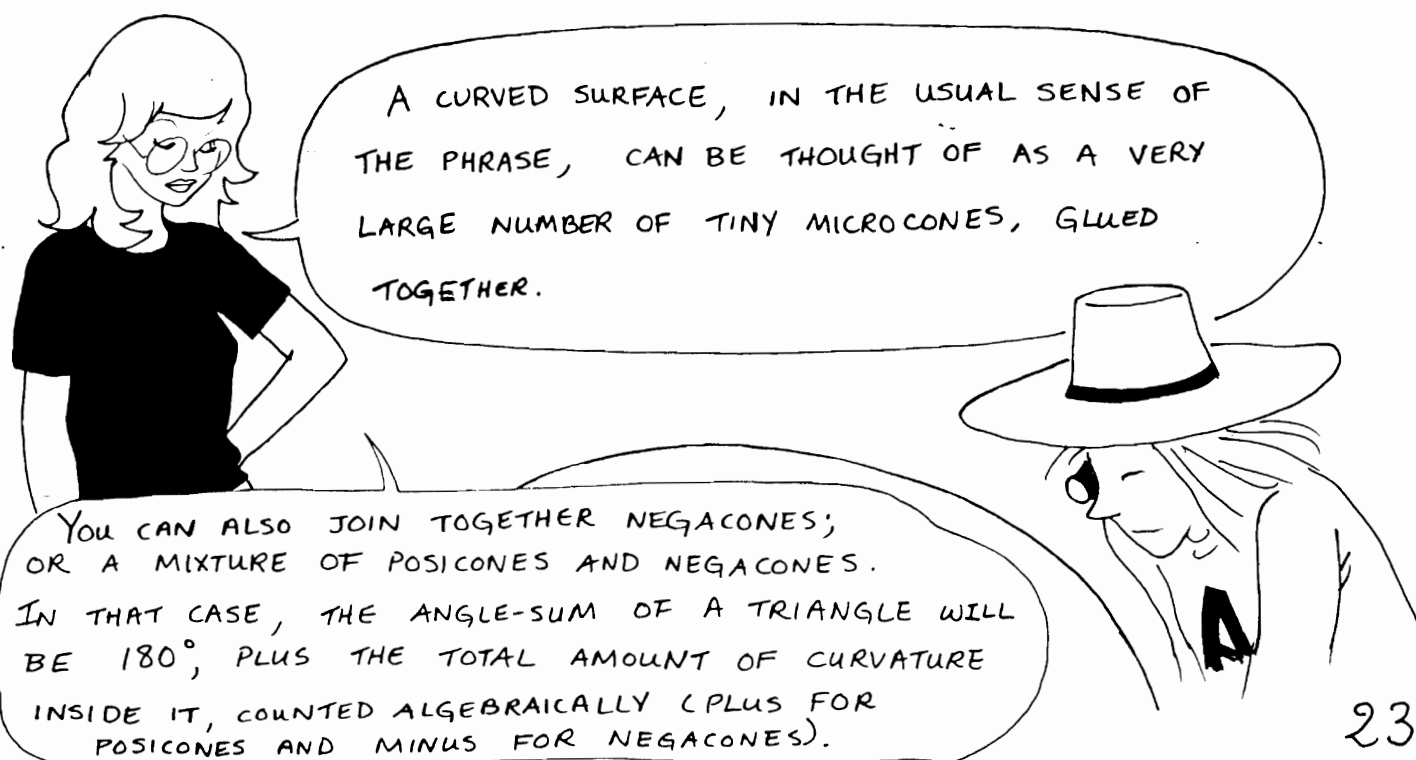
GO ONCE ROUND THE POINT IN ANY DIRECTION.  
IF THE ARROW TURNS THE SAME WAY, YOU'VE GOT A POSICONE.  
THE OTHER WAY, AND YOU'VE GOT A NEGATIVE ONE.

I'LL MAKE SOME NEARLY FLAT POSICONES, EACH WITH A VERY SMALL ANGLE  $\theta$ .



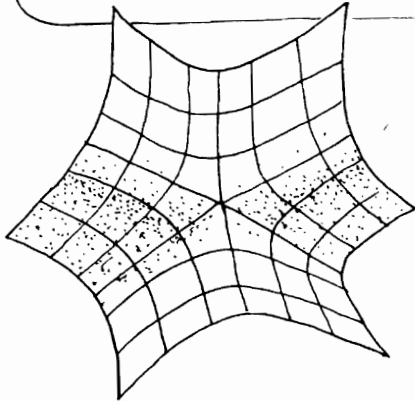
THE ANGLE-SUM OF A TRIANGLE EXCEEDS  $180^\circ$  BY AN AMOUNT  
EQUAL TO THE SUM OF THE ANGLES OF THE ELEMENTARY CONES  
WHOSE PEAKS ARE CONTAINED IN THE TRIANGLE.

*The Boss*



# PATCHWORK

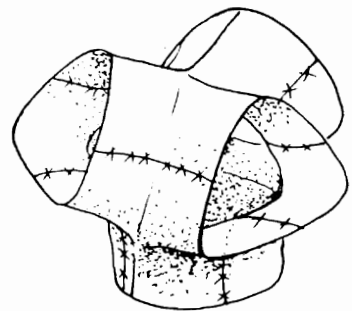
SOPHIE; WHAT WILL I GET IF I ASSEMBLE A LOT OF NEGACONES?



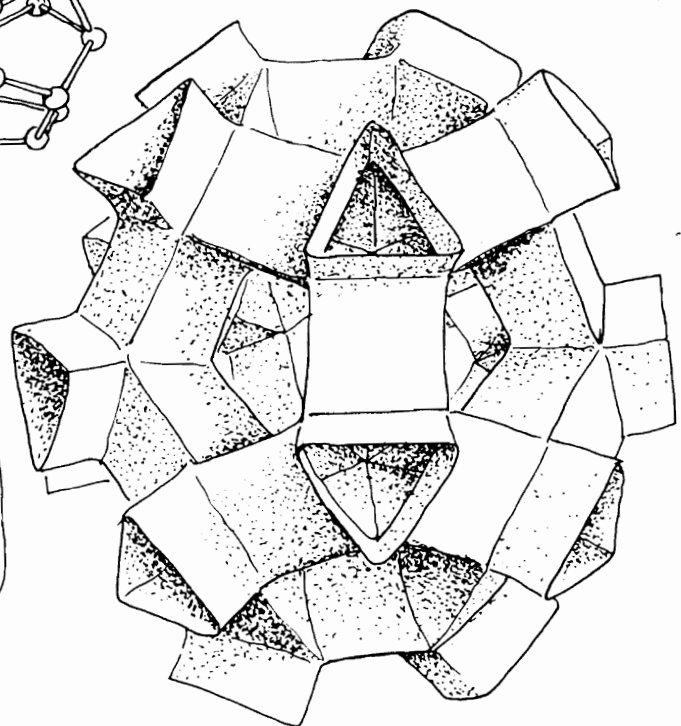
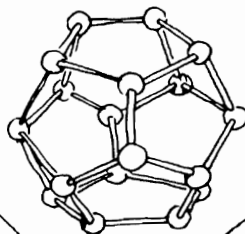
FOR EXAMPLE,  
NEGACONES WITH  
 $\theta = -180^\circ$ . THEIR  
BOUNDARY IS A  
HEXAGON WITH SIX  
RIGHT ANGLES.



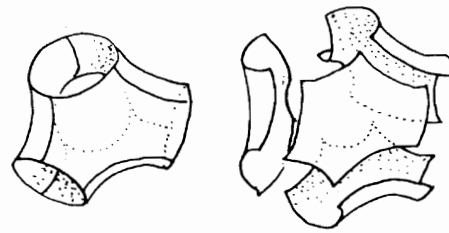
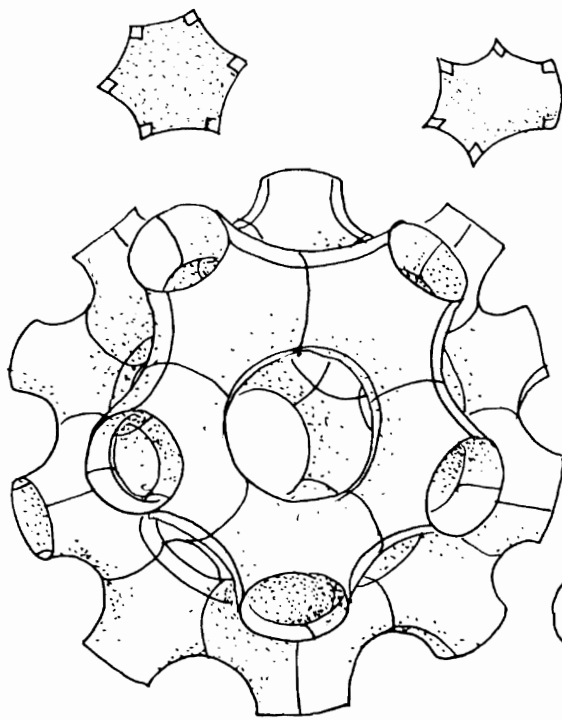
SO YOU CAN JOIN THEM UP,  
FOUR AT A TIME.



BY PUTTING  
TWENTY OF THEM  
TOGETHER, YOU GET  
THIS PIECE OF A SURFACE  
OF NEGATIVE CURVATURE,  
ARRANGED LIKE THE TWENTY  
CORNERS OF A  
**DODECAHEDRON. (\*)**



(\*) FROM THE GREEK: DODEKA = TWELVE 'EDRON = SIDE



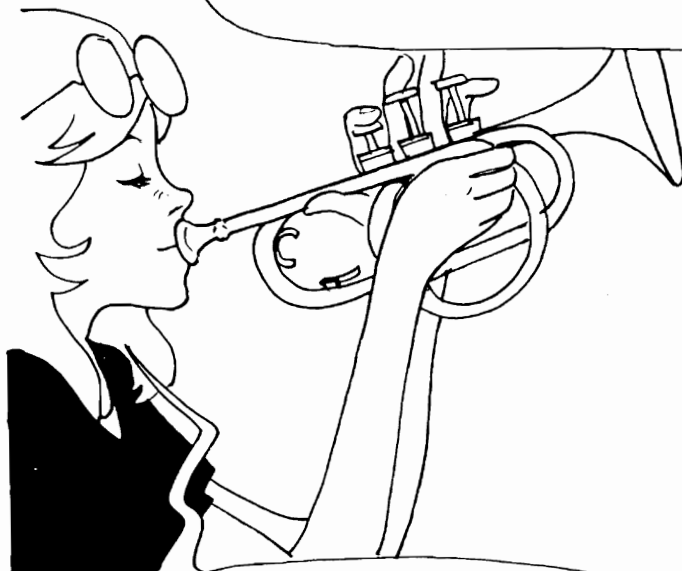
HERE'S THE SAME OBJECT, WITH THE NEGATIVE CURVATURE SPREAD OUT MORE EVENLY. IT'S MADE UP FROM SIXTY HEXAORTHOGONS.

A SIXTYHEDRON, YER MIGHT SAY...

LOOKS MORE LIKE A VERTEBRA OF AN EXTINCT DODECAHEDRODON TO ME.



IF YOUR JOB WAS TO LAY TILES, AND YOUR TILES WERE HEXAORTHOGONS, THAT'S THE SHAPE OF FLOOR YOU'D GET.



HERE'S A GOOD EXAMPLE OF THE WAY THE DISTRIBUTION OF CURVATURE DETERMINES THE SHAPE OF AN OBJECT.

YOU KNOW, ME OLD DUCK, H'IT'S JUST STRUCK ME THAT BY PERFORMIN' A BIT OF GENETIC H'ENGYNEERIN' ON A SNAIL, YER COULD H'ARRANGE FOR IT'S SHELL TO BE...



UGH! How NASTY!

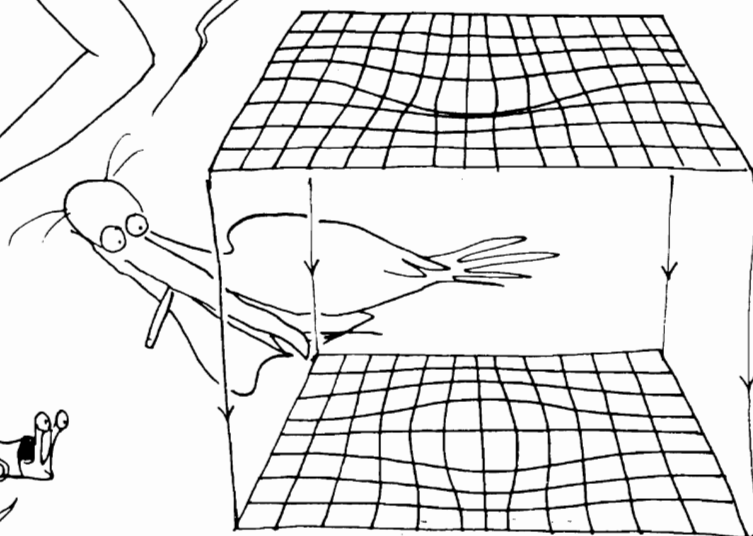
# THREE DIMENSIONS

SOPHIE, IS THERE ANY WAY TO SEE CURVATURE IN OUR USUAL SPACE OF THREE DIMENSIONS?

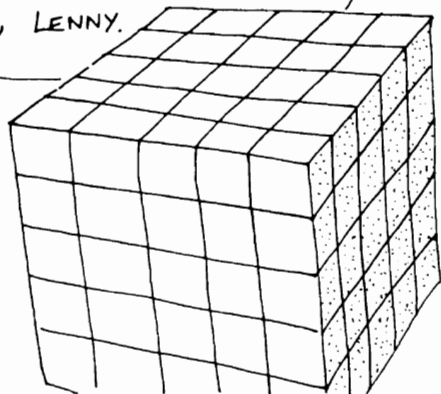
IT'S DIFFICULT, BECAUSE YOU'RE LIVING IN IT.



ONE WAY TO PICTURE THE CURVATURE OF A SURFACE IS TO PROJECT ITS GEODESICS ON TO A PLANE.



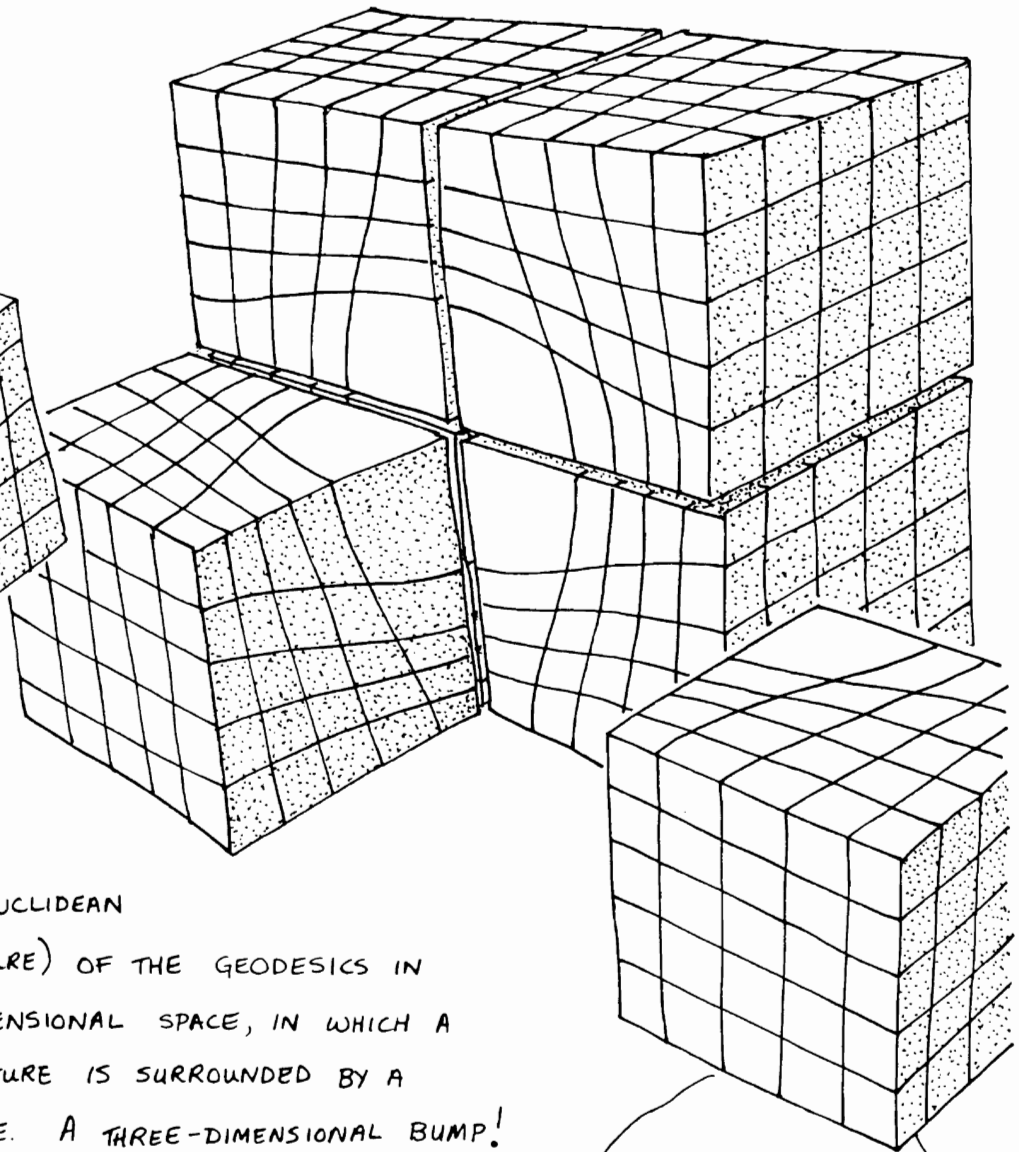
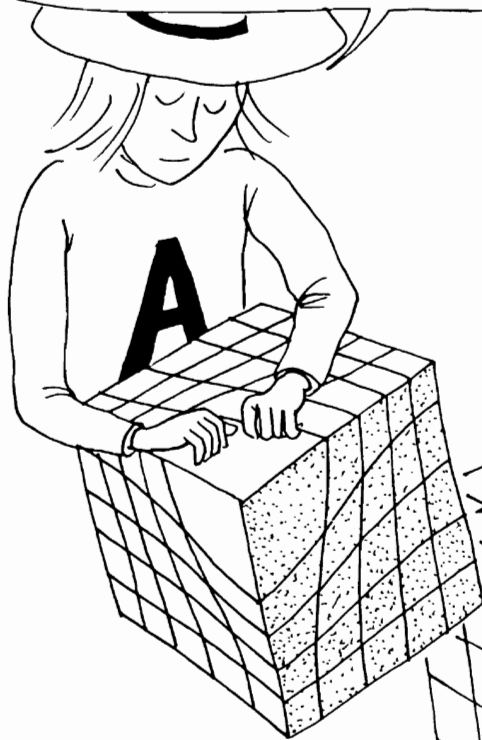
THIS 'BUMP' CORRESPONDS TO A CONCENTRATION OF POSITIVE CURVATURE, SURROUNDED BY A HALO OF NEGATIVE CURVATURE. IT'S AS PLAIN AS THE - ER - BEAK ON YOUR FACE, LENNY.



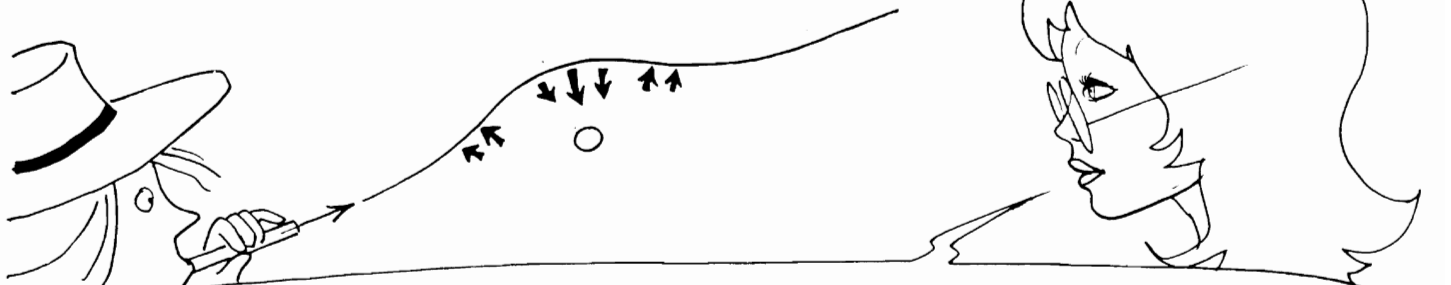
NOW, TAKE A LOOK AT THIS CUBE, ALL TIED UP WITH STRING.



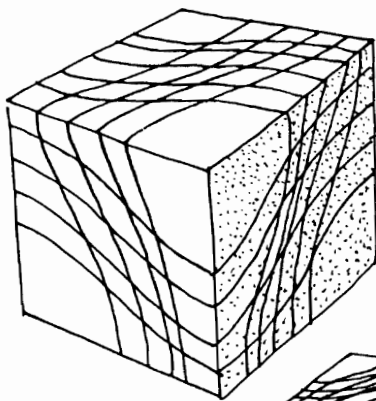
I'LL SLIDE THE STRING SIDEWAYS, LIKE THIS.



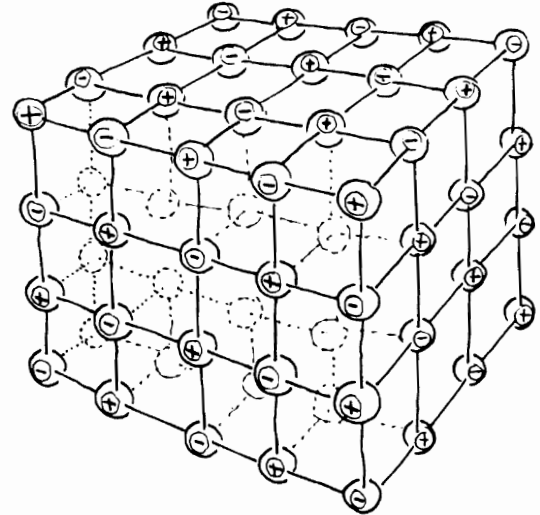
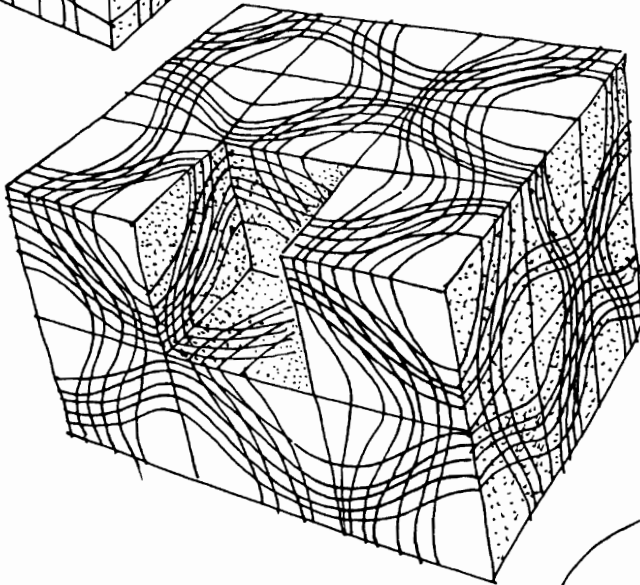
**B**Y FITTING TOGETHER EIGHT OF THESE CUBES, WE GET THE PROJECTION INTO THREE-DIMENSIONAL EUCLIDEAN SPACE (HAVING ZERO CURVATURE) OF THE GEODESICS IN A PIECE OF A THREE-DIMENSIONAL SPACE, IN WHICH A REGION OF POSITIVE CURVATURE IS SURROUNDED BY A HALO OF NEGATIVE CURVATURE. A THREE-DIMENSIONAL BUMP!



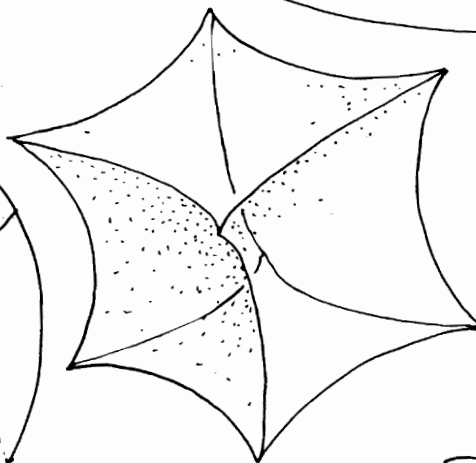
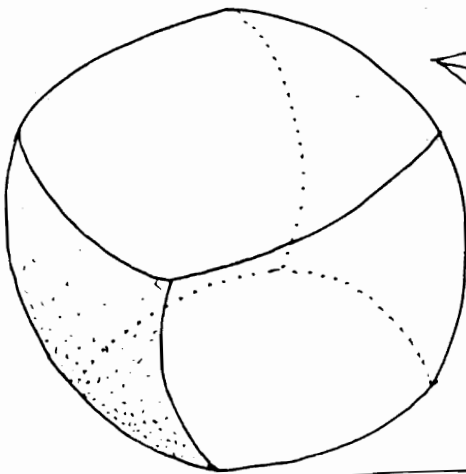
IF YOU THINK OF THESE GEODESICS AS THE **TRAJECTORIES** OF A MOVING PARTICLE, IT APPEARS TO UNDERGO FIRST A REPULSION, THEN AN ATTRACTION, AND THEN A REPULSION AGAIN.



By sliding the strings like this, and joining up a large number of cubes, you can produce an image of a world populated by regions of both positive and negative curvature:



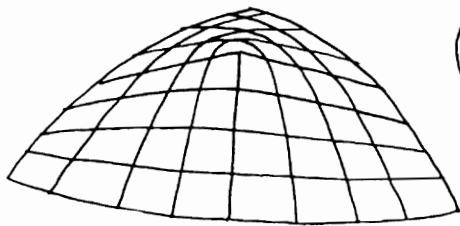
If you look at it closely you'll see it can also be built up by deforming the usual cubes of Euclidean three-dimensional space.



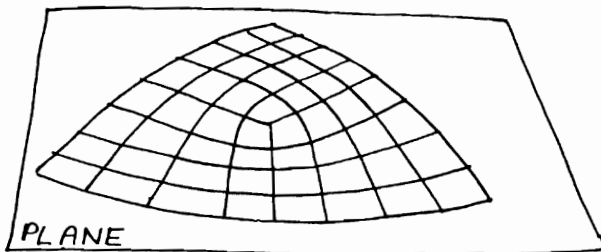
It's very curious that you can pile up all these weird cubes and still fill up the space.



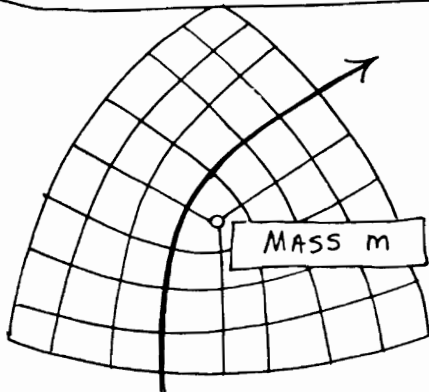
# PROJECTIONS



YOU CAN PROJECT THE GEODESICS OF A CONE  
ON TO A PLANE.



YOU KNOW, THOSE LINES REMIND ME  
OF **TRAJECTORIES** OF PARTICLES.



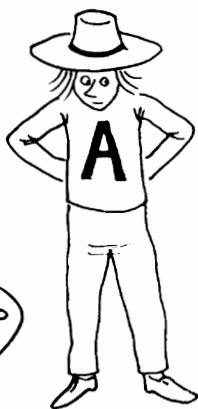
DER IDEA AT DER BASIS OF **GENERAL  
RELATIVITY** IS TO REPLACE **MASS** BY  
LOCAL VARIATIONS IN DER CURFATURE  
OF SPACE.

ARE YER TRYIN' TO TELL ME  
THAT MASS IS A BLINKIN' ANGLE?

HI HI! PUT ME DOWN  
FOR  $\pi/8$

YES - PROVIDED YOU MEASURE MASS AS A KIND  
OF CONCENTRATED CURVATURE.





LET ME CHECK I'VE GOT ALL THIS STRAIGHT, MR. ALBERT. YOU'RE SAYING THAT BENDS IN TRAJECTORIES, CAUSED BY FORCES, ARE REALLY JUST AN EFFECT OF THE PROJECTION, INTO OUR USUAL WORLD, OF A GEODESIC TRAJECTORY ON SOME OTHER SURFACE.

MORE RUDDY METAFIZZICKS!

NO, JUST GEOMETRY.

I GIV' YOU AN EXAMPLE. IMACHIN' YOURSELF TO BE IN A SPACE CAPSULE, IN ORBIT AROUND DER EARTH.

CRICKY! WE'VE GONE WEIGHTLESS!

OH 'ECK!

!IW

NOW WE CAN PLAY A RATHER UNUSUAL KIND OF BILLIARDS.

AS FAR AS I CAN TELL, THIS THING SEEMS TO BE BUILT FROM TWO TRANSPARENT SURFACES, WITH LOTS OF FOLDS AND DENTS, BOTH EXACTLY THE SAME AND LYING PARALLEL TO EACH OTHER.

DAT PERMITS ME TO SHOOT DER TINY MARPLES BETWEEN DEM AND OBSERVE DERE TRAJECTORIES.

THE TRAJECTORIES DO NOT DEPEND ON THE SPEED  $V$  BECAUSE THIS IS DEEMED TO BE CONSTANT THROUGHOUT THE MOTION.

*The Boss*

IN YUST DIS CASE, IT FOLLOWS DAT ALL POSSIBLE TRAJECTORIES ARE GEODESICS. (IF WE WEREN'T WEIGHTLESS, DIS WOULDN'T BE DER CASE.)

OH, LOOK! THE LAMP IS PROJECTING THE TRAJECTORIES ON TO THE FLOOR OF THE CAPSULE!

ANYONE WHO COULD ONLY SEE DER SHADOWS WOULD THINK DAT DER OBJECTS MOOFING IN DER PLANE WERE AFFECTED BY A **FIELD OF FORCES**. BUT REALLY IT'S ALL DUE TO DER CURFATURE OF DER SURFACE.

SO WHEN I OBSERVE THE PATH OF A COMET AROUND THE SUN, IMAGINING THAT IT'S TAKING PLACE IN A THREE-DIMENSIONAL EUCLIDEAN SPACE, WITHOUT CURVATURE, IN FACT THE COMET IS FOLLOWING A GEODESIC IN SOME OTHER SPACE, WHERE IT'S TRAVELING... **STRAIGHT AHEAD!!!!**

WE SEE ONLY THE SHADOWS OF REALITY.

THAT'S A VERY PLATONISTIC SENTIMENT FER A SNAIL, TIRESIAS OLD BEAN.

THE ONLY WAY TO GO IS **STRAIGHT**.

LIGHT ALWAYS  
FOLLOWS A GEODESIC, TOO.

Y'KNOW, THEY'RE FUNNY THINGS, THESE GEODESICS. IF YOU PROJECT THEM IN A DIFFERENT DIRECTION, THEY DON'T WORK. THE SAME WAY AT ALL!

?!?

**TIRESIAS!**

I DIDN'T  
MEAN IT, HONEST!

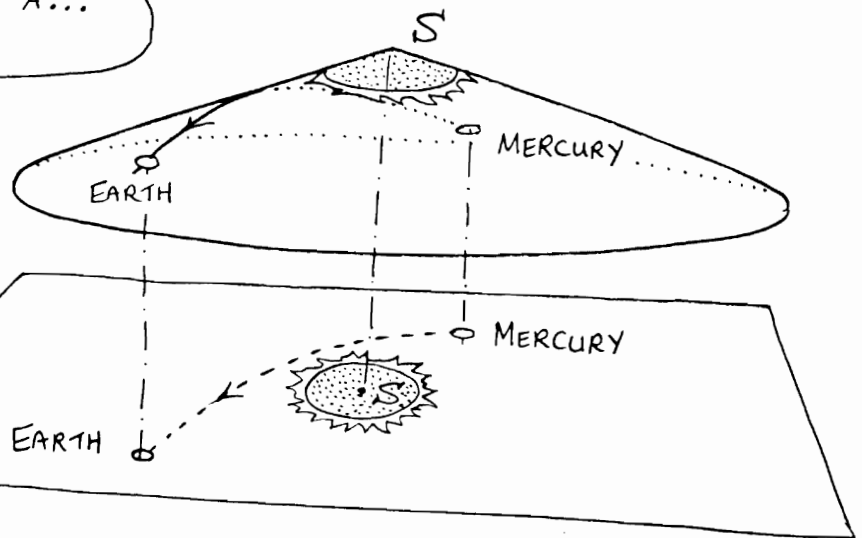


# MASS AND MATTER

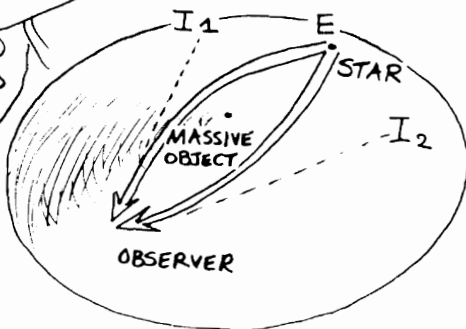
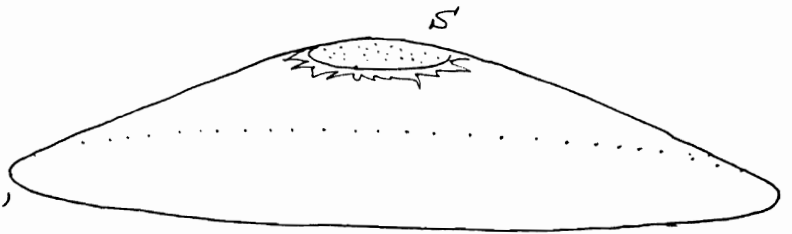
ARE YOU SAYING THAT THE SUN IS A...  
CONE?



WELL, WE KNOW IT BENDS  
LIGHT RAYS FROM MERCURY.



WE USUALLY THINK OF SPACE NEAR  
THE SUN AS BEING **FLAT**. BUT IN  
FACT, BECAUSE OF ITS LARGE MASS,  
THIS STAR REPRESENTS A CERTAIN  
AMOUNT OF CURVATURE. BUT BECAUSE  
THE SUN'S MASS ISN'T CONCENTRATED  
AT A POINT, WE'LL THINK OF THIS  
REGION OF SPACE AS A  
SMOOTHED-OUT CONE.



VERY MASSIVE OBJECTS CAN CURVE SPACE TO  
SUCH AN EXTENT THAT AN OBSERVER CAN SEE TWO  
IMAGES  $I_1$  AND  $I_2$  OF THE SAME STAR E. THIS  
EFFECT, KNOWN AS A **GRAVITATIONAL LENS**,  
HAS RECENTLY BEEN OBSERVED IN LIGHT FROM QUASARS.

THE MASSES OF ATOMS AND PARTICLES ALL  
CONTRIBUTE TO THE GENERAL CURVATURE OF  
THE UNIVERSE.

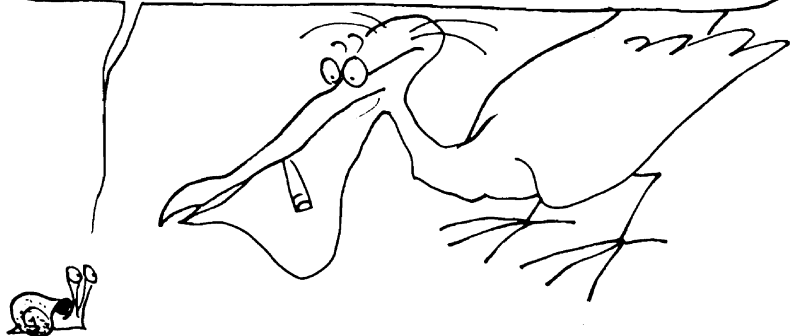
SO MASS HAS A  
GEOMETRIC SIGNIFICANCE.

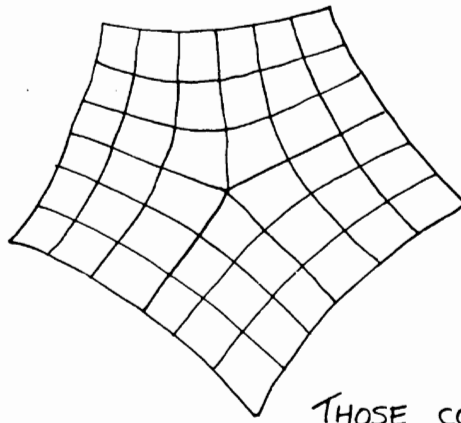
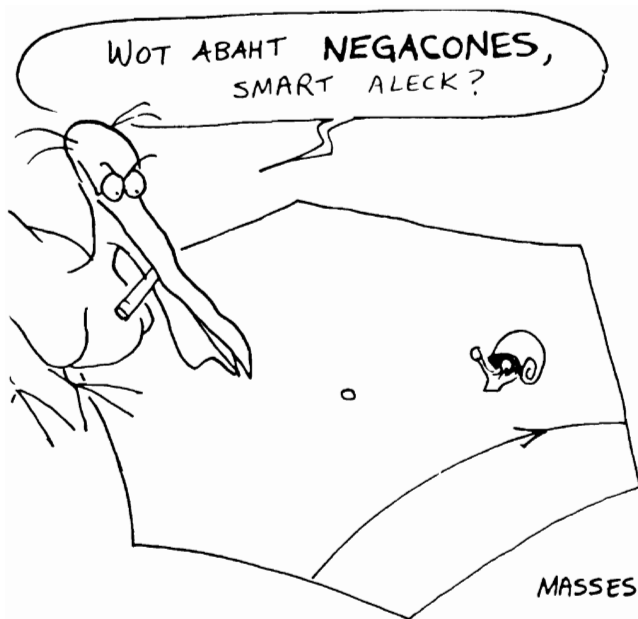
'ANG ON, WOT ABAHT  
BETWEEN THE ATOMS? THERE'S  
NUFFIN' THERE!

I LORST THE  
THREAD AGAIN...

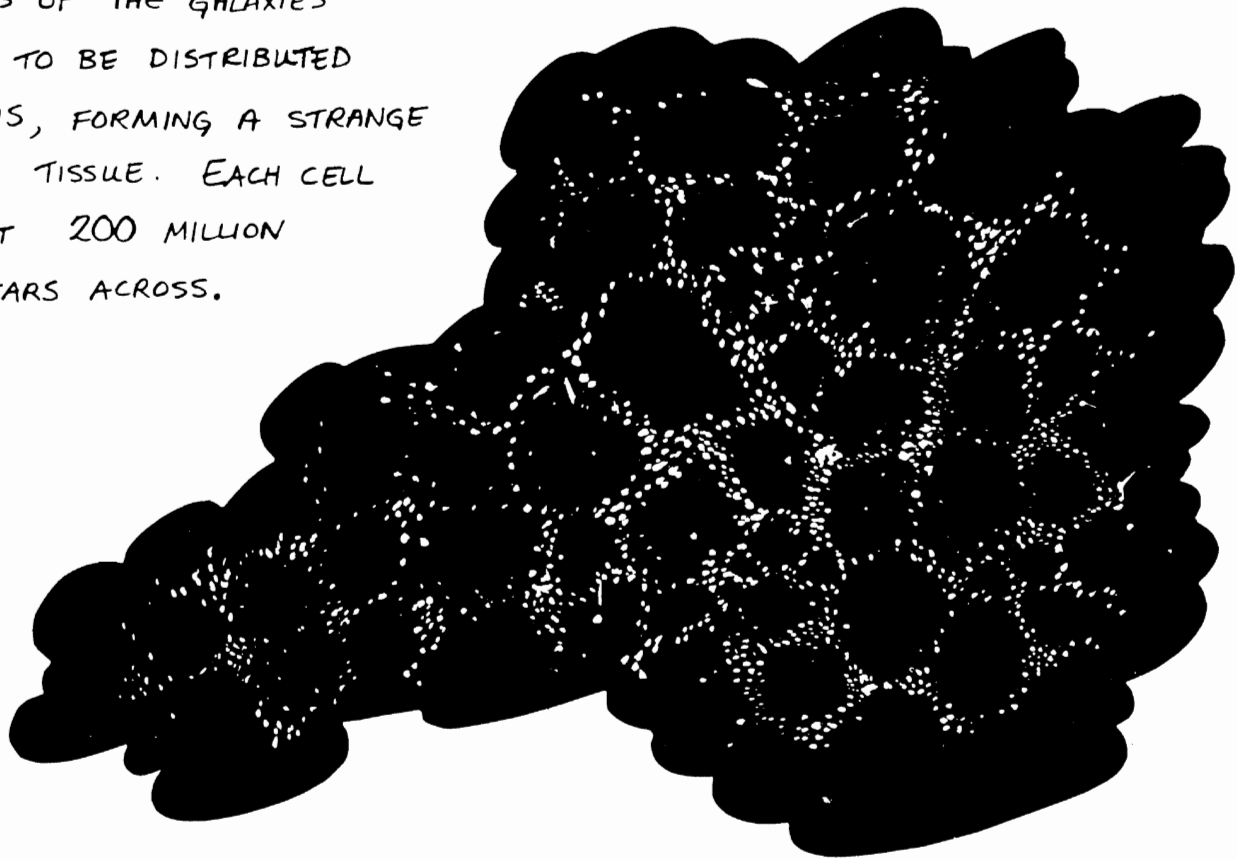
NUFFIN' BUT...  
GEOMETRY???

NOW MY DEAR FELLOW, HAVEN'T YOU  
HEARD THAT THE OLD OPPOSITION BETWEEN  
MATTER AND THE VOID IS TOTALLY  
OUTMODED? THE ONLY THING  
NOWADAYS IS GEOMETRY.



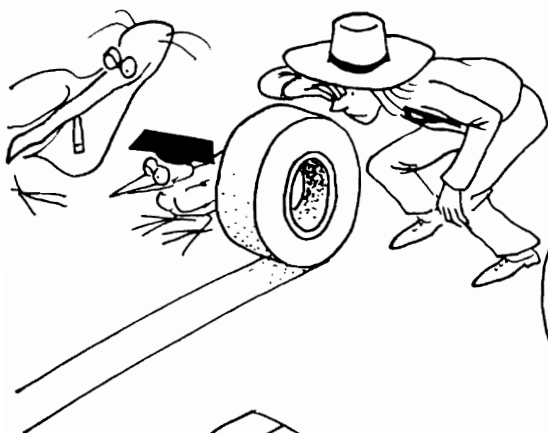


THOSE CONJURE UP THE IDEA OF "NEGATIVE MASS," PRODUCING A REPULSIVE FORCE. A UNIVERSE FULL OF NEGATIVE MASSES WOULD BE VERY PECULIAR. INSTEAD OF GALAXIES, THERE WOULD BE LOTS OF BUBBLES — ENORMOUS VOIDS. IN FACT, THE MASS OF THE GALAXIES SEEMS TO BE DISTRIBUTED LIKE THIS, FORMING A STRANGE CELLULAR TISSUE. EACH CELL IS ABOUT 200 MILLION LIGHT-YEARS ACROSS.

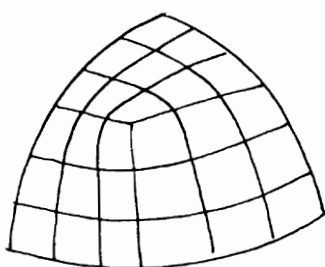


PERHAPS GRAVITATIONAL FORCES BECOME REPULSIVE AT A VERY LARGE DISTANCE.

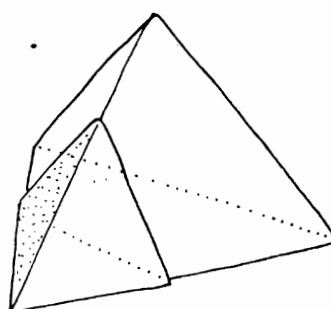
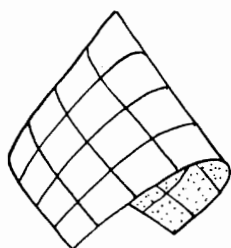
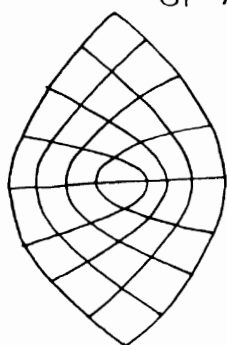
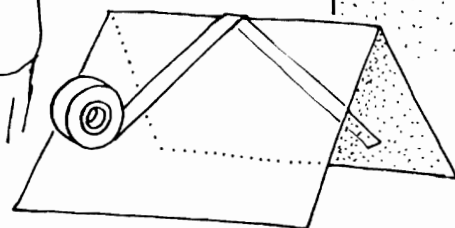
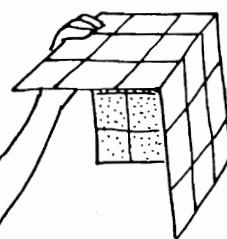
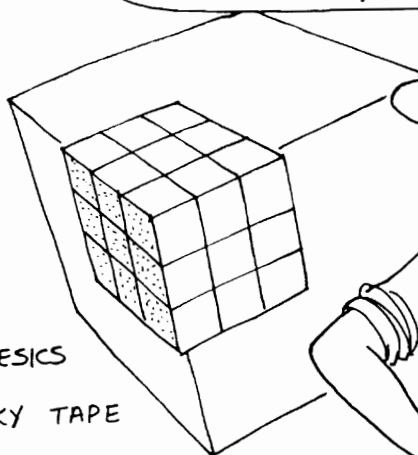
# POLYHEDRA



Now, ARCHIE: REMEMBER THAT YOU CAN PRODUCE GEODESICS ON A SURFACE USING STICKY TAPE? WHAT HAPPENS IF YOU **BEND** THE SURFACE?



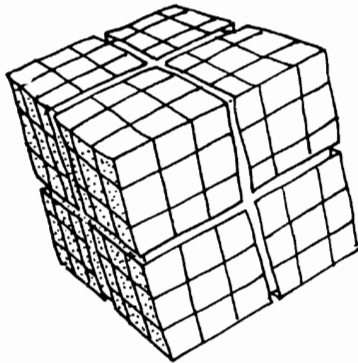
IF YOU BEND THIS CONE ( $\theta = 90^\circ$ ) THE GEODESICS DON'T CHANGE. (THE STICKY TAPE JUST BENDS WITH THE SURFACE.) IN FACT YOU CAN FOLD IT TO FIT PERFECTLY OVER THE CORNER OF A CUBE.



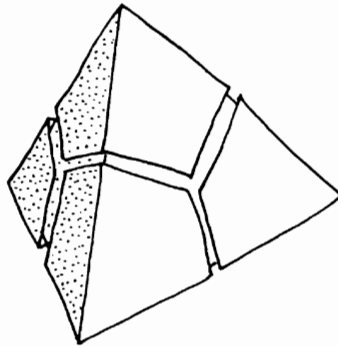
SIMILARLY, YOU CAN MAKE THREE FOLDS IN THIS CONE ( $\theta = 180^\circ$ ) SO THAT IT FITS OVER THE CORNER OF A REGULAR TETRAHEDRON.



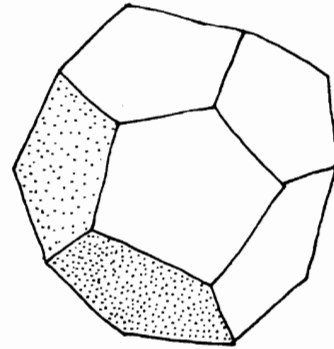
# SPACE MUST BE OPEN OR CLOSED



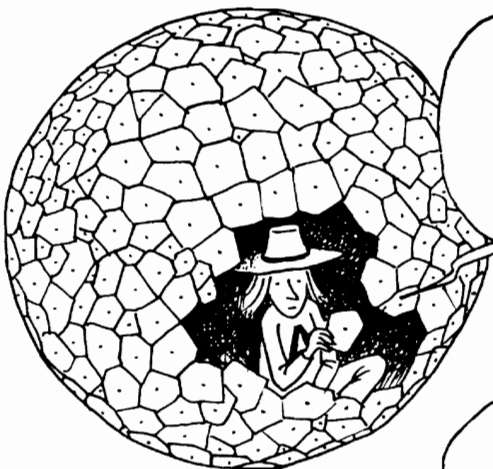
EIGHT CONES ( $\theta = 90^\circ$ )  
CAN BE USED TO MAKE  
A CUBE.  
 $90^\circ \times 8 = 720^\circ$



FOUR CONES ( $\theta = 180^\circ$ )  
CAN BE USED TO MAKE  
A TETRAHEDRON.  
 $180^\circ \times 4 = 720^\circ$



TWENTY CONES ( $\theta = 36^\circ$ )  
CAN BE USED TO MAKE  
A DODECAHEDRON.  
 $36^\circ \times 20 = 720^\circ$



SO, IF I FIT TOGETHER IN A REGULAR WAY  
A LARGE NUMBER  $N$  OF MICROCONES WITH A  
SMALL CURVATURE  $\theta$ , I GUESS THAT WHEN  
 $N \times \theta = 720^\circ$  I'LL GET A - SPHERE!

YOU'D EXPECT THAT, BECAUSE  
THE TOTAL CURVATURE OF  
A SPHERE IS  $720^\circ$ .

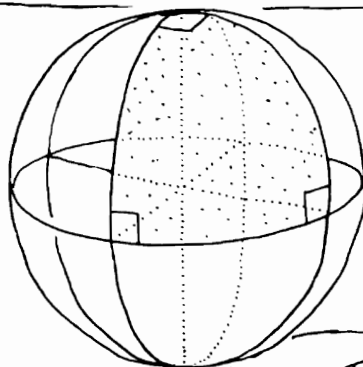
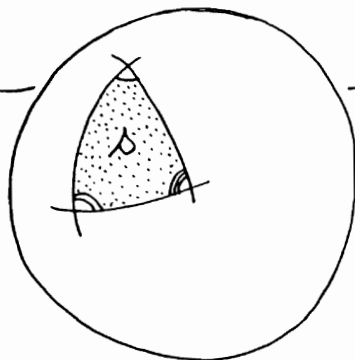
NOW COME OUT OF  
THERE, YOU CLOD.



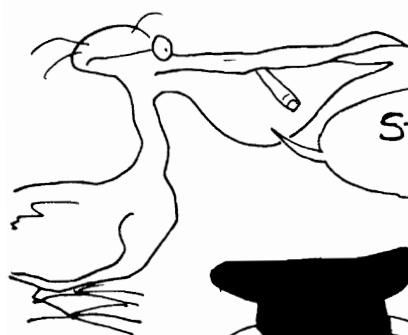


ON A SPHERE, THE CURVATURE IS UNIFORMLY DISTRIBUTED. SO THE SUM OF THE ANGLES OF A TRIANGLE DRAWN ON A SPHERE IS EQUAL TO  $180^\circ + 720^\circ \times \frac{S}{S}$  WHERE  $S$  IS THE AREA OF THE TRIANGLE AND  $S$  THE AREA OF THE SPHERE. THE SECOND TERM  $720^\circ \times \frac{S}{S}$  REPRESENTS THE AMOUNT OF CURVATURE CONTAINED IN THE TRIANGLE. (\*)

The Boss



FOR EXAMPLE, THIS TRIANGLE TAKES UP ONE EIGHTH OF THE SURFACE OF A SPHERE, AND:  
 $\hat{A} + \hat{B} + \hat{C} = 180^\circ + \frac{720^\circ}{8} = 270^\circ$   
 WHICH IS CORRECT SINCE ALL THREE ANGLES ARE  $90^\circ$



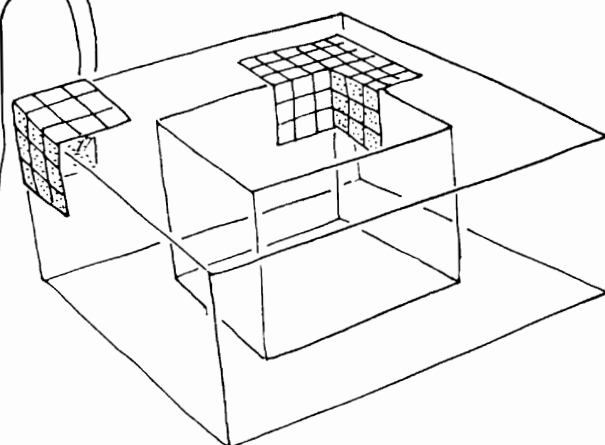
STAGGERIN'!

IN DER SAME CHENERAL LINE OF IDEAS, IF DER MINIMUM DENSITY IN OUR THREE-DIMENSIONAL SPACE (DAT IS, DER CURFATURE PER UNIT VOLUME) IS MORE DAN  $10^{-29}$  GM/CM<sup>3</sup>, DEN SPACE CLOSES UP ON ITSELF LIKE A SPHERE.



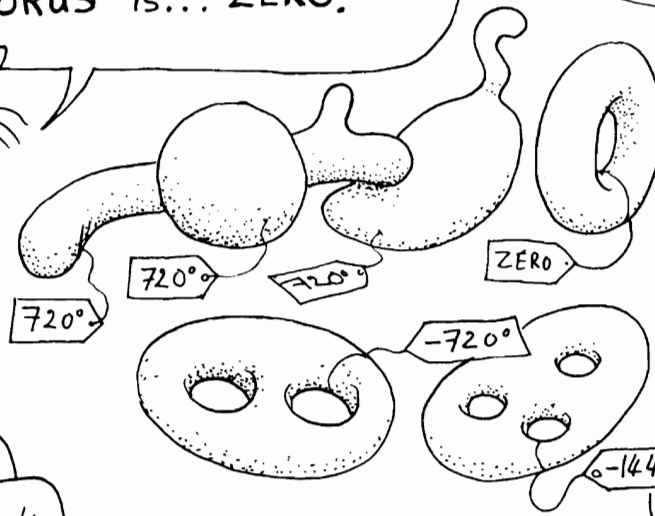
MR. ALBERT, TELL ME, WHAT'S THE TOTAL CURVATURE OF A TORUS?

SIMPLE, ARCHIBALD. ALL YOU HAF' TO DO IS THINK OF IT DIS WAY: EIGHT POSICONES ( $\theta = +90^\circ$ ) AND EIGHT NEGAONES ( $\theta = -90^\circ$ )



(\*) A THEOREM OF GAUSS

THE SUM OF THE SIXTEEN ANGLES—  
SIXTEEN CURVATURES—IS ZERO.  
SO THE TOTAL CURVATURE  
OF THE TORUS IS... ZERO!

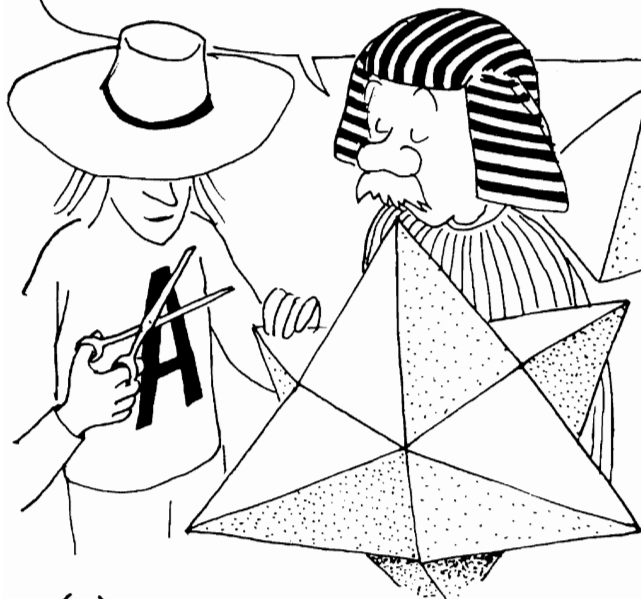


JA, JA.

ANYTHING WITH  
A SPHERELIKE SHAPE  
HAS A TOTAL CURVATURE  
EQUAL TO  $720^\circ$ , DAT IS,  
 $4\pi$  RADIAN.

A TORUS WITH  $N$  HOLES, A FOUGASSE(\*),  
WILL HAVE A TOTAL CURVATURE OF  $-4\pi(N-1)$ . YOU LOSE  $4\pi$  FOR EACH HOLE.

AND IF YOU MAKE AN OBJECT DAT CLOSES UP ON  
ITSELF LIKE A POLYHEDRON, DEN WHEN YOU SUM  
ALL DER CONCENTRATED CURFATURES AT DER  
CORNERS, YOU GET DER TOTAL CURFATURE AGAIN.



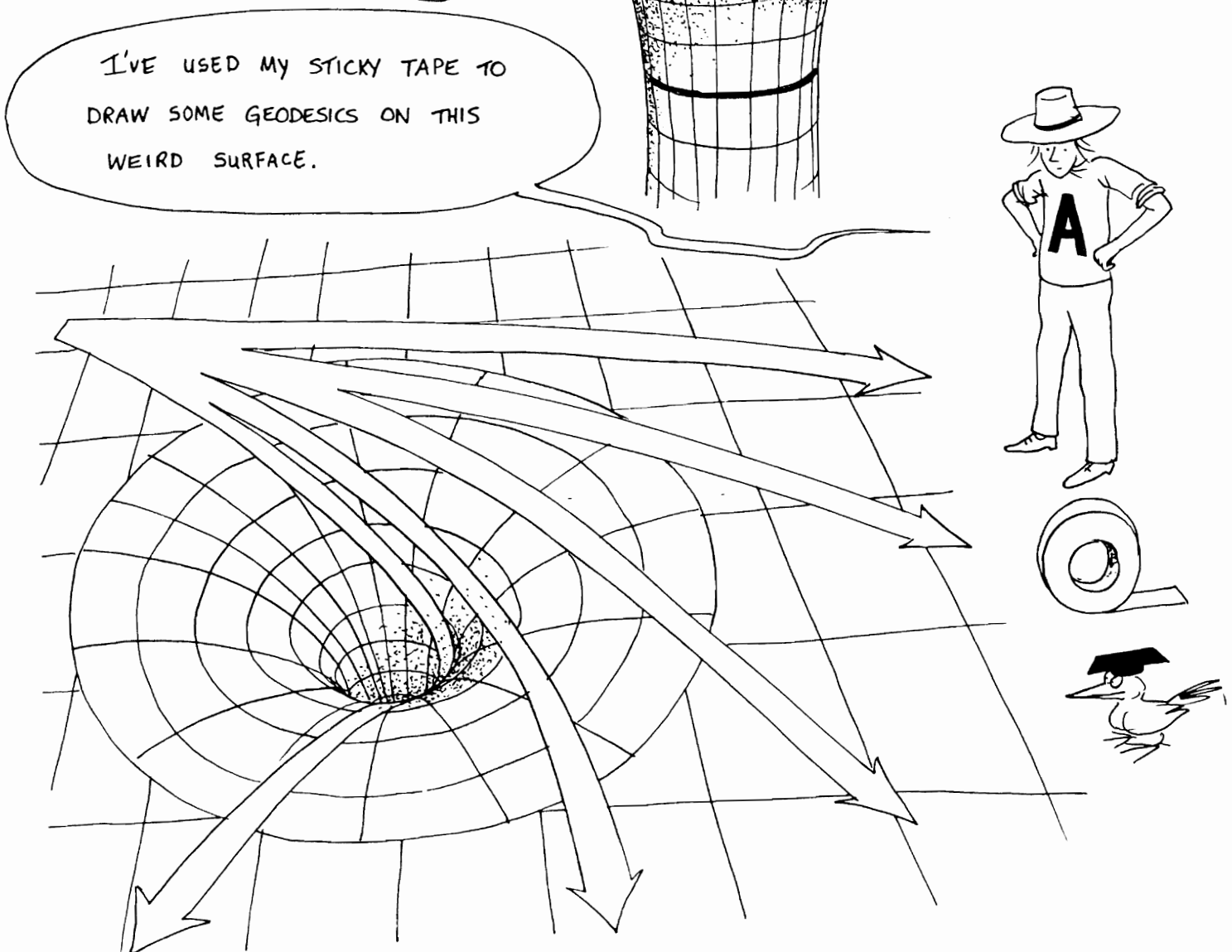
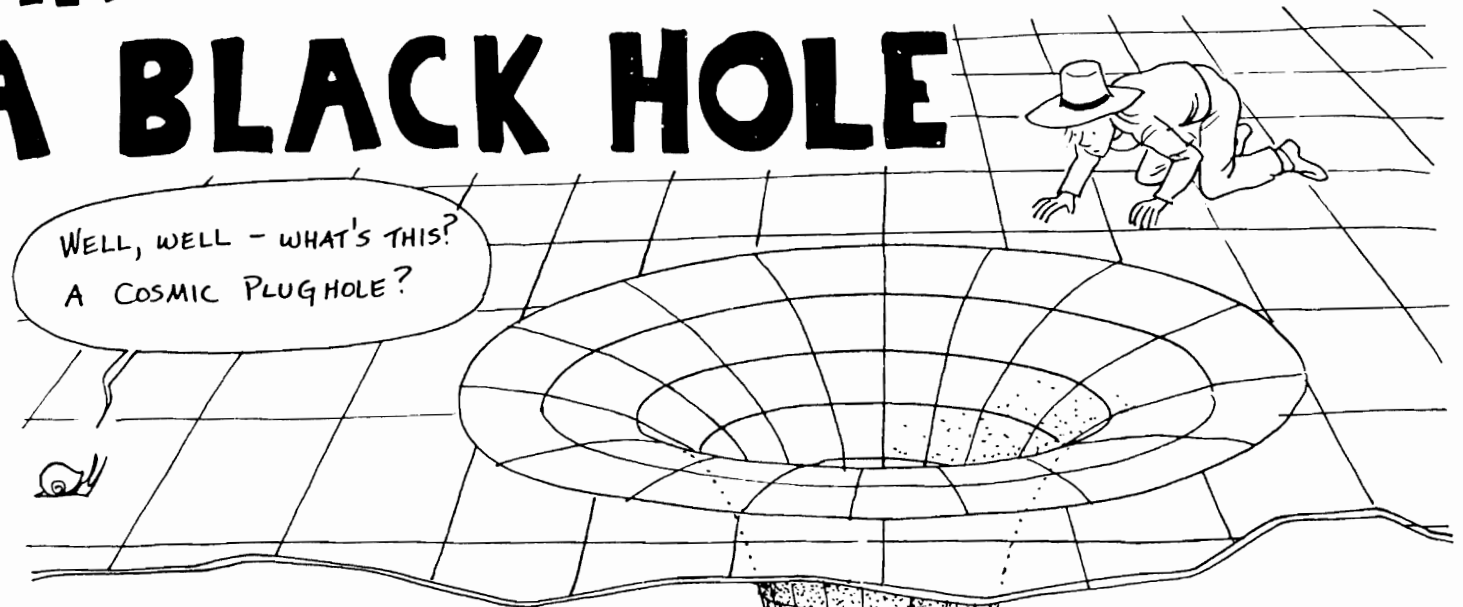
TIRESIAS,  
OLD FRUIT; WOT  
YER DOIN'?

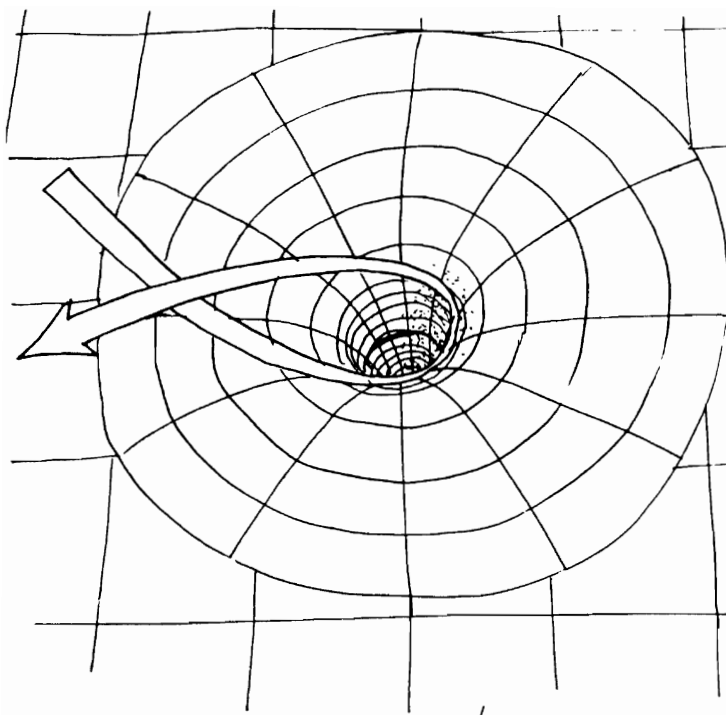
I'M TRYING TO  
FIND MY TOTAL  
CURVATURE.



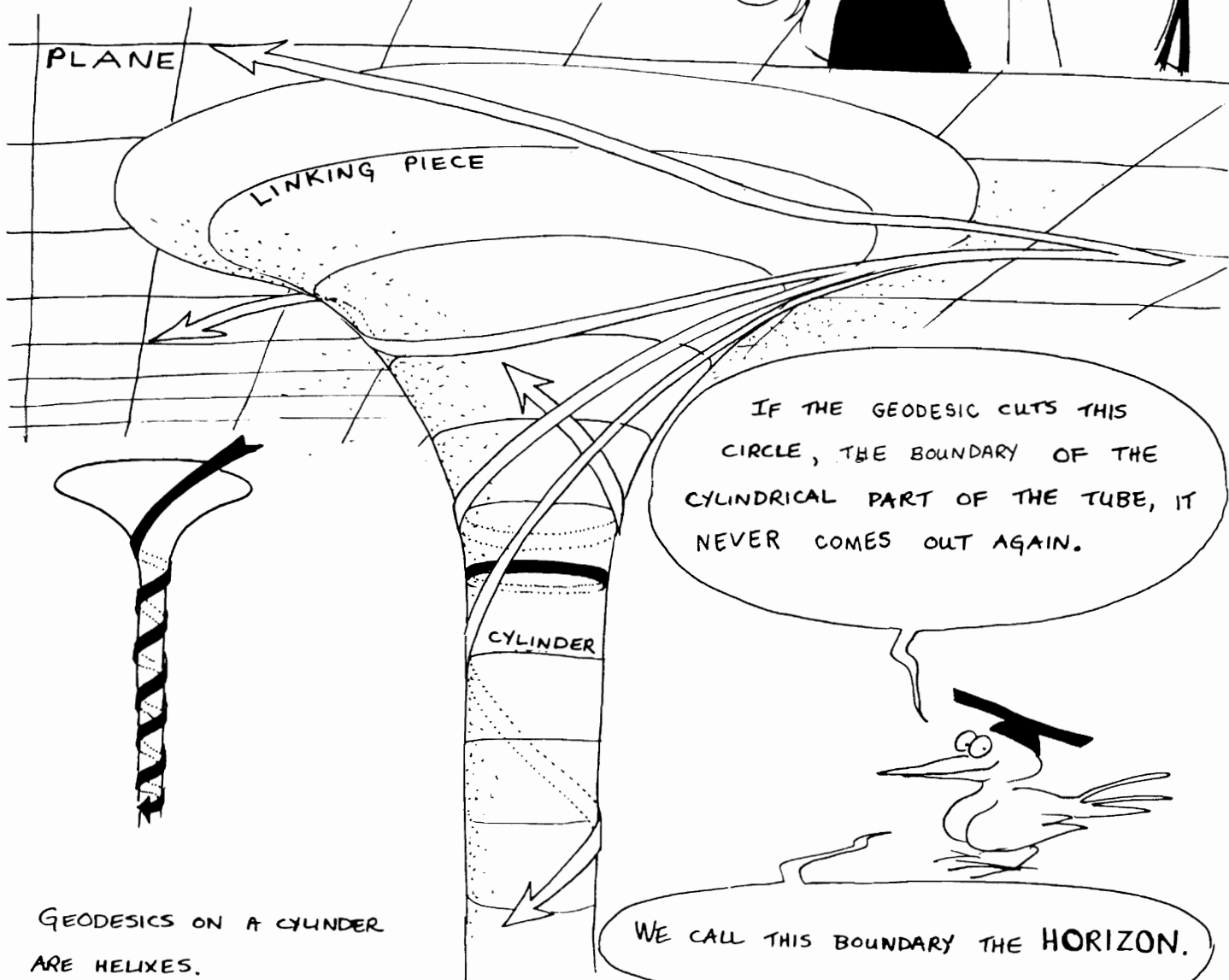
(\*) A FOUGASSE IS A SORT OF LOAF MADE IN  
THE SOUTH OF FRANCE, WHERE THE AUTHOR LIVES.

# FIRST ENCOUNTER WITH A BLACK HOLE





IF THE GEODESIC PLUNGES DEEP ENOUGH INTO THE WELL, THEN WHEN IT COMES OUT AGAIN, IT INTERSECTS ITSELF.

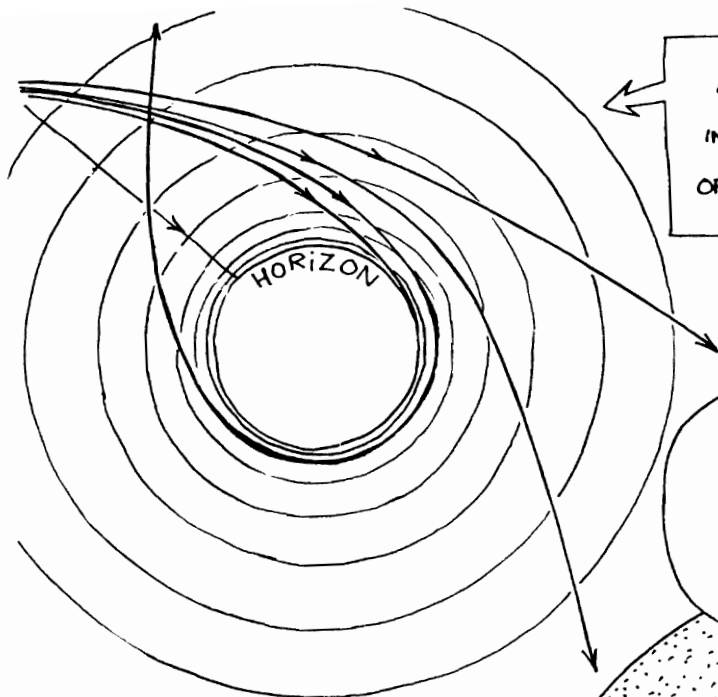


IF THE GEODESIC CUTS THIS CIRCLE, THE BOUNDARY OF THE CYLINDRICAL PART OF THE TUBE, IT NEVER COMES OUT AGAIN.



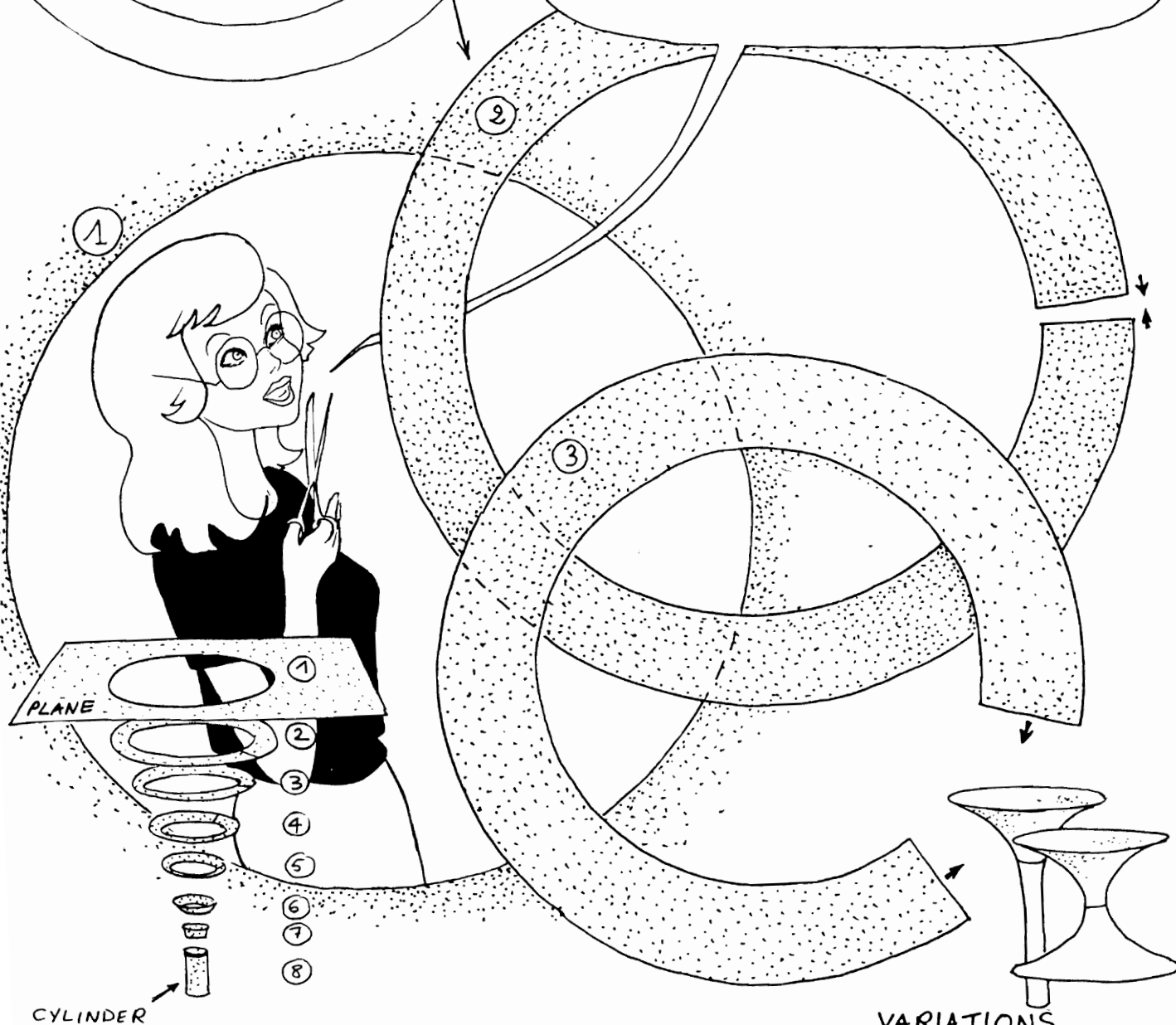
WE CALL THIS BOUNDARY THE HORIZON.

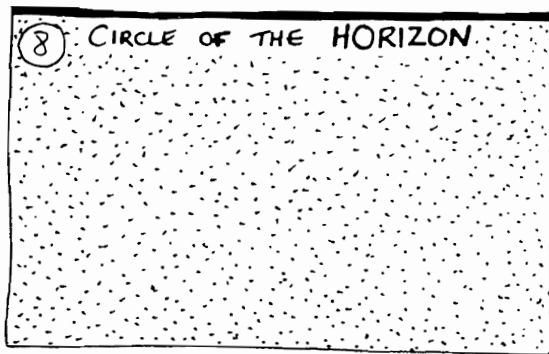
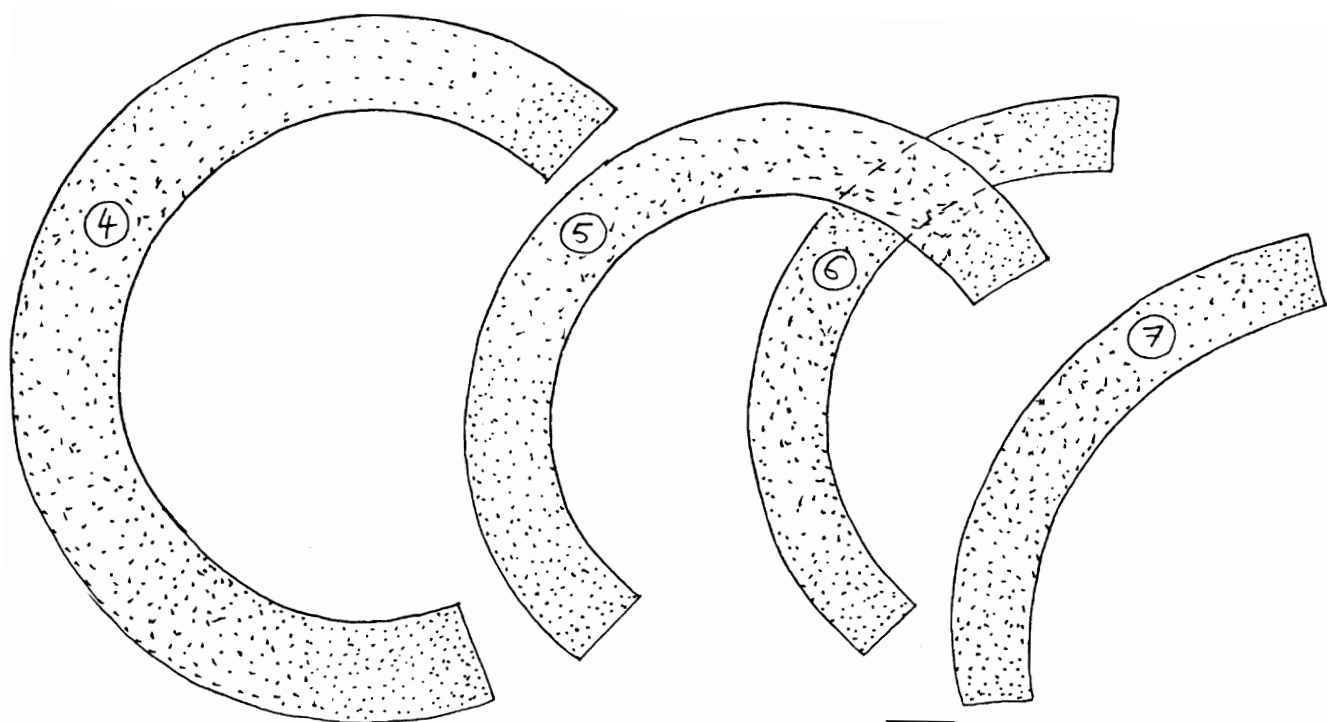
GEODESICS ON A CYLINDER ARE HELICES.



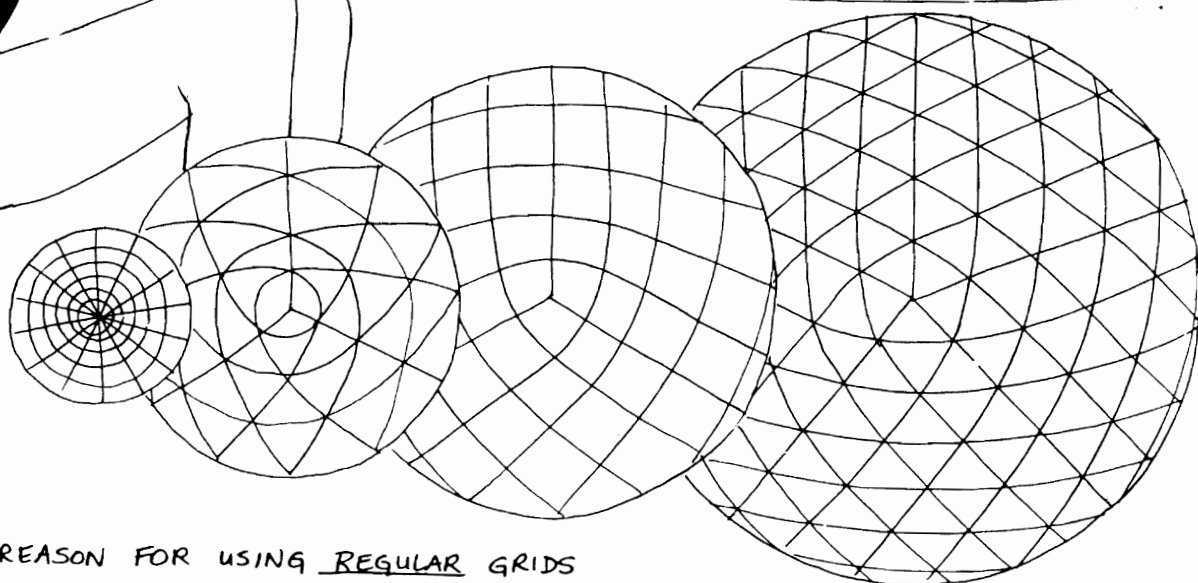
ANYONE WHO THOUGHT HE WAS LIVING  
IN A PLANAR WORLD WOULD THINK  
OF THE TRAJECTORIES LIKE THIS.

YOU CAN MAKE YOUR OWN BLACK HOLE  
USING A PLANE WITH A HOLE IN IT (①),  
SIX TRUNCATED CONES (JOINED EDGE TO EDGE),  
AND A CYLINDER (⑧).

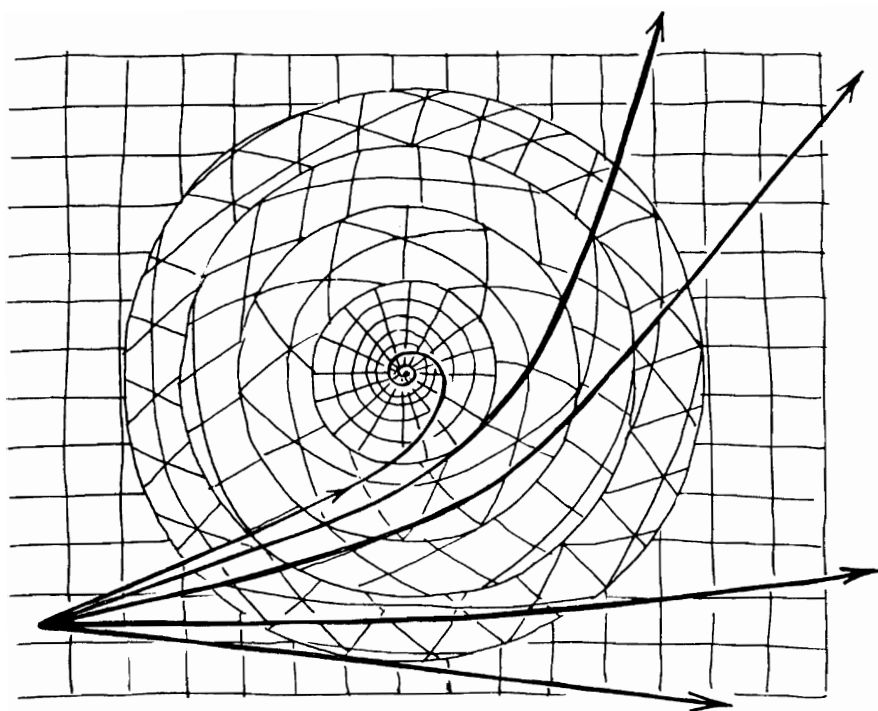




ANOTHER WAY TO MAKE BLACK HOLES IS TO USE THESE GRIDS.



THE ONLY REASON FOR USING REGULAR GRIDS IS TO MAKE THE RESULT LOOK PRETTY.



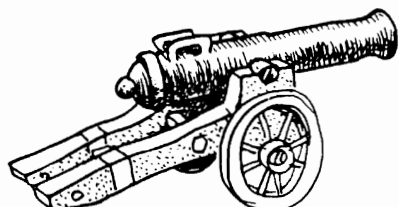
**R**ULES OF THE GAME: YOU MUST DRAW LINES THAT CUT EACH GRID AT A FIXED ANGLE, WHILE MAINTAINING CONSISTENCY AND CONTINUITY AT EACH BOUNDARY CIRCLE WHERE THE GRIDS JOIN UP. THE CLOSER YOU APPROACH THE BLACK HOLE, THE STRONGER ITS ATTRACTION WILL SEEM. WITHIN THE HORIZON CIRCLE THE TRAJECTORY WILL ROLL UP INTO A SPIRAL. NOTE THAT THE CENTRAL GRID, WHICH IS

POLE-SHAPED, CAN BE OBTAINED FROM A GRID OF GEODESICS ON THE CYLINDER, VIEWED IN PERSPECTIVE.

'ANG ON THERE!  
SEEMS TER ME THERE'S SUMFINK  
A BIT COCKEYED ABAHT THIS  
'OLE SET-UP!



YER'VE REPLACED MASSES BY CURVYTURES AND  
TRAJECTORIES BY BLINKIN' GEO-DEESICKS. BUT  
WOTCHA GONNA DO ABAHT THE M'INITIAL  
VELOCIPED?

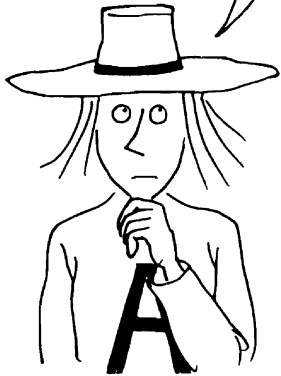


THE TRAJECTORY FOLLOWED BY AN OBJECT  
WITHIN THE FIELD OF FORCE GENERATED BY ONE  
OR SEVERAL MASSE. DEPENDS ON ITS INITIAL  
VELOCITY  $V_0$ .



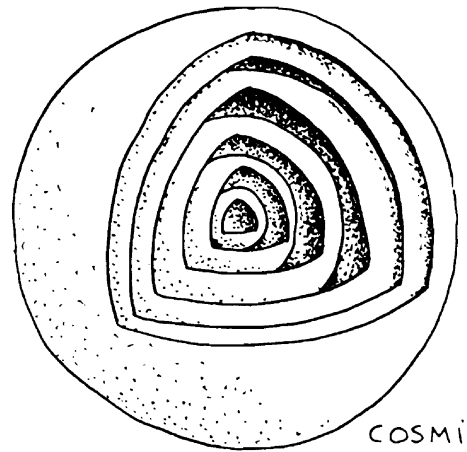
FOR EXAMPLE: CANNONBALLS  
IN EARTH'S GRAVITATIONAL FIELD.

DOES THAT MEAN THAT ALL THE DRAWINGS SO FAR CORRESPOND TO JUST ONE PARTICULAR VALUE OF THE INITIAL VELOCITY  $V_0$  ?



# A THE ABYSS

THINK OF A WORLD BUILT LIKE AN ONION, IN CONCENTRIC LAYERS. (\*)



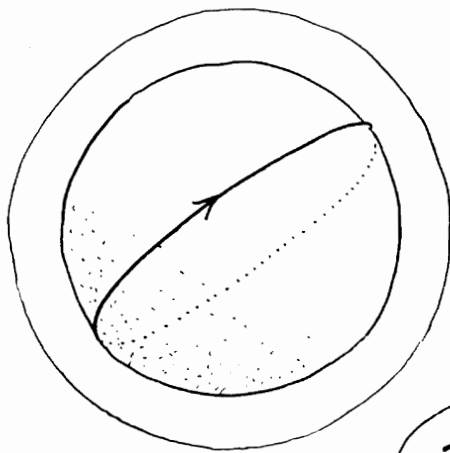
COSMIC PARK

TO EACH LAYER THERE CORRESPONDS A MAGNITUDE  $V$  OF THE VELOCITY. THE FASTER YOU GO, THE DEEPER YOU GO.

AT THE SPEED OF LIGHT, YOU REACH THE MIDDLE OF THE ONION.

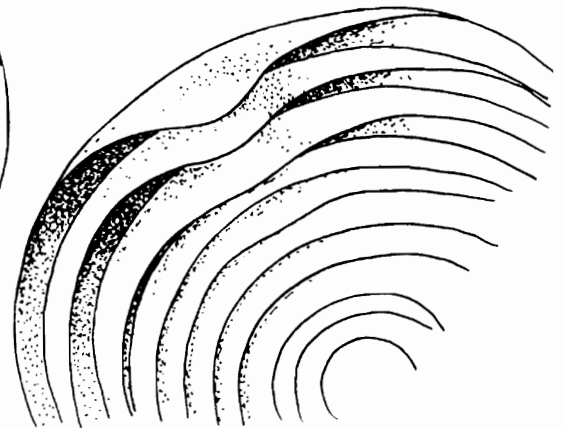
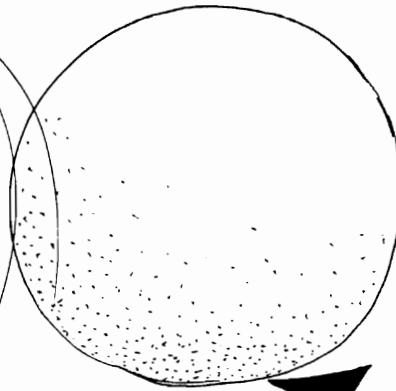
(\*) THIS MODEL HAS BEEN INTRODUCED IN EVERYTHING IS RELATIVE (SAME SERIES) UNDER THE NAME COSMIC PARK.



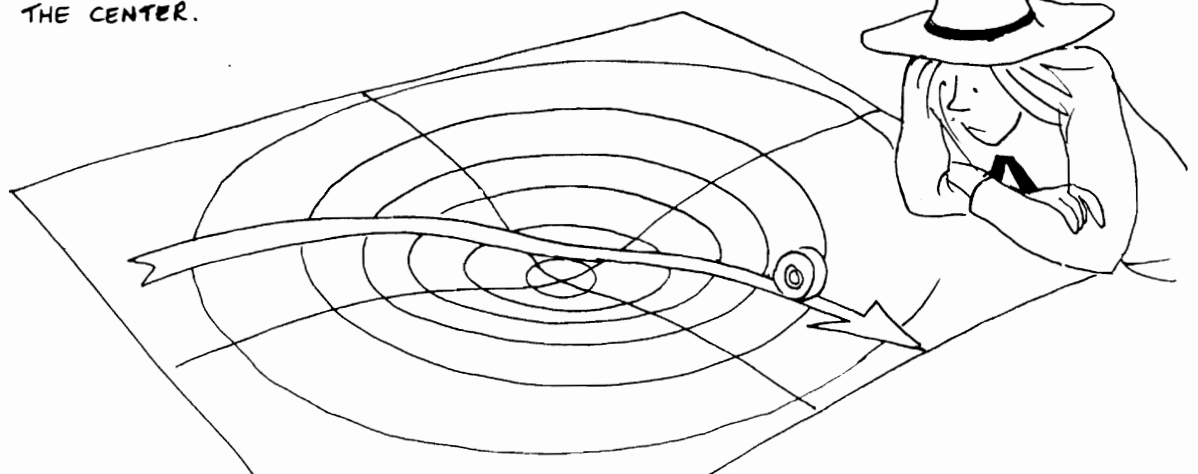


IF THERE ARE NO FORCES, THEN THE SPEED OF THE OBJECT DOESN'T CHANGE. SO IT STAYS ON A **SPHERE**, ALWAYS THE SAME DISTANCE FROM THE CENTER OF THE UNION. IT FOLLOWS A GEODESIC, THAT IS, A **GREAT CIRCLE**, ON THIS SPHERE.

THIS WILL DO THE TRICK!

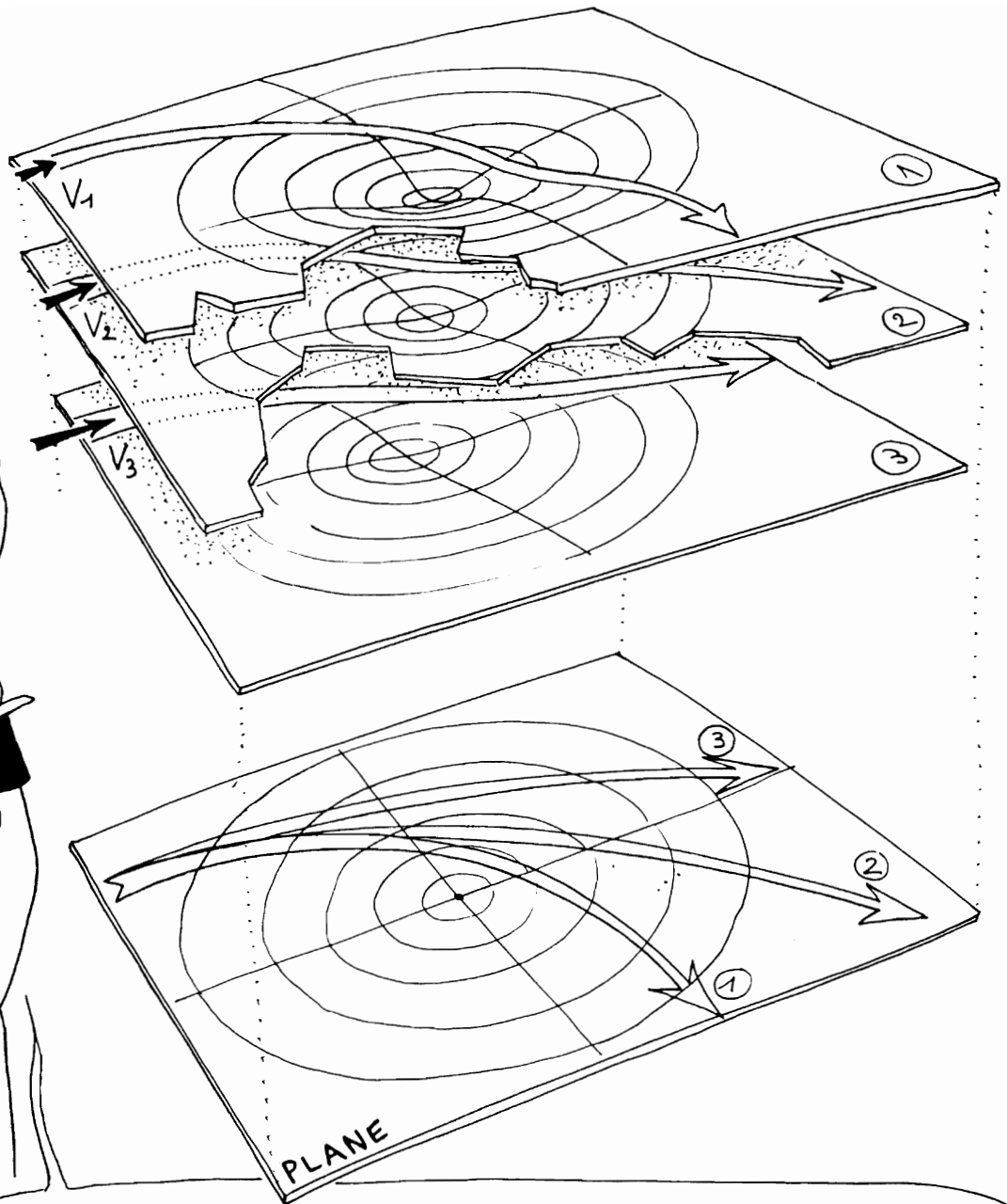


WHEN MR. ALBERT HIT IT WITH HIS HAMMER, THIS IS WHAT HAPPENED. YOU CAN SEE THAT THE EFFECT GETS LESS NEARER THE CENTER.

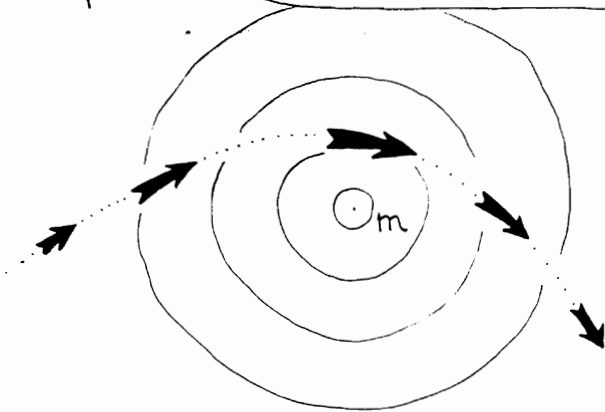


HERE IS A **DENT** (OR A **BUMP**, IT MAKES NO DIFFERENCE). THE **CONTOUR LEVELS** (WHICH ARE **NOT** GEODESICS!) HAVE BEEN DRAWN, ALONG WITH ONE SELECTED GEODESIC.

$$V_1 < V_2 < V_3$$

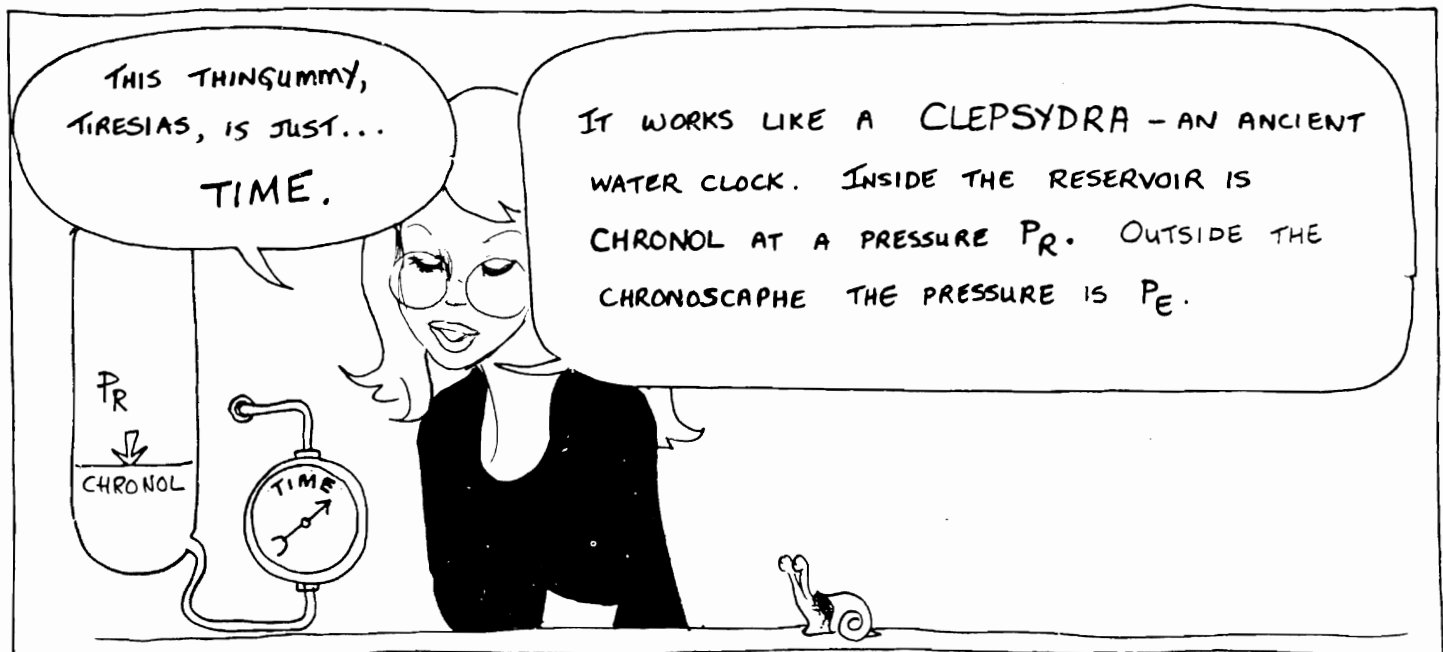


THE SLOWER THE INITIAL VELOCITY, THE MORE NOTICEABLE THE DEFORMATION, AND THE BIGGER THE BEND IN THE TRAJECTORY.



UNDER THE INFLUENCE OF GRAVITATIONAL ATTRACTION, THE SPEED OF AN OBJECT FIRST INCREASES, THEN DECREASES. IT IS GREATEST WHEN THE DISTANCE BETWEEN THE OBJECT AND THE ATTRACTING MASS IS SMALLEST. ASTRONOMERS CALL THIS POSITION PERIHELION.

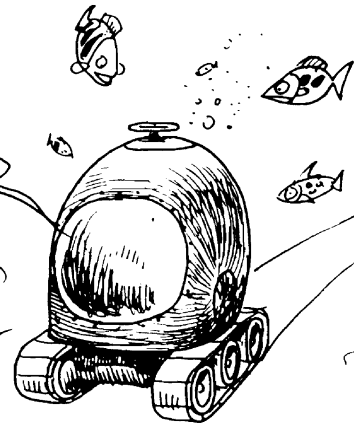




(\*) MEMO: THE SECOND PRINCIPLE OF THERMODYNAMICS SAYS THAT IT IS IMPOSSIBLE TO FOLLOW THE GEODESICS OF SPACE-TIME (COSMIC PARK) IN THE REVERSE DIRECTION.

*The Boss*

SINCE THE PRESSURE  $P_R$  IS GREATER THAN  $P_E$ ,  
THE CHRONOL FLOWS OUT AND THE  
CHRONOMETER SHOWS THE TIME  
THAT HAS PASSED.



THE DEEPER YOU DESCEND INTO THE  
CHRONOL, THE MORE THE PRESSURE  $P_E$   
INCREASES. SINCE THE RATE OF FLOW IS  
PROPORTIONAL TO  $(P_R - P_E)$ , THE PRESSURE-  
DIFFERENCE, TIME FLOWS MORE SLOWLY  
AT GREATER DEPTHS.

THE DEPTH IS THE SPEED. SO  
THE FASTER YOU GO, THE SLOWER  
TIME PASSES. (\*)



AND AT THE SPEED OF LIGHT,  $P_E$   
IS EXACTLY EQUAL TO  $P_R$ , AND TIME  
GRINDS TO A HALT.

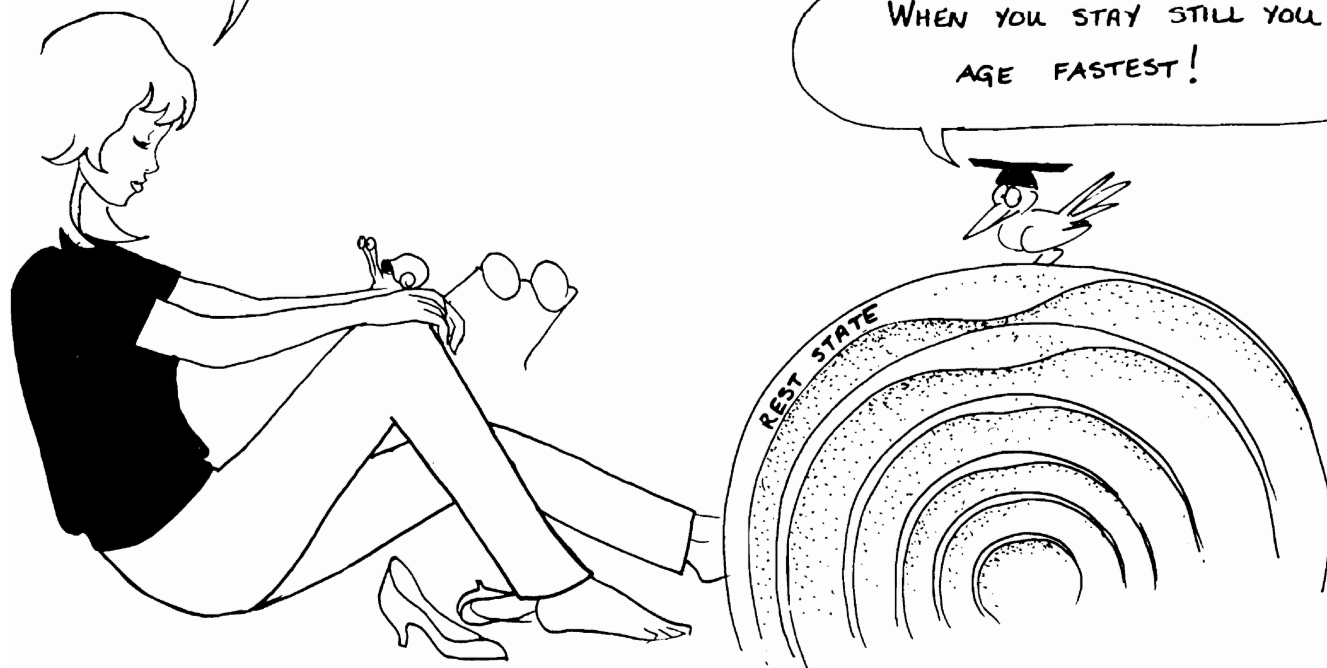


AND YOU CAN'T TRAVEL FASTER THAN LIGHT, BECAUSE YOU  
CAN'T GO ANY DEEPER THAN THE CENTER OF COSMIC PARK.

(\*) SEE EVERYTHING IS RELATIVE, SAME SERIES.

THE OUTSIDE SURFACE OF COSMIC PARK CORRESPONDS TO NO MOTION AT ALL: THE REST STATE.

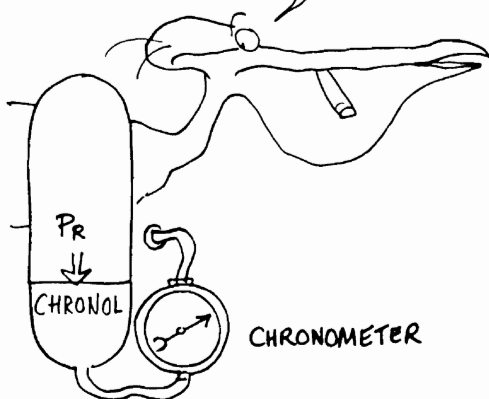
WHEN YOU STAY STILL YOU AGE FASTEST!



A VERY MASSIVE BODY PRODUCES A LARGE AMOUNT OF CURVATURE IN SPACE-TIME. THIS MEANS THAT ANY NEARBY OBJECT, EVEN ONE AT REST, IS IMMERSSED IN CHRONOL AT A HIGHER PRESSURE. SO, FOR IT, TIME FLOWS MORE SLOWLY THAN IT WOULD FOR AN OBJECT AT REST, BUT FAR FROM ANY MASS. THIS SLOWING DOWN OF TIME HAPPENS, FOR INSTANCE, NEAR A SUPERDENSE OBJECT SUCH AS A NEUTRON STAR.

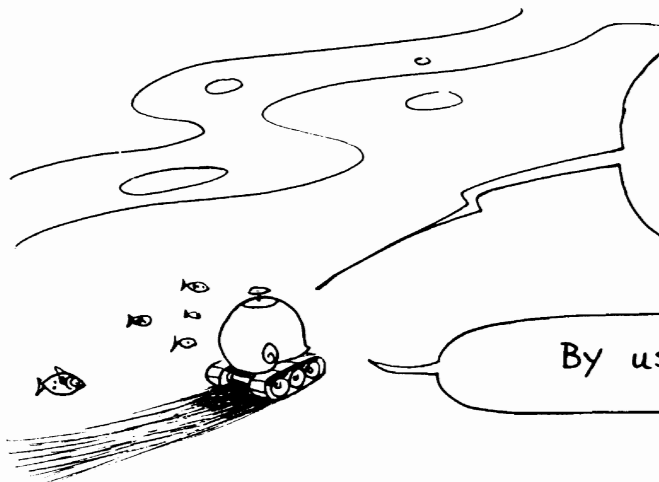
WOT 'APPENS TO A BLOKE 'OO SCARPERS OUT OF 'IS CHRONOSCAPHE?

HE PROBABLY GETS A SUDDEN ATTACK OF OLD AGE.



AND WHEN ALL THE CHRONOL RUNS OUT, IS THAT... DEATH?

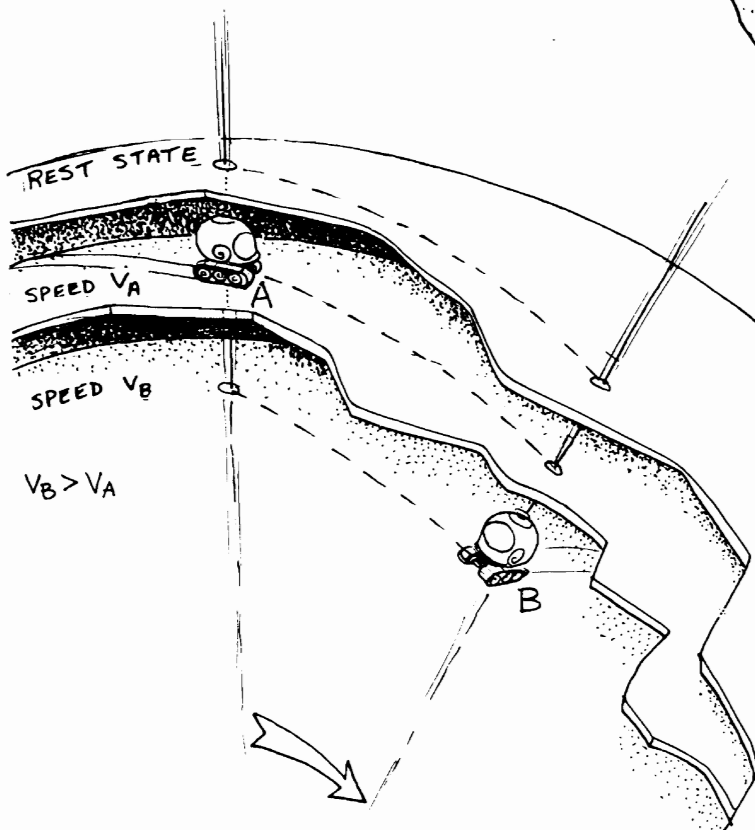
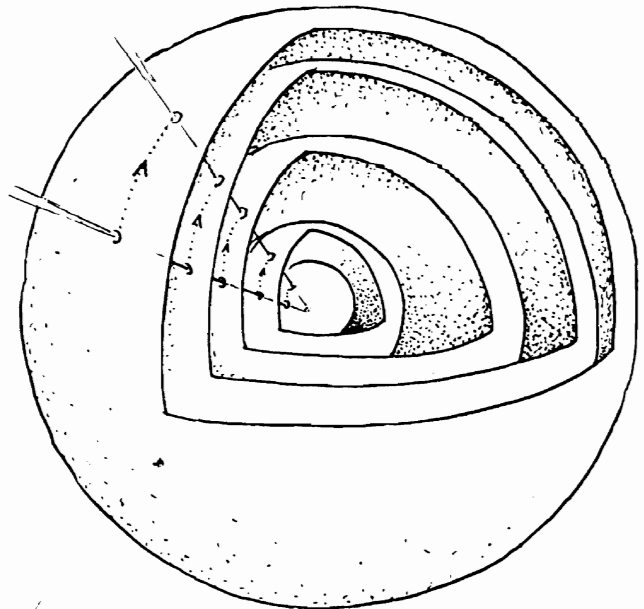
# COMMUNICATION



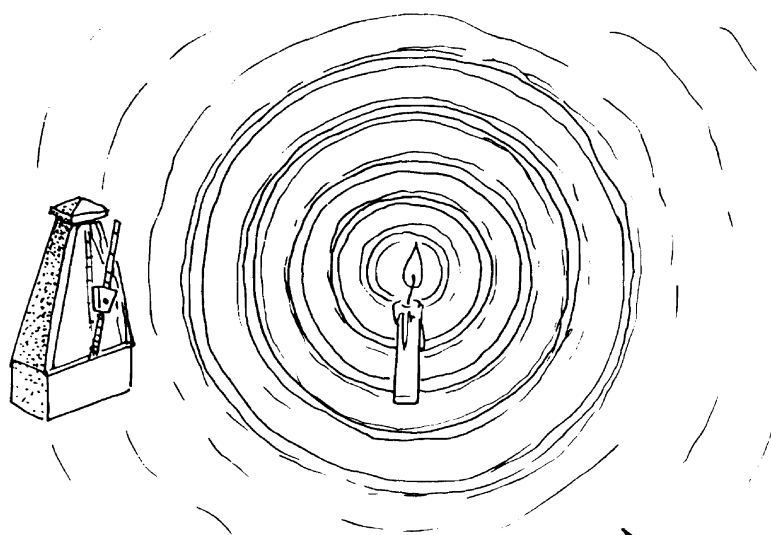
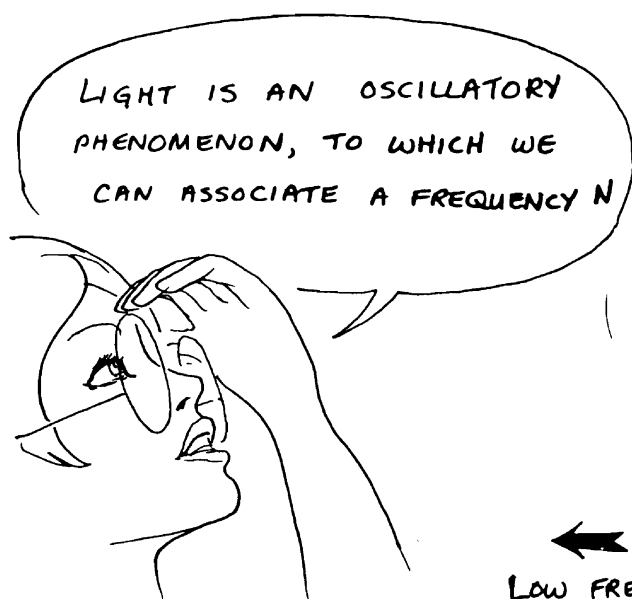
WELL, HERE WE ARE INSIDE OUR CHRONOSCAPHES. HOW CAN WE COMMUNICATE WITH EACH OTHER?

By using PHOTONS.

PHOTONS - TINY QUANTITIES OF LIGHT - BEHAVE JUST LIKE A SEARCHLIGHT BEAM, SWEEPING ACROSS ALL THE LAYERS OF COSMIC PARK AT A CONSTANT ANGULAR VELOCITY.



AN OBJECT A, TRAVELING AT A SPEED  $V_A$ , CAN TRIGGER OFF ONE OF THESE SEARCHLIGHT BEAMS IN THE DIRECTION OF AN OBJECT B, MOVING AT A SPEED  $V_B$ .

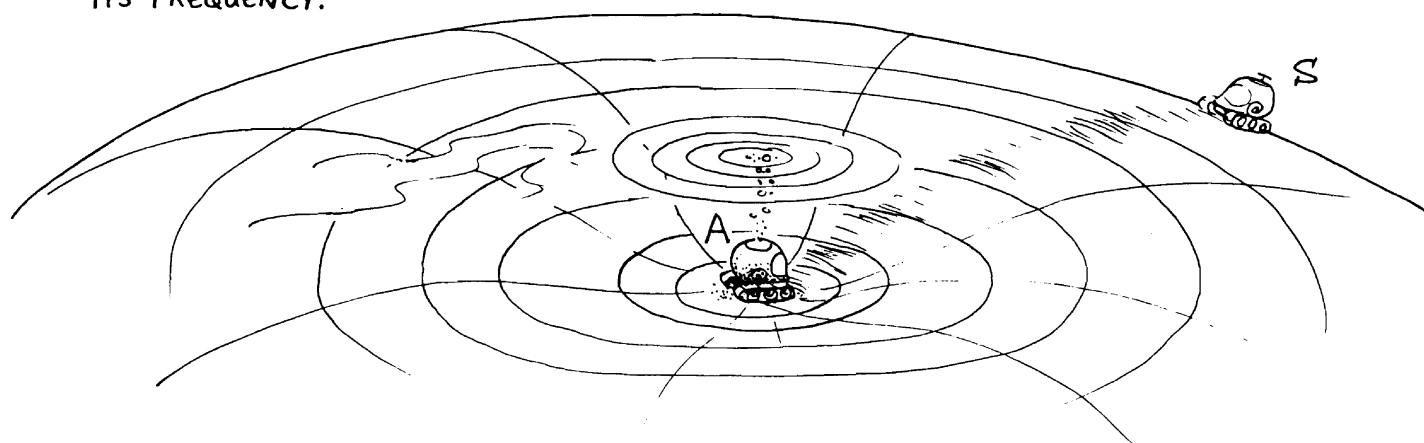


← LOW FREQUENCY

→ HIGH FREQUENCY

AND ITS COLOR IS DETERMINED BY ITS FREQUENCY.

INFRARED RED ORANGE YELLOW GREEN BLUE VIOLET ULTRAVIOLET



THE FREQUENCIES OF THE PHOTONS EMITTED OR RECEIVED WILL BE MEASURED RELATIVE TO THE FLOW-RATE OF TIME IN THE CHRONOSCAPHE OF THE EMITTER OR RECEIVER. IN CHRONOSCAPHE A, ARCHIE SENDS OUT BLUE LIGHT. HE HAPPENS TO BE IN A REGION OF SPACE THAT IS HIGHLY CURVED — FOR EXAMPLE HE MAY BE NEAR A NEUTRON STAR OF ENORMOUS MASS.

SOPHIE, IN CHRONOSCAPHE S, RECEIVES THIS LIGHT. SHE IS A LONG WAY FROM THE SUPERDENSE OBJECT. SO HER TIME FLOWS FASTER, AND SHE MEASURES A LOWER FREQUENCY. TO HER, THE COLOR OF THE LIGHT SEEMS TO HAVE SHIFTED TOWARDS RED.



**A**RCHIE IS STANDING ON A NEUTRON STAR. (WE HAVE TEMPORARILY SUSPENDED THE EFFECTS OF GRAVITY ON HIS BODY, SINCE THAT WOULD INSTANTLY SPREAD HIM OUT FLATTER THAN A PANCAKE.)

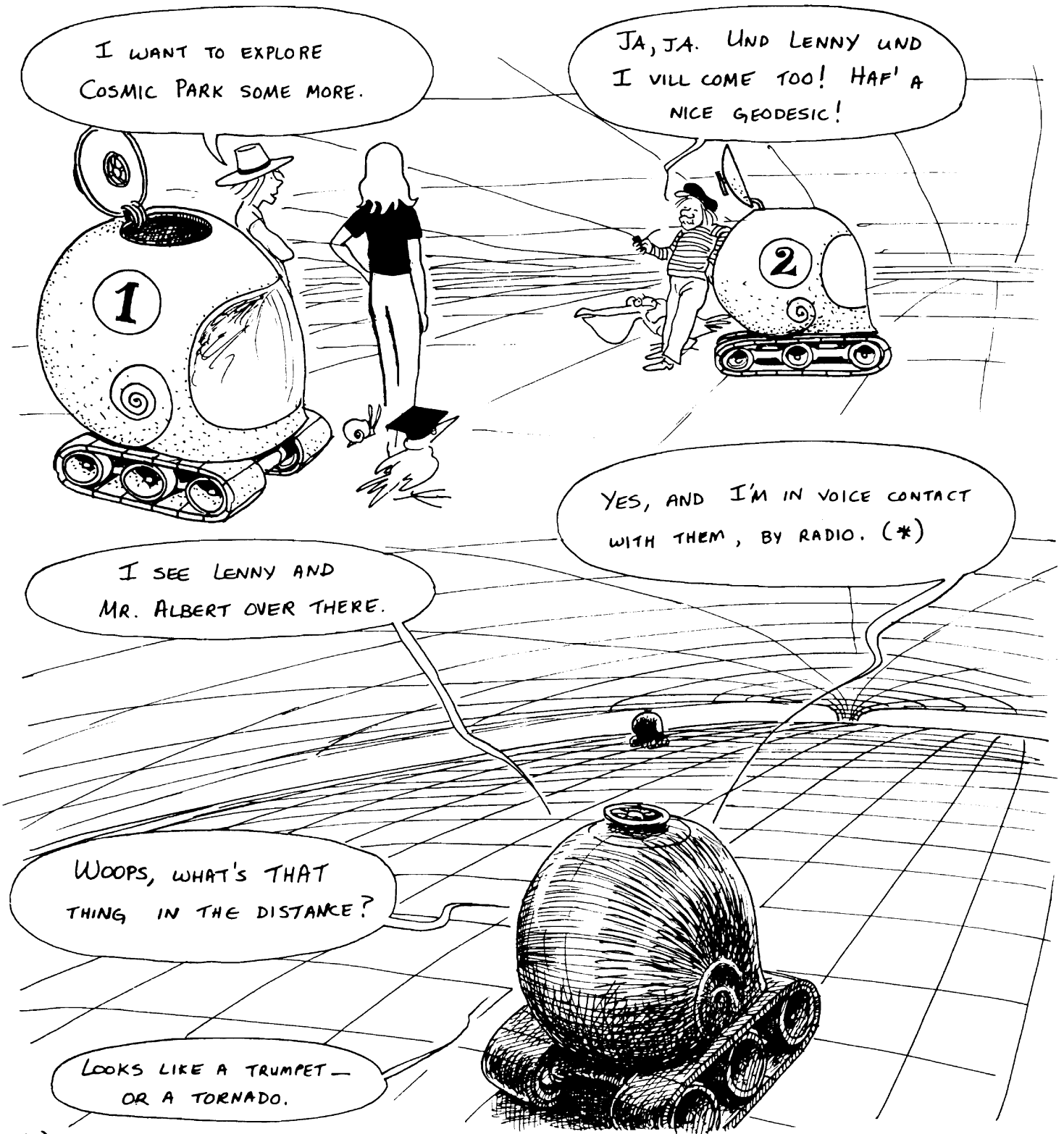


ACTUALLY, THE APPLE WAS GREEN ALL THE TIME, BUT THE EFFECT OF GRAVITY ON TIME SHIFTED IT TO RED.

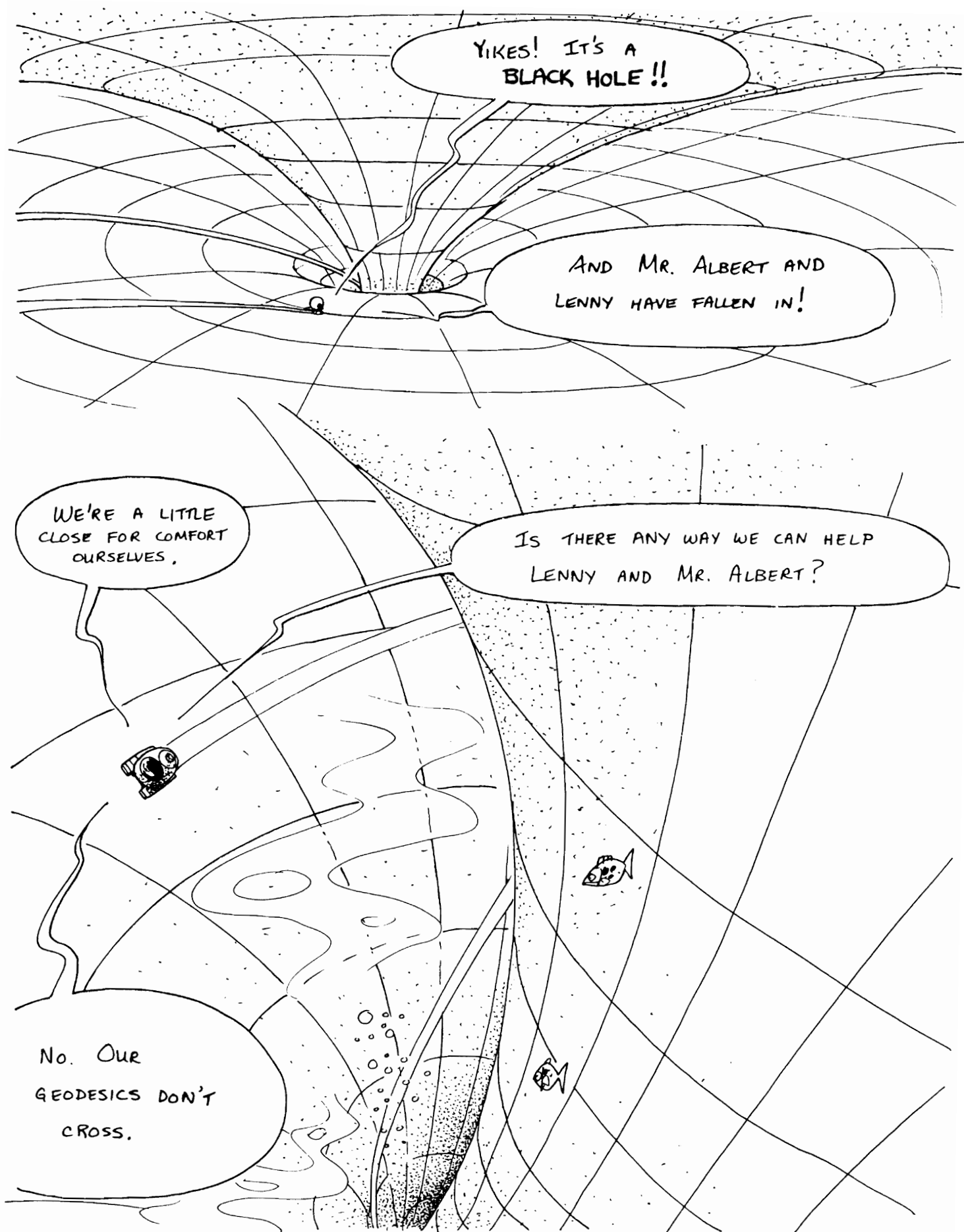
APPLES ARE NOT WHAT THEY WERE IN MY DAY...



# SECOND ENCOUNTER WITH A BLACK HOLE



(\*) RADIO WAVES ARE SIMILAR TO LIGHT WAVES. THEY HAVE THE SAME SPEED OF PROPAGATION  $c$ , BUT LOWER FREQUENCY.



CAN YOU SEE THEM?

THE BOTTOM OF THE BLACK HOLE  
IS TOTALLY OPAQUE.

I CAN STILL SEE THEM, BUT THEIR  
CHRONOSCAPHE HAS GONE A DULL ORANGE COLOR.

HALLO? MR. ALBERT? LENNY?  
ARE YOU RECEIVING ME?

IT'S BAFFLIN! 'IS VOICE  
'AS GORN SQUEAKY AN' 'E'S  
TALKIN' TOO QUICK. SOUNDS  
LIKE DONALD DUCK.

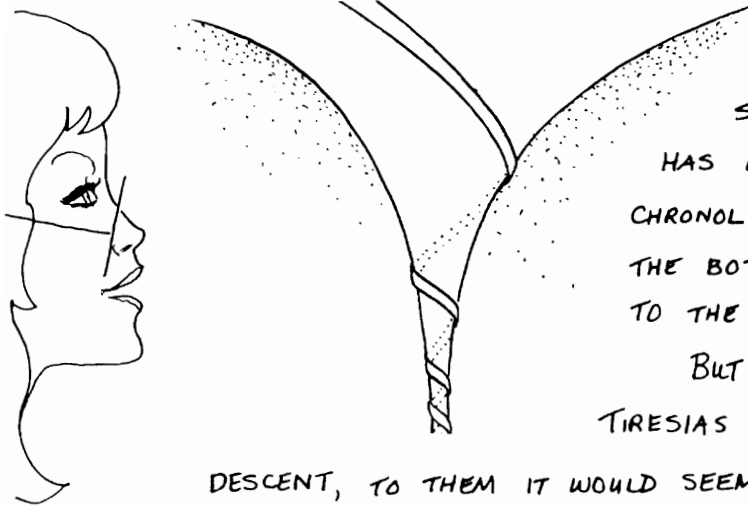
HIS VOICE IS GETTING DEEPER AND  
DEEPER, LIKE A RECORD SLOWING  
DOWN!

**AHHHTEUHHH...**

THERE ARE COMMUNICATION PROBLEMS  
WHEN YOU LIVE IN VERY DIFFERENT  
"TIME ZONES."

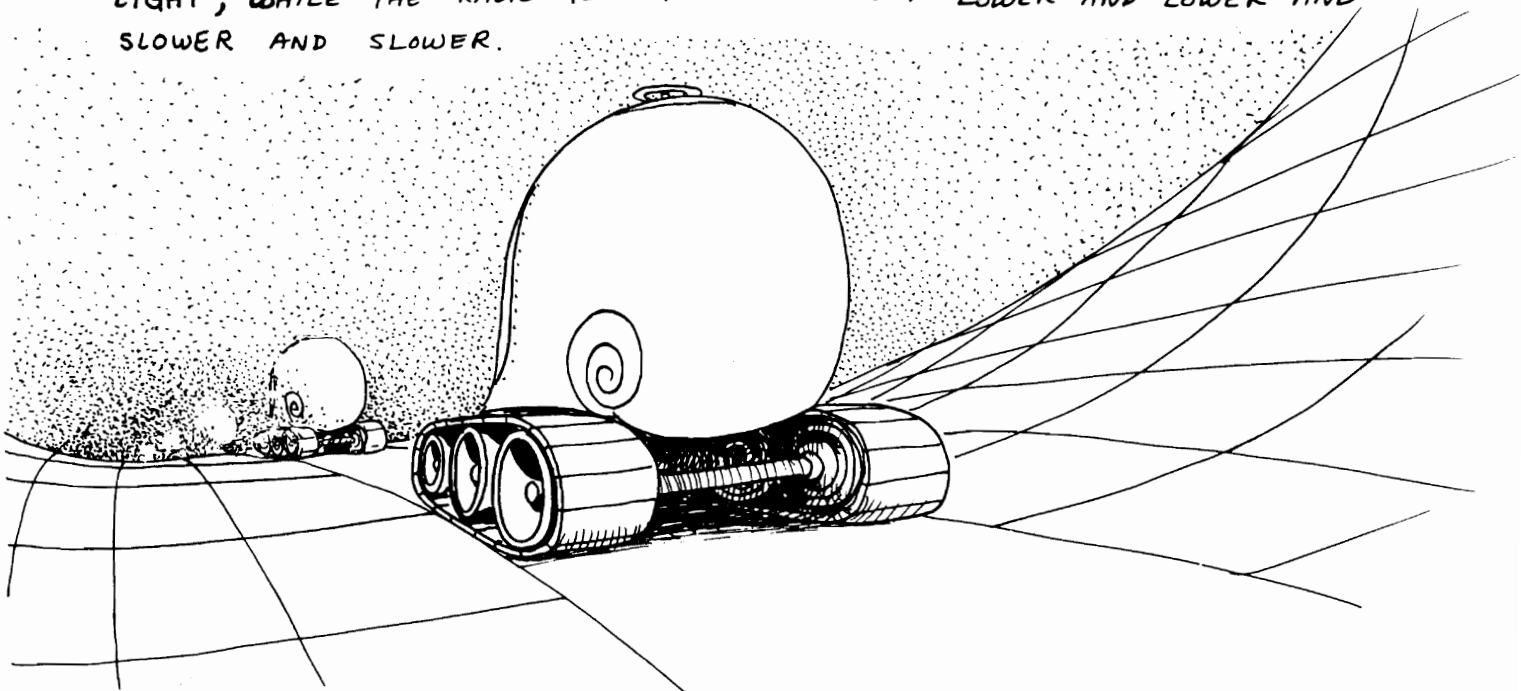
# A MATTER OF TIME

THE DEEPER MR. ALBERT AND LENNY SINK INTO THE CHRONOL, THE MORE THE OUTSIDE PRESSURE  $P_E$  INCREASES, THE SLOWER THE CLEPSYDRA RUNS OUT OF CHRONOL, AND THE SLOWER TIME FLOWS IN THEIR CHRONOSCAPHE.



WHEN THEY GET DOWN TO THE BOTTOM OF THINGS, AT THE SPEED OF LIGHT, THEIR WATER-CLOCK HAS LOST ONLY A LIMITED AMOUNT OF CHRONOL, WHICH MEANS THAT THEY REACH THE BOTTOM IN A FINITE TIME, ACCORDING TO THE TIME FLOWING IN THEIR OWN CHRONOSCAPHE.

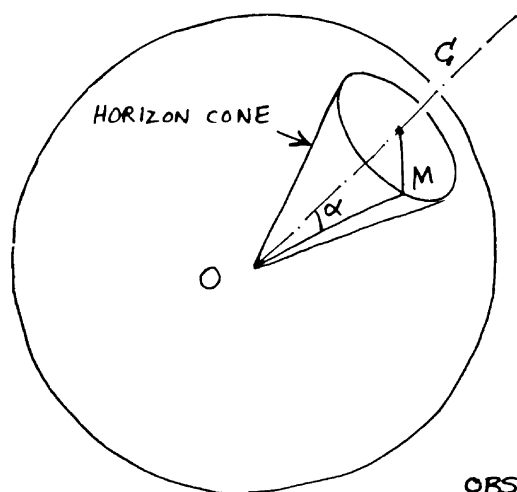
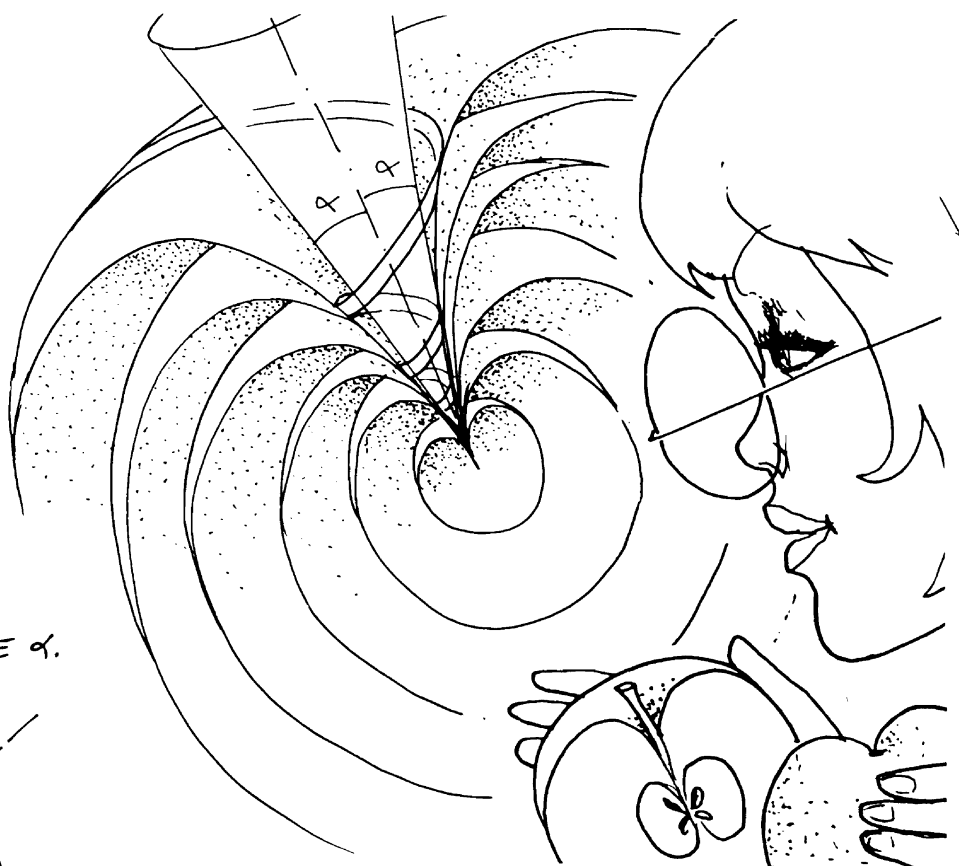
BUT IF SOPHIE, ARCHIE, MAX, AND TIRESIAS COULD CONTINUE TO TRACK THEIR DESCENT, TO THEM IT WOULD SEEM INTERMINABLE. THE LIGHT EMITTED BY THE CHRONOSCAPHE WOULD DROP DEEP INTO THE INFRARED, BELOW THE RANGE OF VISIBLE LIGHT, WHILE THE RADIO MESSAGE WOULD SOUND LOWER AND LOWER AND SLOWER AND SLOWER.



IT REMINDS ME OF THE PARADOX OF ACHILLES AND THE SNAIL. ACHILLES TRIES TO CATCH THE SNAIL, BY REPEATEDLY HALVING THE DISTANCE BETWEEN THEM. YOU'D THINK IT WOULD GO ON FOREVER, BUT THE STEPS ADD UP TO A FINITE TOTAL TIME.

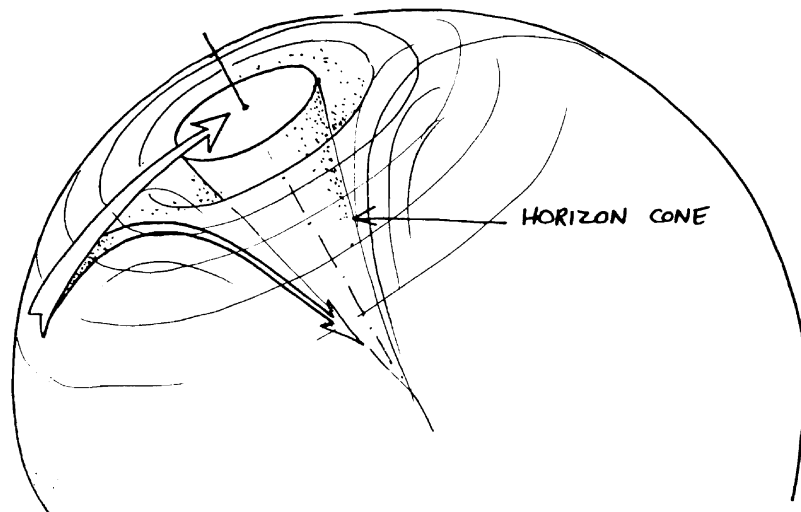
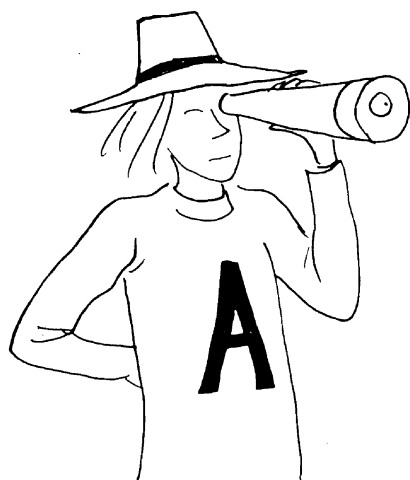


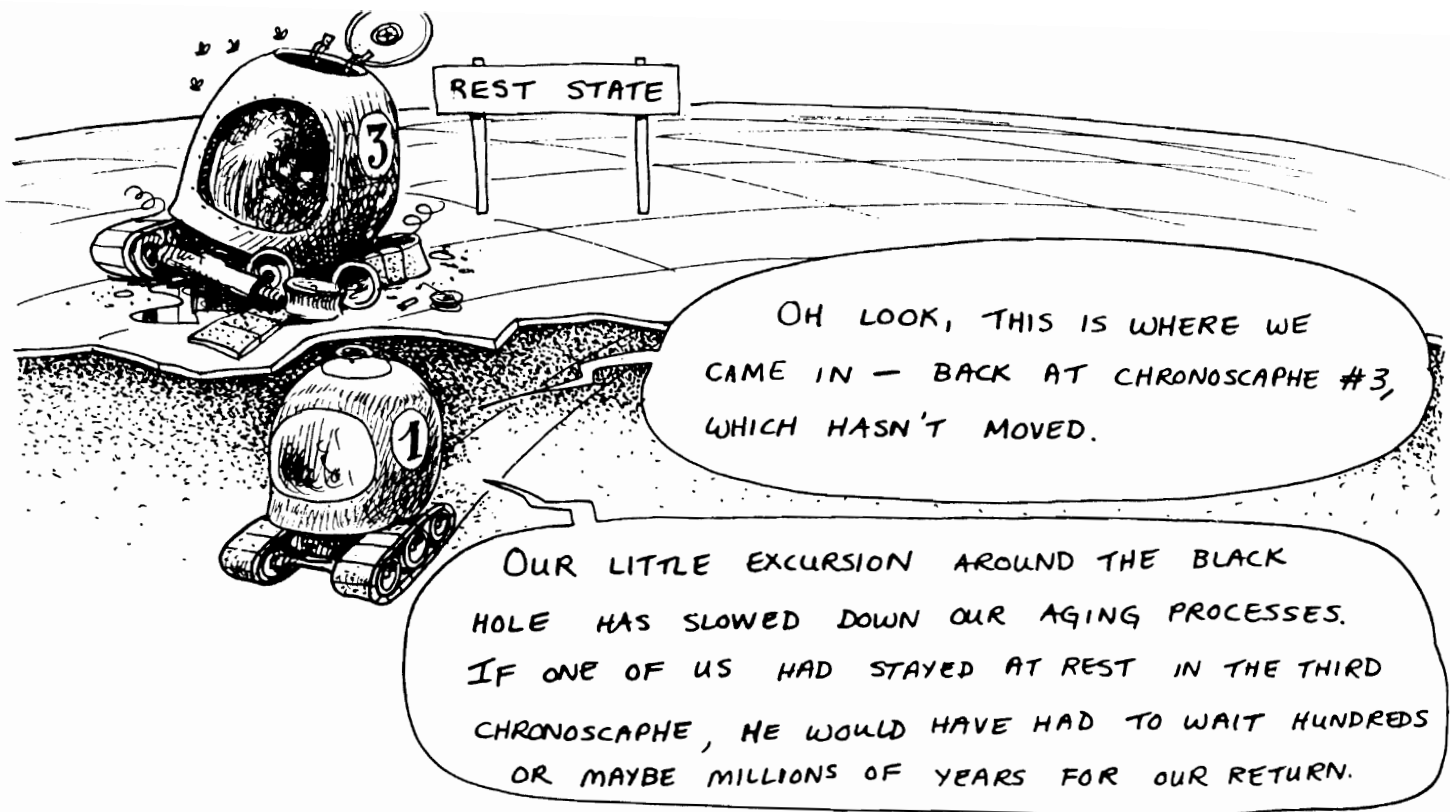
**H**ERE IS A PICTURE OF A BLACK HOLE, ACCORDING TO THE COSMIC PARK MODEL. THE SPIKE HAS PENETRATED ALL THE WAY TO THE CENTER OF SPACE-TIME, WHERE THE SPEED IS THAT OF LIGHT. ALL THE LAYERS HAVE BECOME TANGENT TO A CONE WITH VERTEX SEMI-ANGLE  $\alpha$ .

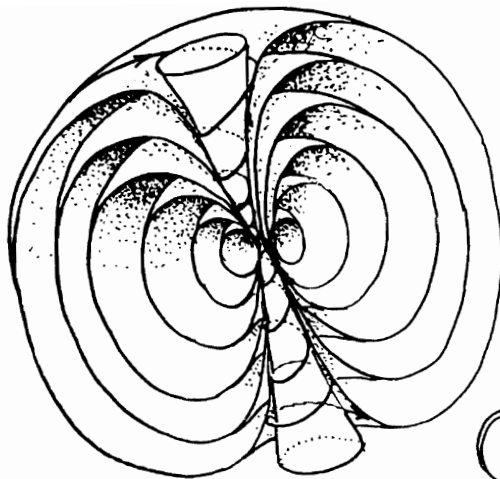


**I**N THIS MODEL, DISTANCE IS ACTUALLY AN ANGLE BETWEEN TWO RADIAL VECTORS, SUCH AS  $\vec{OM}$  AND  $\vec{OC}$ . FROM THE DIAGRAM ABOVE YOU CAN SEE THAT NOTHING CAN PENETRATE INSIDE THIS CONE WITH SEMI-ANGLE  $\alpha$ . IMAGINE AN OBSERVER IN A REST STATE AT THE SURFACE OF

THE CHRONOL, WHO DOESN'T REALIZE SPACE-TIME IS CURVED. TO HIM, THE FRONTIER OF THE BLACK HOLE - THE **EVENT HORIZON** - LOOKS LIKE A **CIRCLE**, WHICH IS REACHED AT THE SPEED OF LIGHT.







IN THE COSMIC PARK MODEL, HERE'S A WAY YOU COULD JOIN UP A BLACK HOLE/WHITE FOUNTAIN PAIR.



THE WHITE FOUNTAIN IS EXACTLY THE SAME, EXCEPT THAT ITS GEODESICS HAVE THEIR ORIENTATION REVERSED.



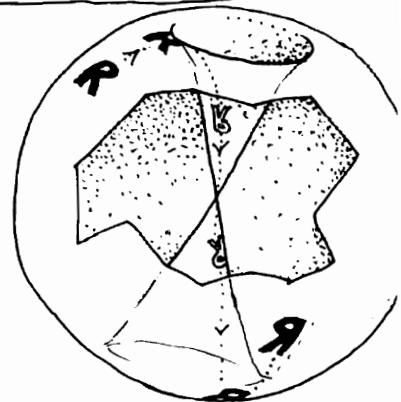
BUT WOT'S H'INSIDE A BLACK 'OLE, OVER THE BLINKIN' 'ORIZON? IS IT JUST A LOAD OF... NUFFIN'?

YOU MEAN THAT THE INTERIOR OF A BLACK HOLE IS PURE NONEXISTENCE?



NO, NO! THE "INTERIOR" OF THE BLACK HOLE IS JUST THE EXTERIOR OF ITS ASSOCIATED WHITE FOUNTAIN.

THE ALERT READER WILL HAVE NOTICED THAT IN THIS MODEL THE BLACK HOLE/WHITE FOUNTAIN PAIR GIVES ALL THE LAYERS OF COSMIC PARK THE STRUCTURE OF A NONORIENTABLE SURFACE, WITH ONLY ONE SIDE. PASSAGE THROUGH THE HOLE SENDS OBJECTS INTO THEIR MIRROR IMAGES. FOR EXAMPLE,  $R$  COMES OUT AS  $\mathfrak{A}$ .





# AS CLEAR AS MUD

BUT THERE ARE OTHER THEORIES TOO. SOME PEOPLE THINK BLACK HOLES PUT US IN CONTACT WITH A TWIN UNIVERSE.



OR PERHAPS WITH A UNIVERSE WHERE EVERYTHING IS A MIRROR IMAGE OF THIS ONE - INCLUDING TIME.



HAVING SAID WHICH, IF THERE ARE ANY WISE GUYS WHO'VE GONE INTO A BLACK HOLE, NONE OF THEM HAVE COME BACK TO TELL THE TALE.

PER 'APS TIRESIAS'S SHELL IS REALLY JUST A BLOOMIN' BLACK 'OLE!



MOMMY!

LENNY, DON'T BE  
HORRIBLE TO TIRESIAS!

DON'T WORRY,  
TIRESIAS. THE IMPORTANT  
THING IS TO BE COMFORTABLE  
IN YOUR OWN SHELL.

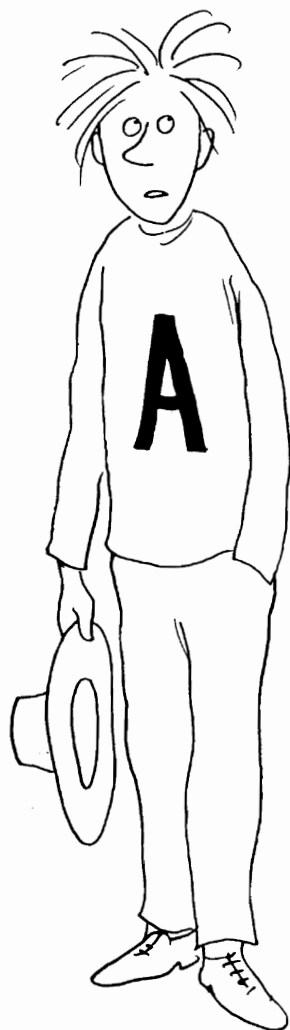
MI!

# EPILOGUE

LET ME SEE... VOID  
AND MATTER ARE THE SAME  
THING... SPACE CAN CLOSE UP  
ON ITSELF... AND THE ONLY  
WAY YOU CAN GO IS  
STRAIGHT!



IF THIS UNIVERSE IS THE BEST  
OF ALL POSSIBLE WORLDS, I'M GLAD  
I DON'T LIVE IN ANY OF THE OTHERS.



THE  
**END**