DOME COOKBOOK

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by Steve Baer

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FLOW SHOT 1
SOL SHOT 1

I am the boss of these words, take complete responsibility for what they do. The great invention, language. I take it without letting it take me. I stay ahead of it because I know that it is like a trailer and will jack knife if you let it lead. It's a human product for me to use, for you to use. I am an inventor and I start this way as an homage to our greatest invention, language. No contracts to sign, no electrical or mechanical breakdowns, no cornering of parts, able to be rebuilt, self repairing but none of these things unless we do it. Lighter than the lightest aluminum tubing and canvas camping equipment. The most beautiful of inventions, an invention of such an order that today I know it isn't so that we are only some debris in front of a bulldozer blade on our way out. We inve nted language, we can improve today's terrifying man made world.

← came to this from reading Lewis Mumford's the Myth of The Machine

no other beginning. The cube! What about the cube? Is the cube as they say "dead" or is it instead another type of life form that with its characteristic rectalinear grid is slowly taking over the planet like some kind of galactic impetigo? Is my discussion already hopelessly compromised, lying as it does on rectangular sheets of paper? I can not answer these questions. The cube assumes a significance that goes beyond the geometric properties it enjoys for it has imposed itself upon us. Perhaps any geometric system would end by imposing itself on man. They start as forms which answer a need but end by answering even when they are not called. People are trained for the construction of the form, special tools are designed and manufactured, a language grows up with the workers finaly the relationship between need and form capsizes and instead of forms being thrown out because they don't fulfill the needs just the opposite occurs.

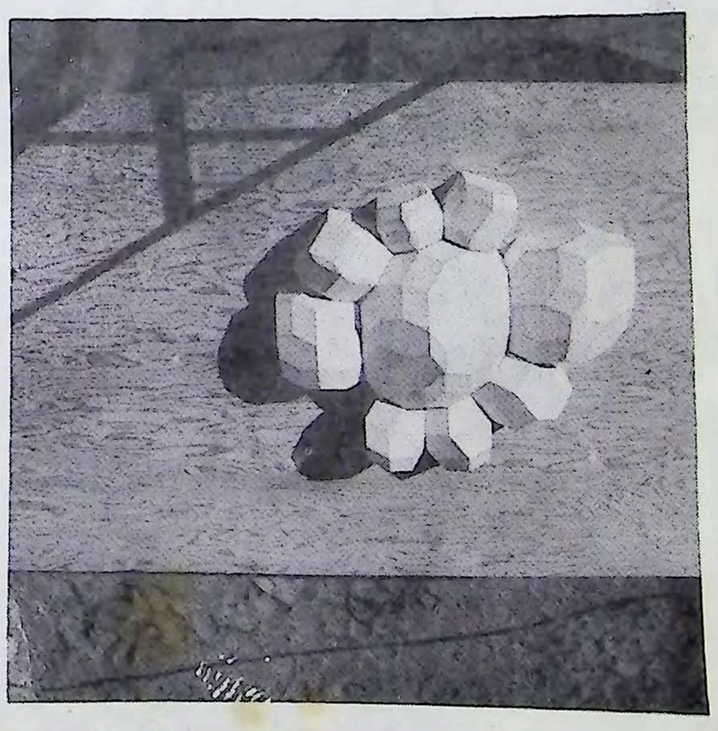
What can be done about this? The first step is for architects to become familiar with the territory within which our present day technology and our ideas of what is economical force him to work. If he must remain with a small number of different kinds of angles and faces then he should know what is possible within these limitations. There are figures other than the cube and the rest of the prisms. At present almost no architects are at all familiar with the study of convex figures and this is apparent in their work.

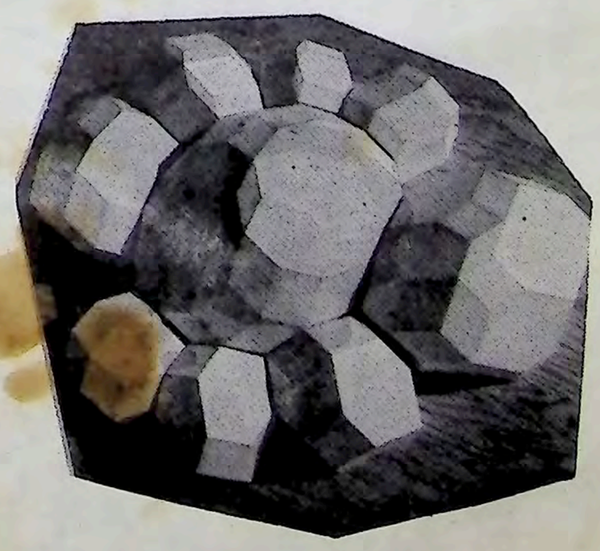
These are instruction on how to almost break out of prison. The prison is the paucity of shapes to which we have in the past confined ourselves because of our technology-industry-education-economy. There are no dramatic disclosures here, those have already been made by all of us when as children we first drew polygons, patterns and messes of straight and squiggly lines. At anyones finger tips lie many more solutions to the architectural geometric problems of enclosing areas and volumes than a life time of study of geometric regularities and systems offer. But we have sensable reasons for not breaking out into the huge freedom of irregular shapes- once done we would no longer have the aid of our machines, tools and simple formulae. Our first move can be to explore the territory we have confined ourselves to, it is far bigger than we think. Eventually we must, aided by different kinds of tools and methods drawn from as yet unrelated branches of our sciences, go forward so that we find ourselves back with the man who works with branches, reeds and mud and who needn't worry about the angle a saw blade was set at years ago in a mill in another town.

In the future the architect will work with volumes and areas with the same freedom that he has while playing with a balloon filled with x cubic inches of water or with a gathereing of y roller bearing needles which pack together in deformable bushles displacing z square inches. He will need to concentrate only on the inescapable problems such as the ratios of enclosed volumes and floor space to building surface areas or the connectivity of spaces or the rigidity of the structure. Freed from the confines of geometric systems he would truly be able to practice his art ~~which I believe~~

ending part?

The relation ship has already capsized. Today the designs we carry out upon our earth resemble nothing so much as a succesion of Architectural bombing runs. The entire affair is conducted from a HQ that never view the site themselves or the inhabitants, only maps and briefs are used until the last minute when perhaps one member appears to watch as the raw materials follow their predetermined trajectories.

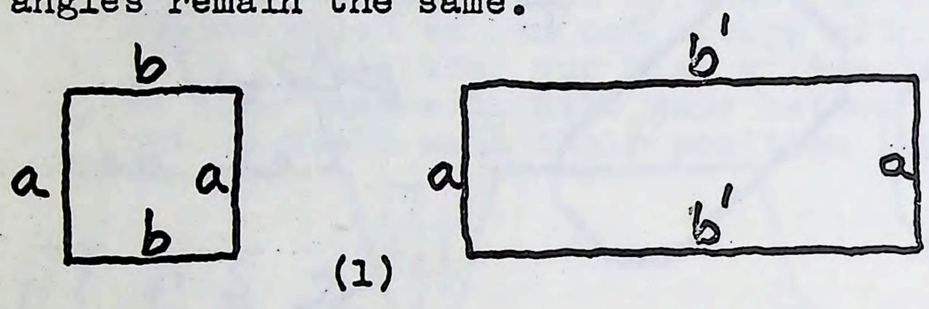




This article will concern geometric qualities of interest to the architect, particularly families of figures which share regularities but yet are free to assume totaly different shapes.

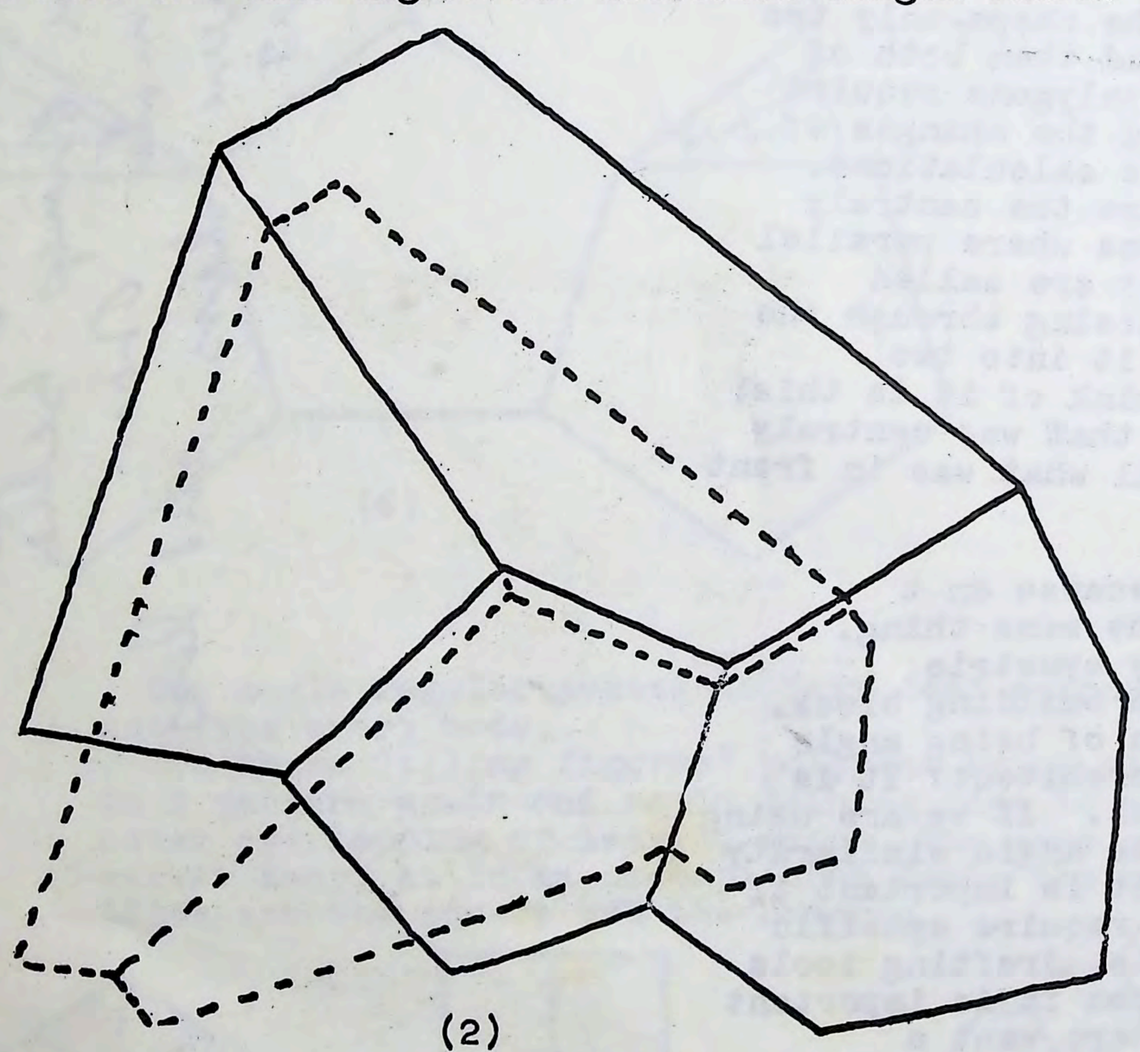
First let us discuss the simplest of polygons, those which exhibit regularities. We have two places ~~in our definition~~ to look for regularity, the line segments and the angles between them. If we make all the line segments the same length and all the angles between connecting pairs the same then we have the "regular polygons" the equilateral triangle, the square the regular pentagon etc. ~~Because we have specified both~~ These figures are both side and angle regular one of

The only freedom that can be taken with these figures is to magnify ~~them~~ it or shrink ~~them~~ it, any other transformation destroys the double regularity. This is confining, what happens if we relax our requirements are ~~their~~ figures which are only side regular? ~~Unfortunately for the engineer~~ this is true of all polygons except the triangle. If more than three members are placed together in a polygon there is nothing predetermined about the angles between them, for the polygon can wiggle. And the other way around, are there angle regular polygons with different length sides? The triangle is again an exception, you can not alter its sides without also altering its angles, however the square can be stretched while its angles remain the same.



(1)

Any polygon of more than three sides has related polygons which have the same angles but different length sides.



(2)

In (2) the dashed line polygons are angle similar to the corresponding solid line polygons

Stacks of papers on a desk
drawings, equations, blueprints
the plans of a building.
What will the building be?
What will it be? It will of
course be the structure described
in that stack of papers.

The plans are duplicated.
Complete sets are given to
different crews who depart
on space ships to members
of a family of replica planets.

The same thing can be done in
different ways. A beam that
can be cut with a power saw
can also be cut with a hand saw.
A crew of men can be a platoon
in the army or 20 civilians.
The same assemblage of men
and machinery can act in one
fashion under one boss and
in another under a different boss.

As construction goes on the
planets differentiate themselves.
Giant earthmovers scrape a hole
on one, a crew carrying buckets
dig a hole on another.

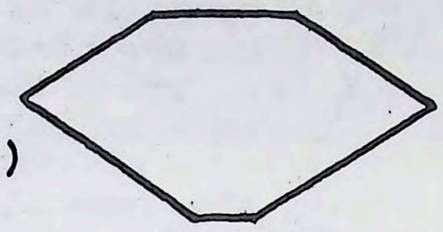
Two years go by, the work is
finished on each planet. The
ground is landscaped as directed
in the plans. The buildings
are exact productions and
therefore identical. The crews
board their space ships and
blast off. The planets are
seen to again be replicas of
one another.

But if the crews stay the
planets will be different places.
However the work was done will
be evident in those who did it.

A crew that was forced to work
by armed guards might have
revolted and perhaps dynamited
the structure. Or if they are
still under the control of
the guards perhaps they would
be digging pits then refilling
them.

We recognize that there is a name for angle regular four sided figures, they are the rectangles.

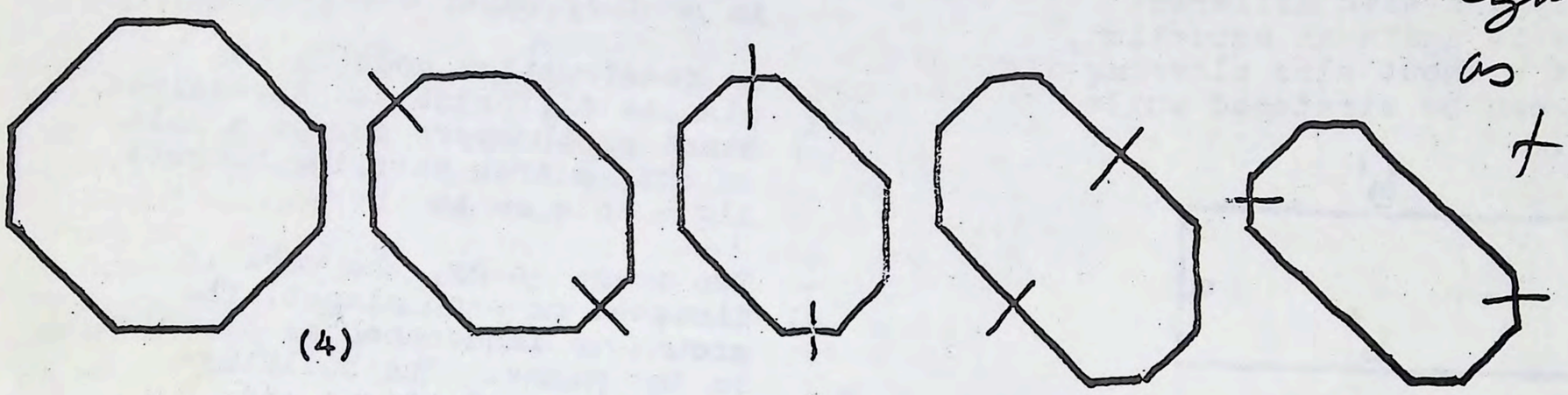
There is a class of polygons which are specialy easy to work with, these are the zonagons. A zonagon is a polygon with the property that each side has another side parallel to it. All zonagons have an even number of sides and all regular polygons with an even number of sides are zonagons. A zonagon needn't have regular sides or angles, they only need to be in parallel pairs



(3)

The irregular hexagon in (3) is a zonagon.

What is it about zonagons that makes them easy to work with? If we examine any pair of parallel sides we see that it is like a neck with the other sides forming caps at both ends. The necks can stretch or be compressed without altering the caps or the angles they make with the caps.



(4)

(4) shows an octagon having its zones altered one by one.

~~With a zonagon~~ in order to alter the shape only two sides need to be changed at a time and then both of them by the same amount. All other polygons require three sides to be changed at once and the changes of length generaly require trigonometric calculations. A special subclass of the zonagons are the centraly symmetric polygons, these are zonagons where parallel sides are also equal in length. They are called centraly symmetric because a line passing through the center of such a figure always cuts it into two congruent pieces. Another way to think of it is this; if we were placed in a walled plaza that was centraly symmetric we wouldn't be able to tell what was in front of us from what was in back of us because on t turning 180 degrees we always see the same thing. Later we will return to the centraly symetric ly polygon for it is a common geometric building block.

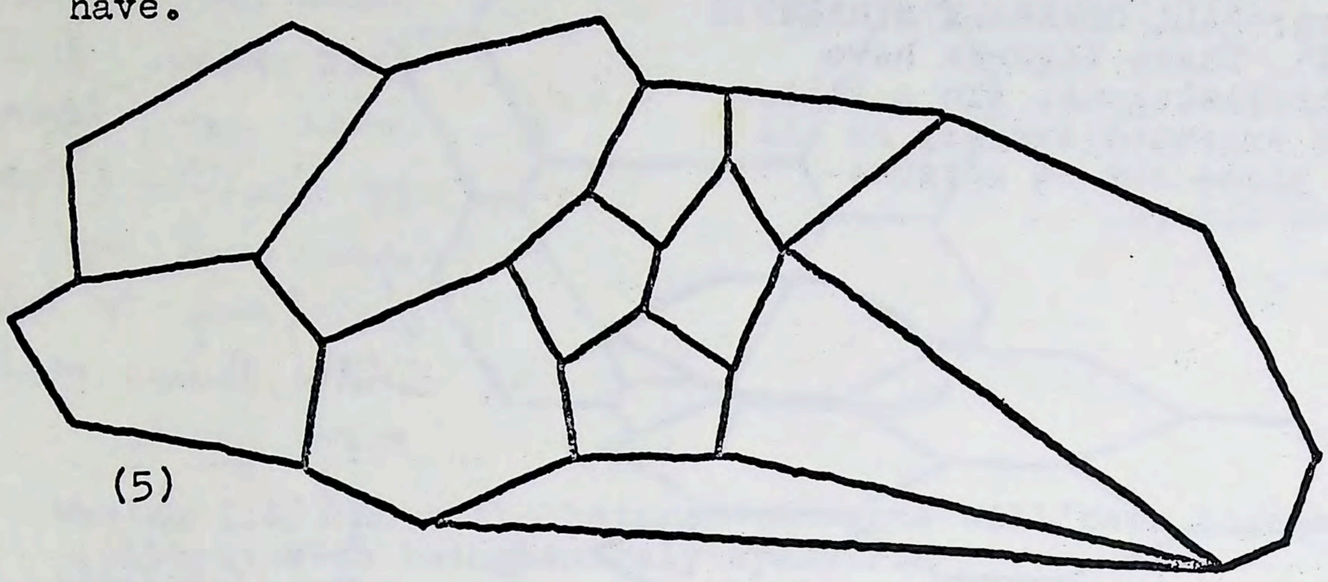
Of what importance is the relation of being angle similar, what could it mean to the architect? It is important mostly for external reasons. If we are using machinery and manufacturing processes angle similarity means fewer different operations. It is important if we already have other objects which require specific angles to be used. (brackets, joints, drafting tools miter boxes, our very minds) And then it is important in itself. Most planners and designers want a mystique about their work, a system (preferably complex appearing) to be understood. I sometimes suffer from a fear that I will realize that the best method for making architectural shapes will be something uncomplicated like blowing bubbles, deforming them as desired and then photographing them, or perhaps simply proping long unmeasured poles in place to create the desired polyhedra, working "by eye". The motivation for many of us is not so much creating the shapes as finding a circuitous route filled with proofs and formulae, a route we can claim leads through a wilderness of mental exhaustion. Then we carefuly brush out the tracks behind us.

3

People who had constructed their buildings by throwing a few switches on the automatic machinery which had travelled with them on their space ship might regard it simply as a new feature of the planet's terrain

It is the way to make things better or make them less and less apparent.

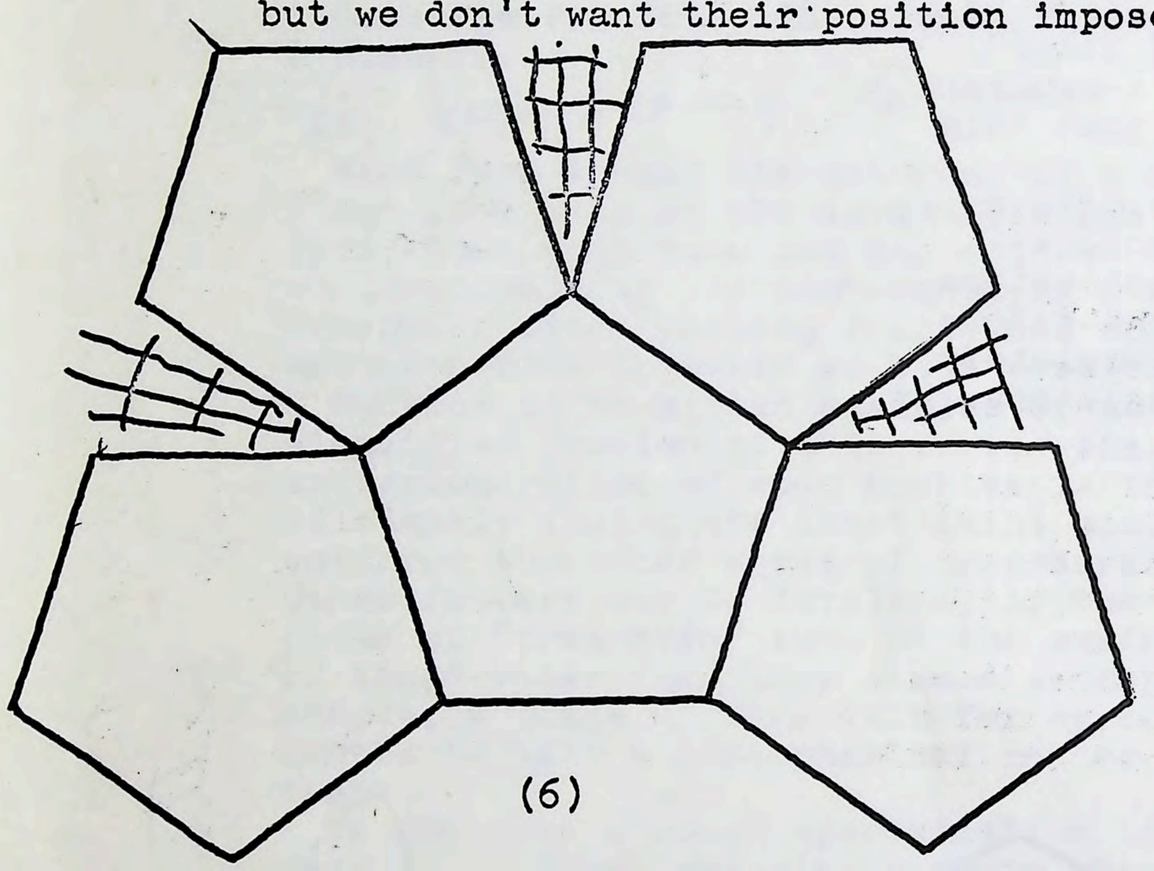
To every child who has ever played with a pencil it is obvious that you can draw a polygon and then adjoin another along one of its sides and go on and on with this and never stop, you even have considerable freedom as to the sizes and shapes the individual polygons will have.



(5)

This is a wonderful quality of space, we can eat it up in different sizes and shapes in infinite numbers of ways.

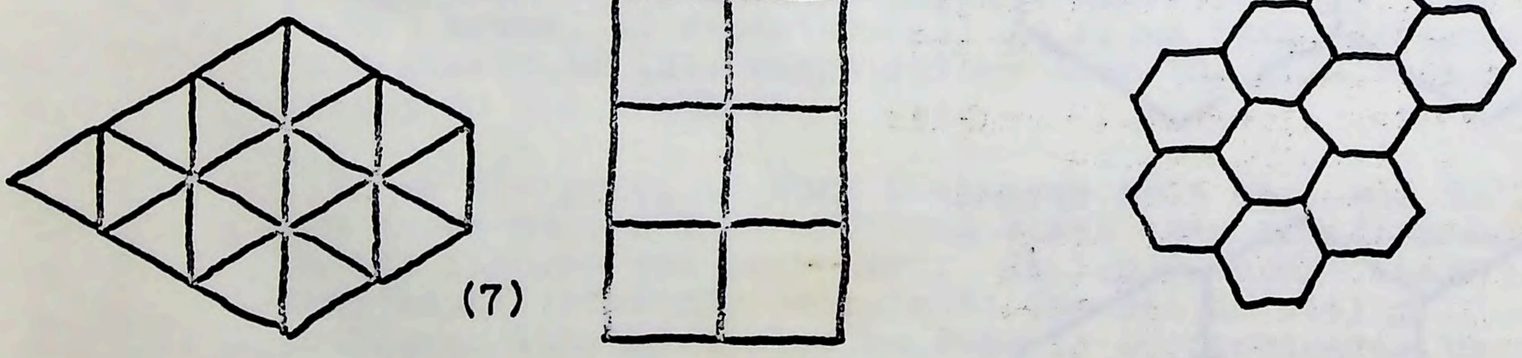
If we adopt a family of angle regular or merely angle similar polygons to be used as floor plans of rooms, city blocks, etc. one further property we will almost certainly want is that the figures don't, as we place them side by side, have gaps appear, dead spaces which we can not accupy with any of our figures. It is likely that our plan will not be a dense packing, we ourselves will make gaps between the polygons, but we don't want their position imposed upon us!



(6)

The angle regular pentagons have dead spaces fanning out from every node.

Are there "tiling figures" polygons which can be used in a pattern again and again joining edge to edge never overlapping or leaving gaps? The name gives the answer away, it is an accomplished fact, the common tiles are the square and the hexagon.



(7)

The equilateral triangle, the square and the side&angle regular hexagon are the only regular polygons which tile. In fact only three, four and six sided convex polygons tile, regular or irregular.

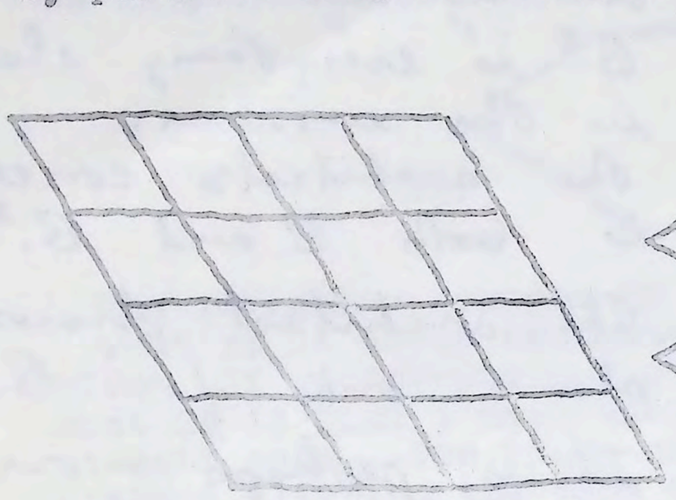
(4)

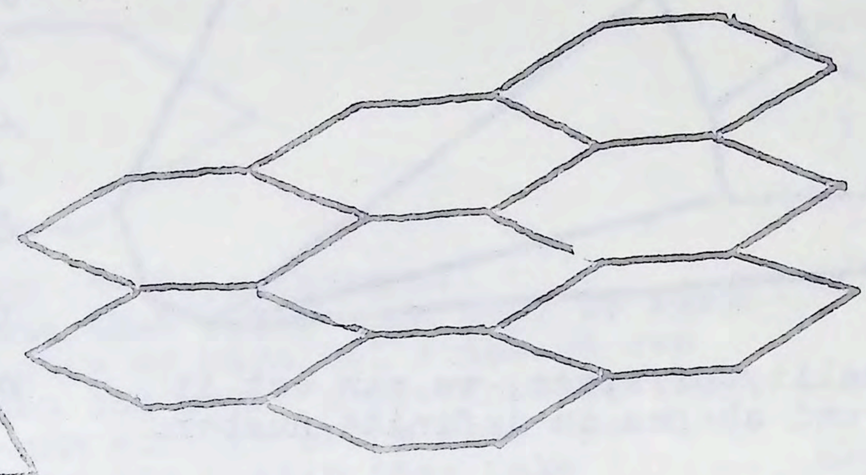
An architect does not work only on the building and the building site. Call the space of his building site B - Then B* is everything else in the universe. The architect's concern is both B and B.* The architect draws plans only for B. It is perhaps more difficult for him to describe the effect he wants on B*.

MISCONCEPTION that an alien crew of space travellers are hired for the construction and that they scrupulously hide their tools, fatigue and feelings during construction and after the last nail is driven depart for another galaxy on their space ship.

The regular pentagon fails because its internal angles (108 degrees) are too big to fit four at a corner and too small to fit three without a gap. All regular polygons with more than six sides have internal angles greater than 120 degrees and therefore can not fit three at a corner.

We will now skip to a class of polygons we mentioned earlier, the centraly symmetric polygons. We state without proof the following fact; "ALL CENTRALY SYMMETRIC FOUR AND SIX SIDED FIGURES TILE" These figures have a special name, they are the parallelogons. In a tiling of parallelogons each figure is oriented exactly as all the others, that is the entire plane can be covered by parallel displacements of one figure.

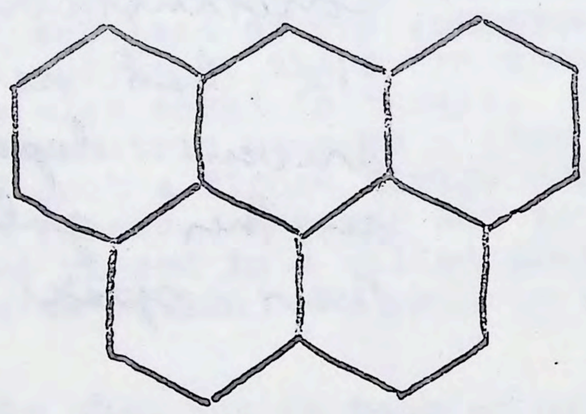


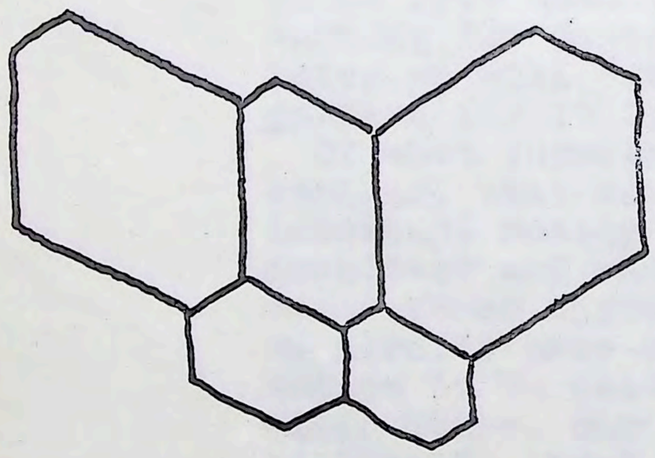


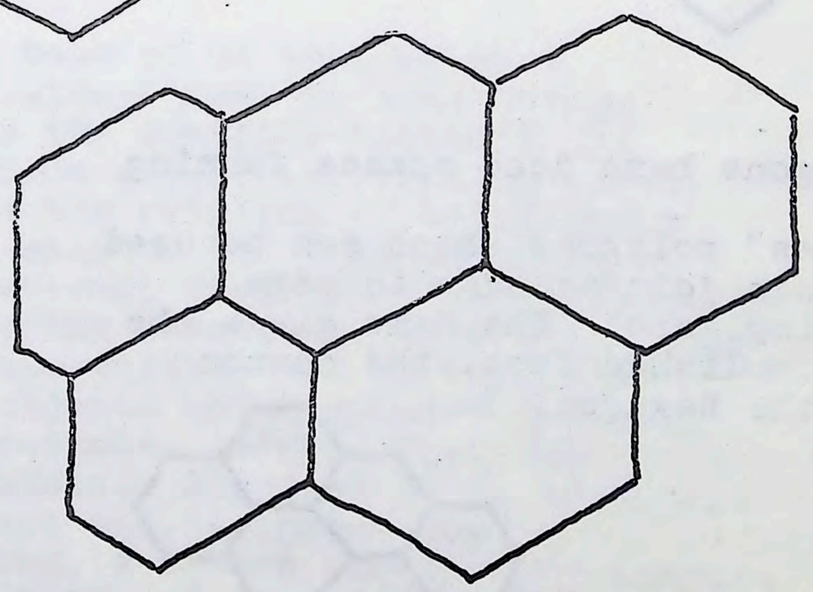
The plane can thus be divided into sections so that we can not tell one section from another and further from what we said before about centraly symmetric polygons we know that we can't tell one end of one section from the other. Is this uniformity necessary? Once we have adopted the regularity of using parallelogons must we, in order to have them close pack make all of them identical?

(All through this we keep leading to points where we would naturaly expect regularity of angles and other conditions such as central symmetry to impose a regularity of shape upon the figures and we keep finding that this is not true.)

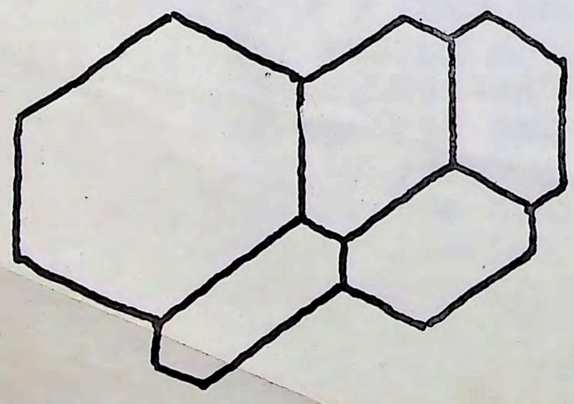
Just as in (4) where we took a regular angle octagon and by stretching pairs of sides deformed it into a completely different shape, so now we take a collection of close packed side&angle regular hexagons and deform them by stretching or compressing zones into completely different shapes, still close packed, still angle regular. still centraly symmetric.

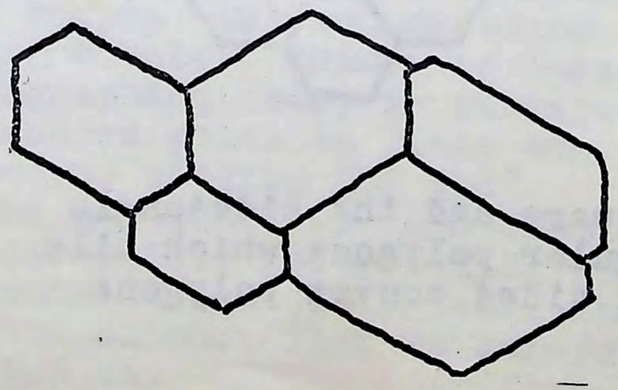






(9)

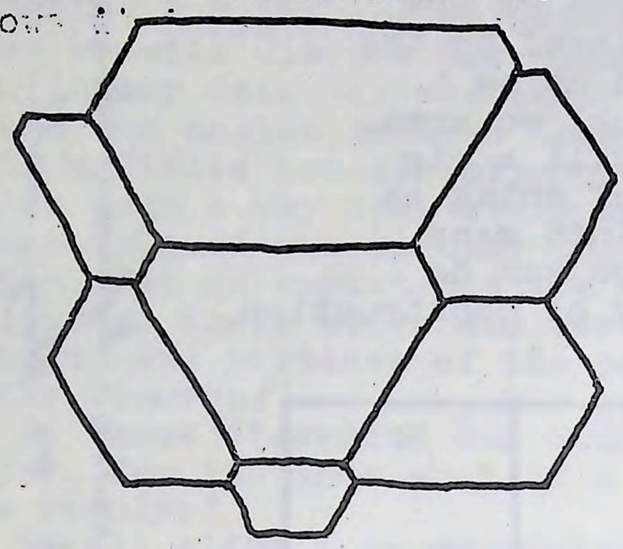




The tools needed to break out are the same tools they used to build this mess. But once you learn to use the tools you end up wanting to build with them. make more junk.

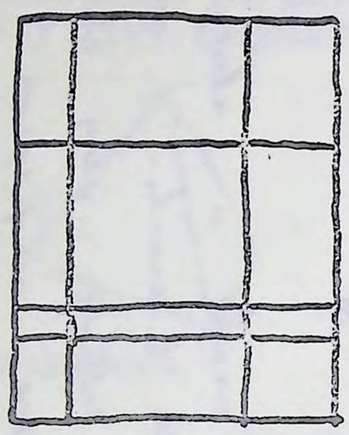
It's cheaper to pour concrete than to remove it. concrete and thought patterns

All the above collections of figures are composed of angle regular centraly symmetric hexagons and they are all derived from the uppermost side regular example by stretching or compressing zones. The amounts which the zones were stretched or compressed I determined by drawing the new zone lengths in each case from a table of random numbers.



As (10) shows the hexagon-zonagons will pack together without even being centraly symmetric

(11)



(11) shows a "patchwork" tiling of rectangles. It is impossible for four sided zonagons not to be centraly symmetric.

A beginning answer to the question

What form should the exterior of a building take? "That form made by the external walls of the component rooms when each room has the optimum shape possible while maintaining its membership in a regular or irregular close packing family and when the rooms are connected together as best possible."

Bubbles offer myriad examples of solutions to a simplified problem of this sort. The shape assumed by an agglomeration of soap bubbles is that which most eficiently (using the least skin) encloses and divides one from the other a set of predetermined volumes. Other factors may be involved, if the bubbles have a plane of "free skin" such as the surface of a dish of soapy water then they assume appropriately different shapes, a plane of free skin for example causes a single bubble to take a hemispherical rather than spherical shape.

To get even a rough approximation to these optimum results by first choosing a shape whos volume was equal to the sum of the volumes of the seperate bubbles and then partition it into compartments of the proper volume would be a next to impossible task.

Soap bubbles are specialy simple examples, the shape we must give a room can not always be left for an elastic skin to choose (although if the floor is a free skin these shapes are usualy suitable) man's needs are more complicated and yet our attack is almost invariably the backwards attack of the fission of big volumes rather than the fusion of small volumes, we are like hermit crabs, an exterior hull is found then the organism fits itself to this shape rather than the hull being fitted to the organism.

If we are going to work backwards this way, and in man cases we can't do anything else, then our demands on the figures are increased. It isn't enough that they be satisfactory components for use in design problems, they must also be capable of fissioning by some uncomplicated process into smaller figures each of which is a satisfactory component itself. We are asking that our figures be components and sums of components simultaeneously.

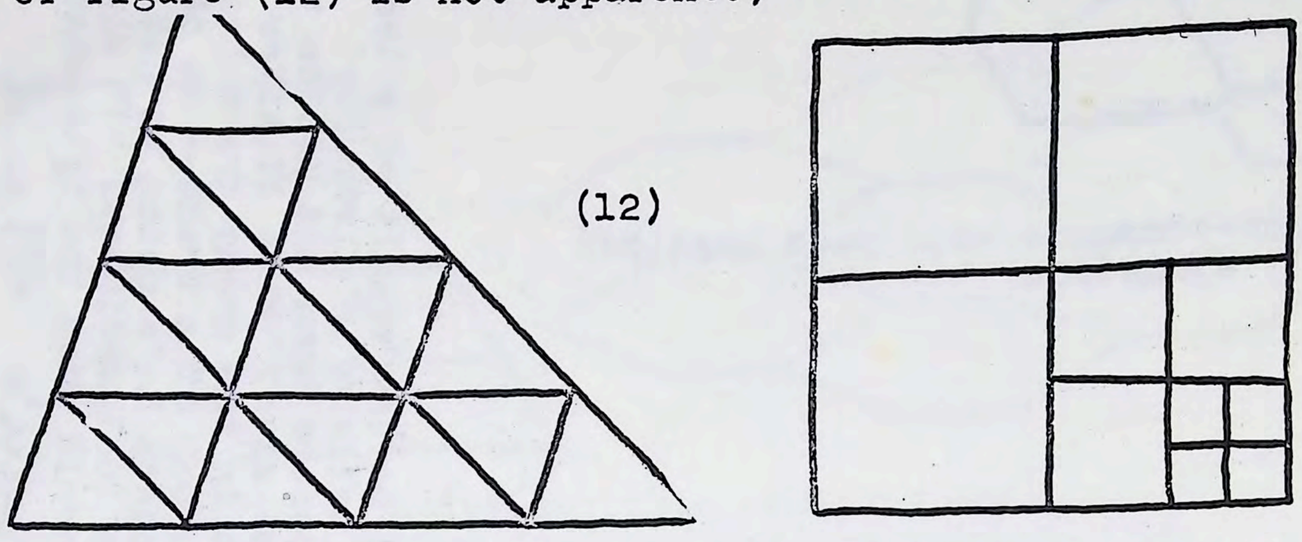
---

you blow would be the result of a less basic decision. Do you really believe in diversity? Would the people get together before hand and decide to make all the tracts the same size? What if after this was agreed on the hidden nut in the group grabs his tube and starts blowing? whopper of a tract-- an obviously irrational act since the piece he's going to get is probably shrinking because of his foolhardiness. It might be worth it if you yourself could push the interstate freeway into a bend.

Ellis's Band.

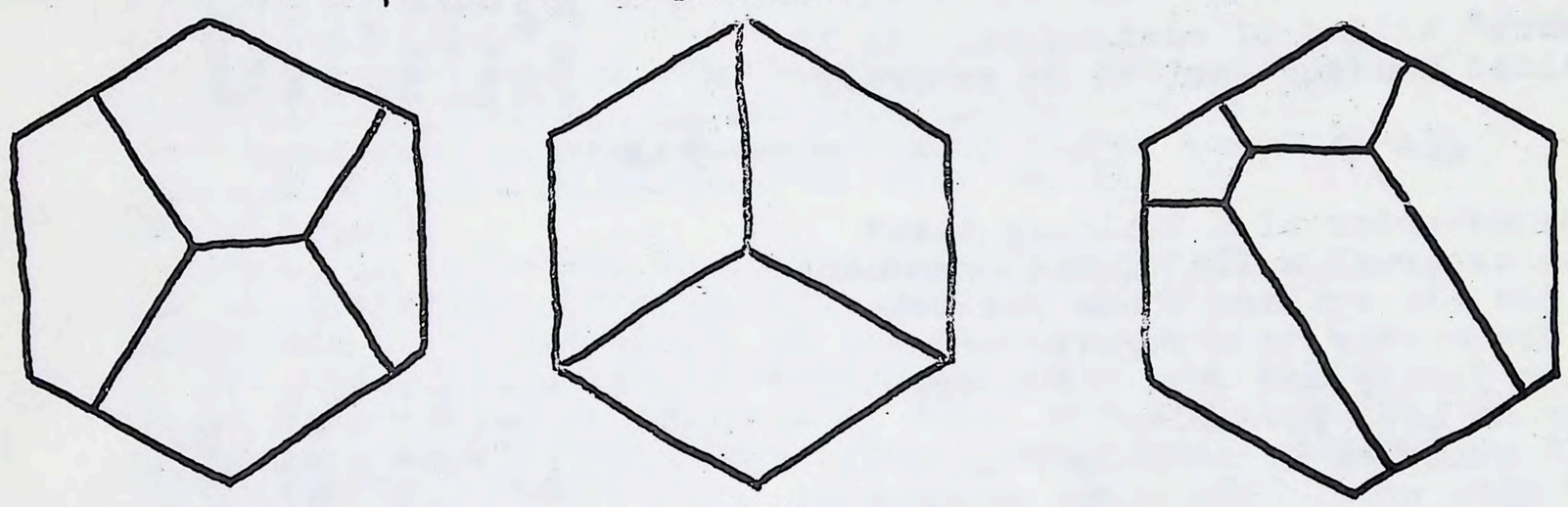
A way to divide up space- take a sample of people and let them all have tubes which are connected to balloons which are packed together in a container the cutline of which is the outline of the space to be divided. They all blow- some of the balloons get big others are crowded to almost nothing. If each person were blowing for himself it would obviously be unfair, someone with a strong set of lungs would get too much. But what if it were understood that what was done at this time would divide up the land but would not decide who would get what piece. So how hard

An interesting group of figures which answer a sharpened demand of this sort (here we are speaking of two dimensions)are the repligons. A repligon is a polygon which can fission into smaller figures similar to itself. Their commonest representatives are the triangle and the parallelogram and we are all familiar with this property as displayed by the square. We can make a huge checkerboard using checkerboards themselves as the individual squares. (Here I have made a common mistake, I built a big checkerboard out of small ones instead of doing as I promised and dividing a large figure into many small ones, you of course see that if you can do one you can do the other for the history of construction of figure (12) is not apparent.)



(12)

We should remember that a figure being a repligon is a sufficient but NOT a necessary condition for fulfilling our demand. For instance the hexagon is not a repligon, but can be divided in several uncomplicated ways into different sets of suitable components.



(13)

Most of today's large buildings have illegitamate designs, the exterior form appears without a history, owing nothing to any natural step by step process of creation. Their form as a sum of components is a forgery, worked in backwards by vertical and horizontal partitions. This is like choosing the manufacturing process for an article by deciding first which by-products it is to have, or like writing the last chapter of a novel and then arranging five thousand sentances chosen by someone else so that they lead up to it.

In the simple world of the cube these things are possible. The cube offers entry into a reversible universe where as long as we conform to a few basic rules such as not violating the right angles or overstepping limits of volume, we may plan backwards or forwards, by fission or fusion.

If we think of the cube as a servant to the architect then these qualities are the ones which will at first endear it to its master, but ultimately he will see that although things have been done quickly and efficiently nothing is in exactly the right place.

(1)

... - dodecahedron
... Holly made a rhombus - icosa...
... living in Zurich. I started to ...
... Connie white very clearly ex...
... they were intension to the ...
... figures That could assume ...
... allegiance I read in Coxeter's ...
... in the spins of 65 in a ...
... entire form could be ...
... pentagonal hedra and have an ...
... fit together.
Regular Polytopes about (still ...
The two ends would ...
the p...

The geometric solids when ... plastic tops which we used ... them: In December 64 ... (3, 4, 4, 5) and how ... new lines - looking for figures ... in the spins of 65 in a ... started me thinking along ... and yet fit together. (then ... Regular Polytopes about (still ... The two ends would ... the p...

I first got interested in ... (3,4,4,5) with some clip together ... splitting them up - clustering them ... wrong with four figures - ... started me thinking along ... and yet fit together. (then ... Regular Polytopes about (still ... The two ends would ... the p...

THREE DIMENSIONS

In two dimensions we discussed one dimensional figures (line segments) and the angles between them. In three dimensions we will discuss two dimensional figures (polygons,(in our case restricted to plane convex polygons) and the angles between them.

" A polyhedron is a finite set of polygons arranged in space in such a way that every side of each polygon belongs to just one further polygon with the restriction that no subset has the same property. The polygons, their sides and vertices are called faces edges and vertices of the polyhedron." (Fejes Toth- Regular Figures)

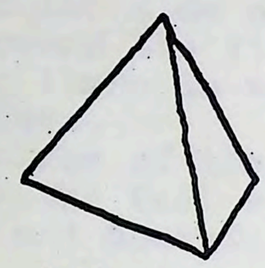
Now that we are in three dimension our study naturaly becomes more complex, for instance when is a three dimensional figure regular?

Its vertices must be all alike (or equivalently its polyhedral angles must be all alike)

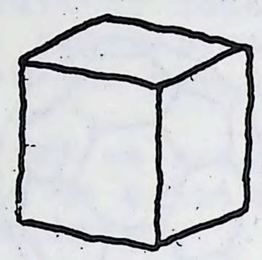
Its faces must all be regular polygons. (side&angle regular)

All of its faces must be alike.

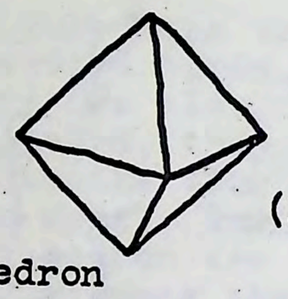
There are only five regular polyhedra (14)



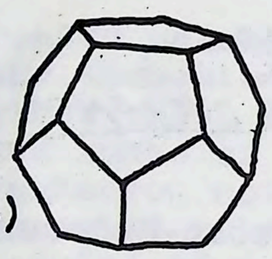
tetrahedron



cube

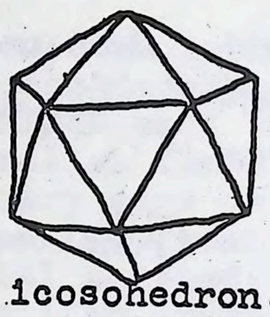


octahedron



(14)

dodecahedron

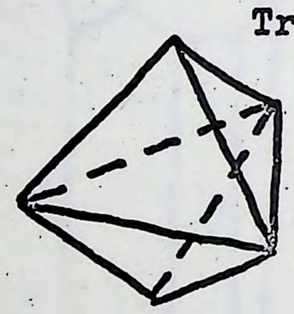


icosohedron

As we did in two dimensions we will go from the regular figures to others which satisfy less rigid restrictions. For instance are there figures whos faces are all regular polygons and all alike but whos vertices are not all alike?

Trihedral vertex

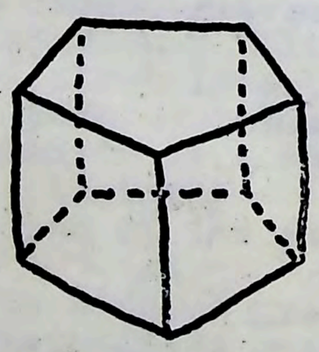
(15)



Tetrahedral vertex

(15) is an example of such a figure, it is made of six equilateral triangles and has two trihedral vertices and three tetrahedral vertices.

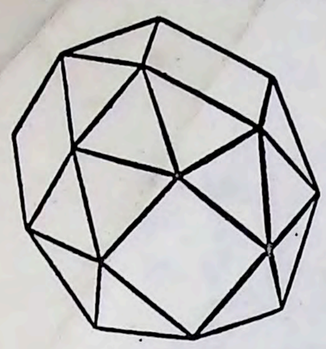
Are there figures whos faces are all regular polygons but are not all alike yet whos vertices are all alike? All prisms with regular polygon bases and square sides satisfy these requirements. (16)



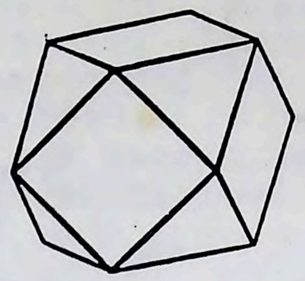
Besides the prisms there are thirteen other such polyhedra they are called the bodies of Archimedes. (17)

Today you hear people who are said to be ahead of their Time "the world is a huge space ship" I suppose that it is sometimes to think of the planet as a space ship. The Trouble is that space ship was not built by men - Man is built by men but a living variable of our environment - To in our space ship - living machine. I see to take over and complete it into a giant place alone. To this planet was not planet in this way - this planet was not planet in this way - living machine. I see this as the work of an administration. Living more disciplined more on a dead Carry on these progressive system.

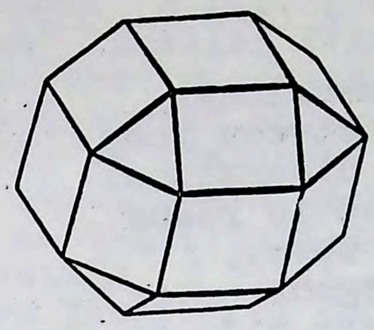
diminished cube



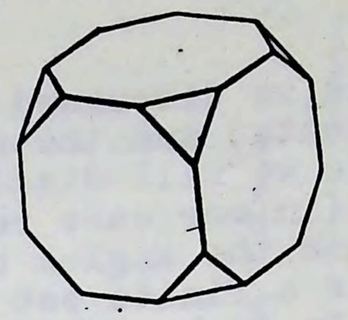
cubo-tetrahedron



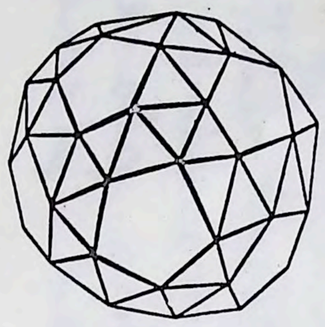
rhombo-cubo-tetrahedron



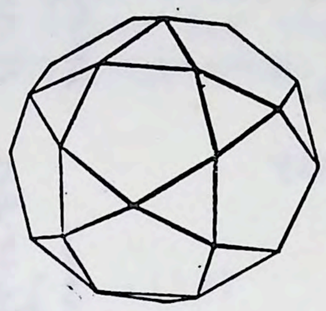
truncated cube



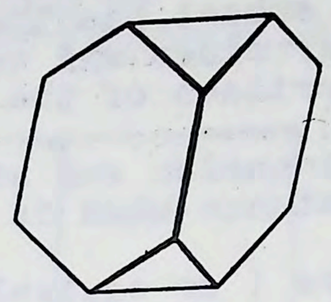
diminished dodecahedron



icoso-dodecahedron



truncated tetrahedron

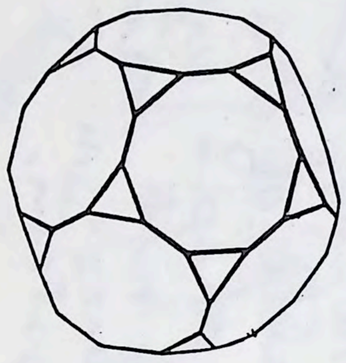


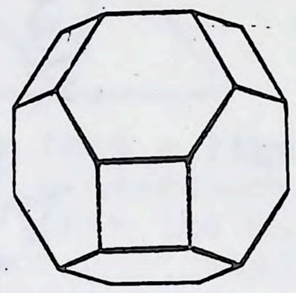
truncated dodecahedron

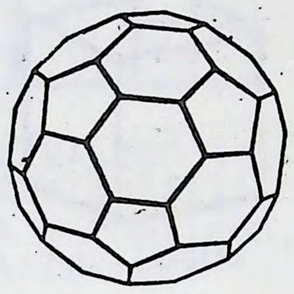
truncated octahedron

truncated icosohedron

(17)

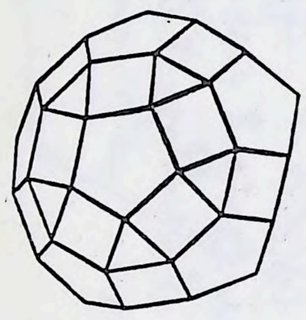




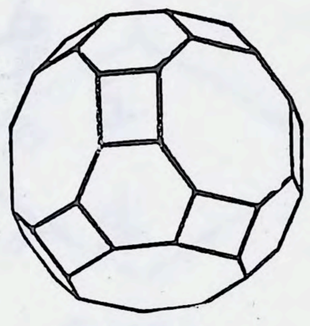


all these drawings were taken from Feyes Toth's Regular Figures

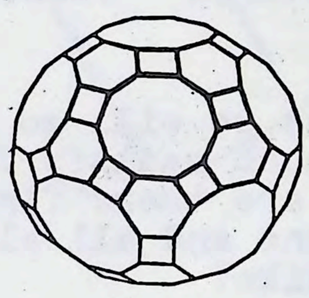
rhombo-icoso-dodecahedron



truncated cubo-tetrahedron



truncated icoso-dodecahedron



In two dimensions there are polygons which are angle regular but not side regular. We have now encountered a number of vertex regular polyhedra, do these vertex regular polyhedra have related polyhedra with the same vertices but of different shape? Or in other word could we use rigid joints built to recieve the rod-edges of a model of one of these figures and then by using different length rods construct figures of different shapes? A joint gathers the interior angles of polygons together in one point, and because this joint is rigid it will gather these and only these angles, we know therefore that the angles of any new faces must be the same as the angles of the old faces. But this restriction does not dictate a shape to the polygon faces for in the beginning of the article we showed that polygons with similar angles can have different shapes. The problem is whether or not the polygon faces can assume any of these new shapes and still fit together in a polyhedron. They can as long as polygon sides which joined in an edge in the original figure maintain their equality in the new figure. This is not always an easy problem to solve. For polyhedra covered by a dense enough web of triangles there are no vertex similar shapes. tetrahedron, octahedron, icosohedron diminished cube, diminished dodecahedron are examples.

deteriotes from here out.

jump to page 13

How have all this time been able to spend building these building with Polydens and many tools and materials. I wonder how much time it takes to do things. I think two time as much time using cheap. Principly two expansion - most often I began with plywood - the first building was very important

geometry and elinar

↑

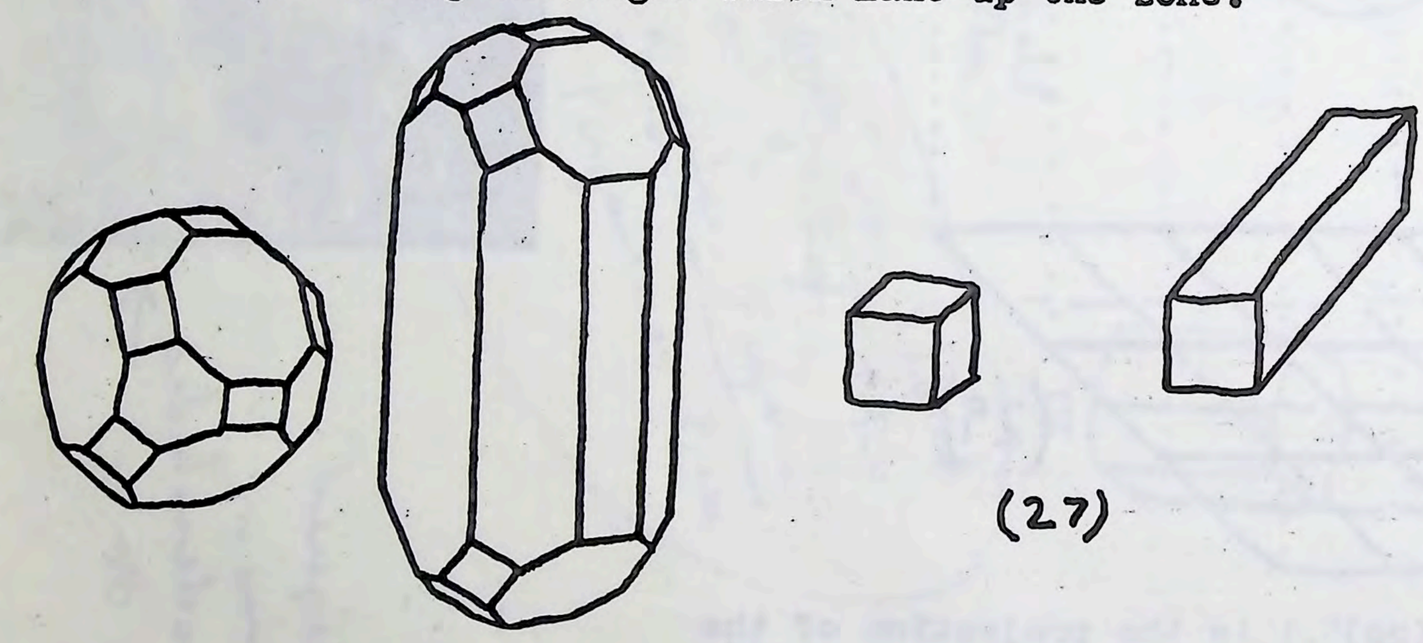
What we need is a three dimensional counterpart to the two dimensional zonagon- a kind of polyhedra that is easy to distort without altering vertices and among which there are hopefuly some families which close pack.

There are such figures, they are called zonahedra, any polyhedron all of whos faces are zonagons is a zonahedron. They are easy to distort because whether it is in a tiling of the plane or a closed polyhedron, as long as edges of zonagons coencide with edges of other zonagons then the zones of parallel sides propagate themselves through the entire collection of polygons. We see that the edge of ~~a zonahedron~~ the solid must also be the edge of a zonagon (two as a matter of fact) and therefor has a parallel partner at the other side of the zonagon face and this parallel side is also the side of a further zonagon so we can march around the figure, every time we leave an edge knowing there is another one parallel to it across the face.

An examination of the figures we have discussed so far shows the following to be constructed only of zonagons and therefore zonahedra.

The cube, the truncated octahedron, the truncated cubotetrahedron, the truncated icoso-dodecahedron. There are also figures which we might call partial zonahedra, they have zones of parallel faces but unlike the true zonahedron not every edge is part of a zone. The truncated cube and the rhombo cubo tetrahedron are examples of partial zonahedra.

Every zone that a zonahedra has (for example the cube has three and the truncated octahedron has six) gives the figure an axis along which it can be stretched or compressed simply by lengthening or shortening the edges which make up the zone.



(27)

(27) shows the truncated cubo tetrahedron and the cube before and after a zone is stretched.

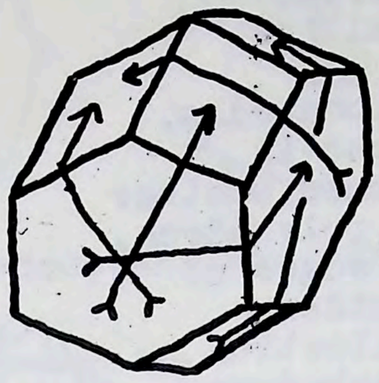
We will now ~~investigate~~ study the three dimensional analogs of the two dimensional tiling polygons-- these are the parallelohedra first investigated by the Russian crystalographer E.S, Federov in 1890.

A parallelohedron is a convex polyhedron with the characteristic that space is filled without holes if parallel replicas of the figure are placed together face to face.

We will state without proof a quality which parallelohedron must have. Their faces must all be centraly symetric which means that the faces are zonagons and that parallelohedra are also zonahedra. The following derivation of the five families of parallelohedra was invented by the Russian mathematician Boris N. Delaunay.

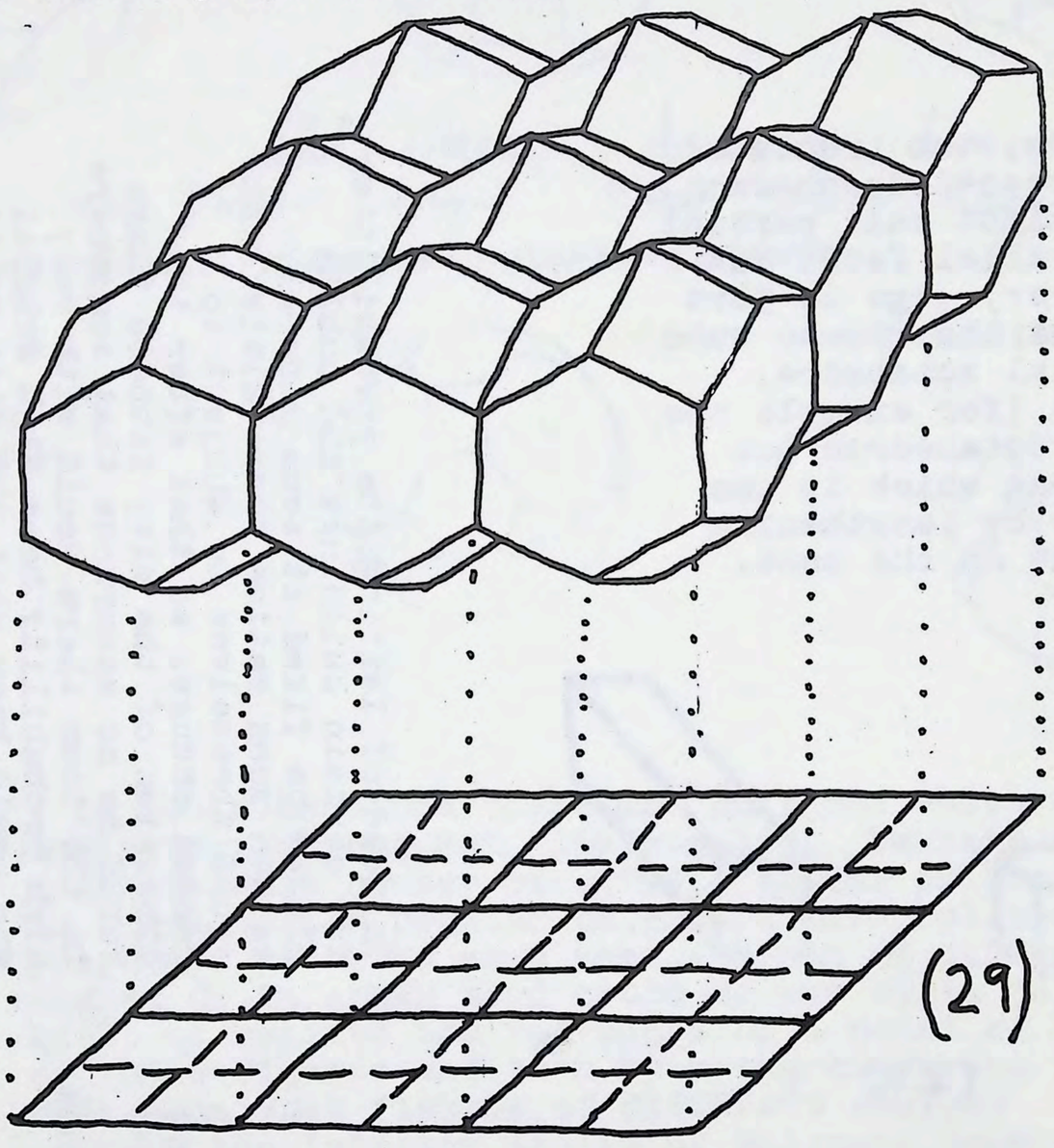
Instead of letting the probabilities and skating rings. Now imagine for certain buildings and public has been yourself, after the public has been places be fixed at some generaly madness, as the agreed upon ratios these divisions official it clerk or what ever of the dice. Could would be who rolled the results anyone ever question that you produced. Could it be proved that a mistake had been made? Why not cheat like a son-of-a-bitch? Could an imaginative planner work better behind such a facade, could this keep the preasure off him like a deep sea diver's suit.

Planning could be done at random. A house could be built by dividing a lot into sections and then deciding by a toss of a coin whether a section was to be a room or part of the outside. Cities could be planned this way- a roll of dice deciding what would be done with each block- the probabilities having been agreed upon ahead of time. But we could go more deeply into this.

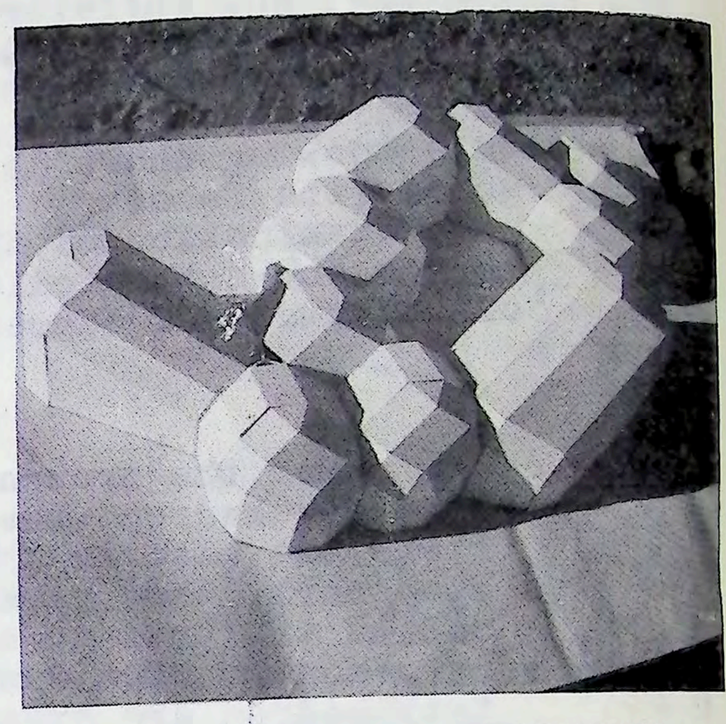


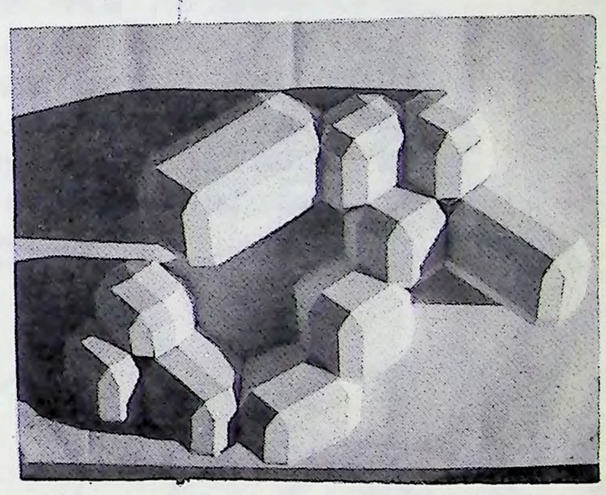
(28)

A parallelhedron, because it is a zonahedron is circled by zones of faces. F(28)3.0 shows a zonahedron-parallelohedron and its five zones. In a packing of parallelohedra the same zone appears in every figure because every figure is the same. Further a face belonging to a zone touches, in the adjacent figure, a face from the same zone-- the one corresponding to the face across from it. A zone of faces is adjoined on all sides by equal and similarly placed zones these zones and the figures which contain them extend in a solid layer over an entire plane. But this means that these figures are like tiles and therefore their cross sections must be tiling polygons, parallelograms or centraly symetric hexagons.



(29)





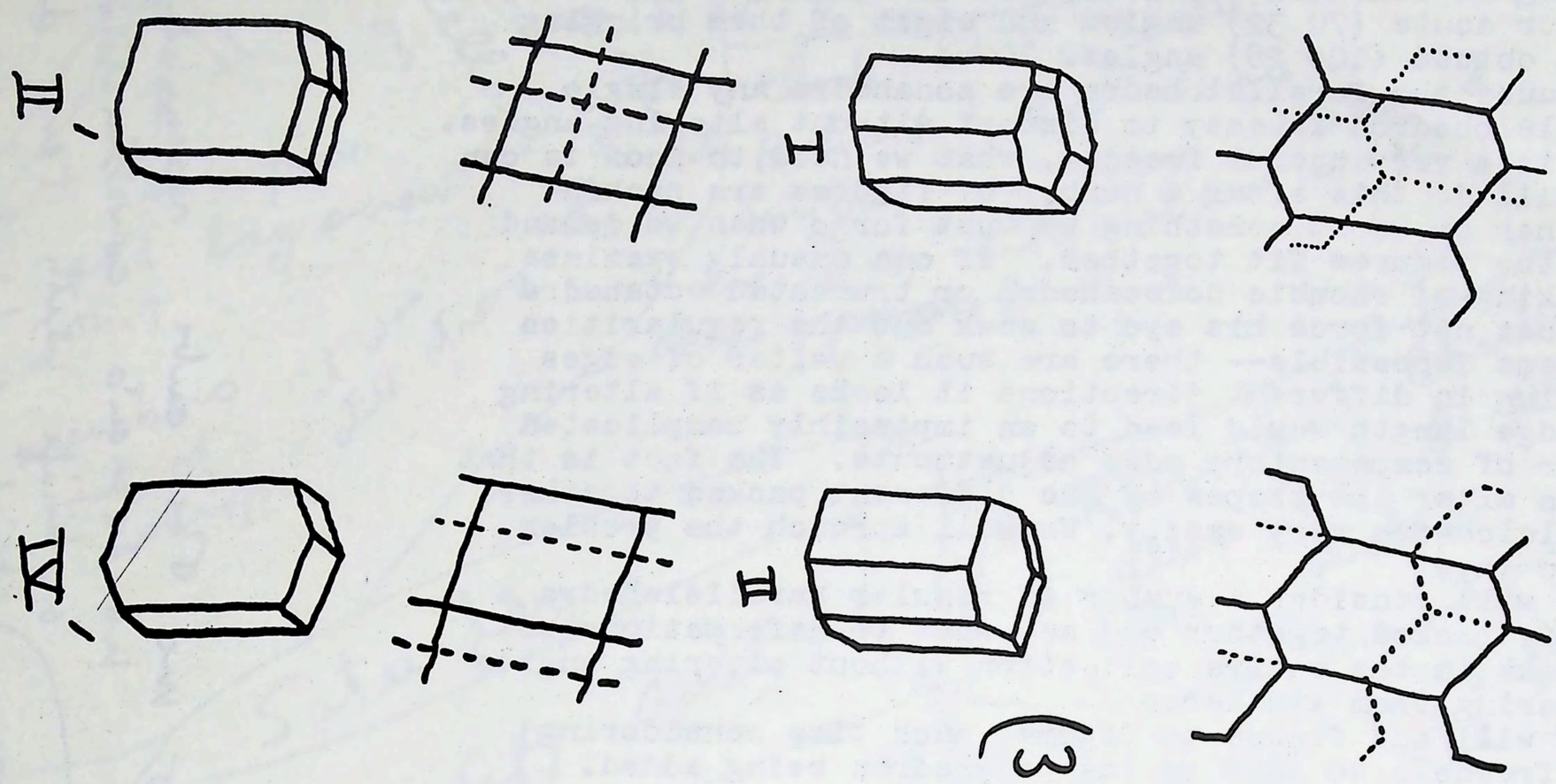
Diedii Raven designed this house using 3 mono-explored rhombic dodecahedra → We couldn't get a lon or a brief it.

The solid line grid of F(29)3.1 is the projection of the zones that are shared by the layer of figures shown above the grid. The dashed line grid is the projection of the layer of polyhedra which would fit directly above the existing layer. These two grids are equal and parallel but displaced with respect to each other.

The position of the corners of one grid inside the tiles of another dictate where the vertices at the top and bottom of the figures will lie. The projections of the vertices on the sides of the figure are buried in the solid grid lines.

Our method seems backwards, here we are deriving the grid from the figures instead of the other way around, the reason is that this particular route is most easily explained while travelling backwards along it.

The point of all this is that now we have found a characteristic of all parallelohedra, one which is different for different types of parallelohedra and a characteristic so revealing of the parallelohedron that we can ~~work backwards from it to~~ create the three dimensional figure.



(30)

(6)

We mentioned before that there were only two types of tiling polygons, the parallelograms and the hexagons, it would seem then that there should be but two types of parallelahedra. There are in fact five kinds of parallelohedra we owe this abundance to the different ways in which these grids can overlap each other. The illustrations in (30). show the different grids and all possible ways of overlapping, below are shown the associated figures with the distinctive grid patterns apparent in the edges of the tops.

Some of the parallelohedra associated with different grids are the same, these are the parallelohedra which have both four and six sided zones, from one angle they project parallelograms from another hexagons, and so working backwards from the grids they are created in both ways.

In this entire derivation we have never mentioned any specific angles, there has been nothing said of regular polygons, our only requirement has been that the faces be centraly symmetric. There are members of these families which do have regularities, for instance V, the parallelepiped has the cube as a special member. Continuing we see that as special cases of II and I V we have the familiar bodies of Archimedes, the hexagonal prism and the truncated octahedron. Case III has as its most regular member the regular rhombic dodecahedron, a figure composed of twelve equal rhombs meeting at fourteen vertices, six of these being gatherings of four acute (70 32) angles and eight of them bringing three obtuse (109 28) angles.

Because the Parallelohedra are zonahedra any single parallelohedron is easy to distort without altering angles. This is a very useful freedom, what we need to know is can we still do this after a number of figures are packed together or is it something we must forgo when we demand that the figures fit together. If one casualy examines a packing of rhombic dodecahedra or truncated octahedra and does not force his eye to seek out the regularities it seems impossible-- there are such a welter of edges pointing in different directions it looks as if altering one edge length would lead to an impossibly complicated number of compensatory edge adjustments. The fact is that we can alter the shapes of the different packed together parallelohedra very easily. We will aproach the problem in two ways.

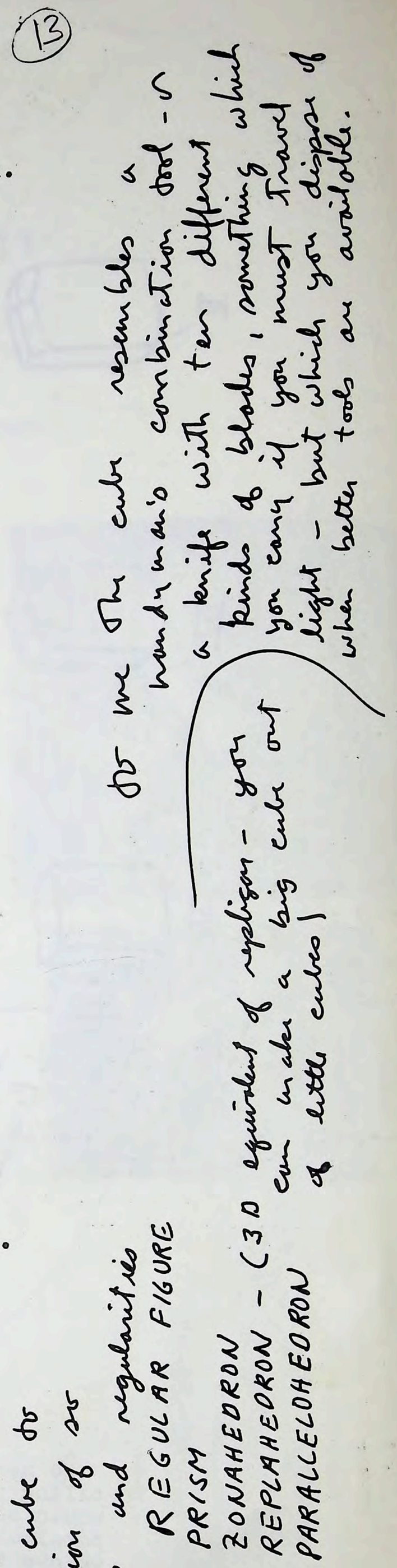
1) We will consider a number of regular parallelohedra a already packed together and see what transformations we can make in the entire collection without altering angles or tearing them asunder.

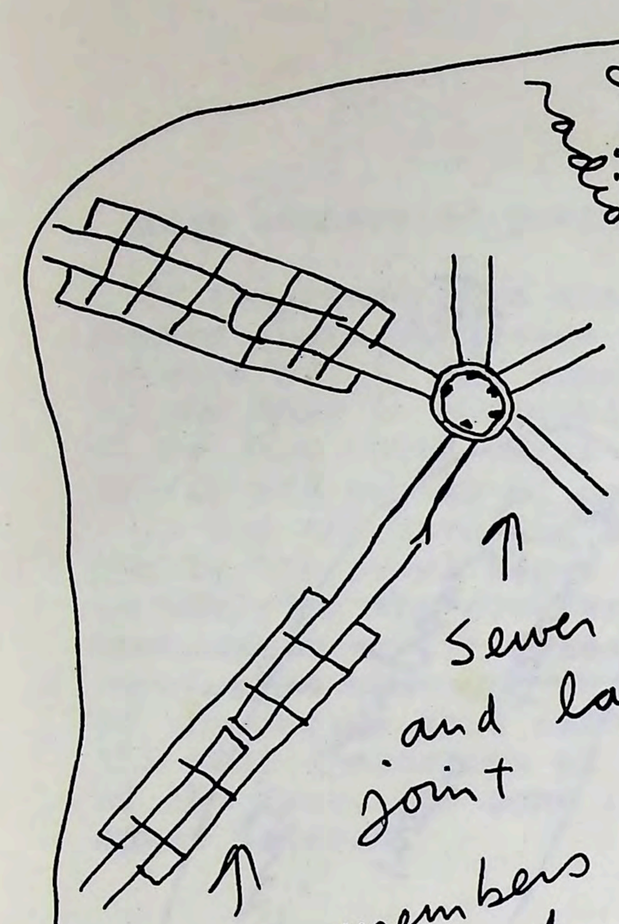
2) We will add figure to figure, each time considering what freedoms we have in the polyhedron being added.

-(1)- In Delaunay's derivation of the parallelohedra we showed how zones of edges exist in layers and that the layers must extend as far as the figures because the figures are bound by their construction to carrying through themselves all zones their faces adjoin to. A layer is simply a multitude of parallel polyhedron edges all connected to one another by a baffle of zonagon faces. Such a layer of edges divides whatever conglomeration of polyhedra it is part of just as pilings divide a pier from the water. The length of the edges in such a layer realy has nothing to do with the form of the two parts which they seperate, lengthening or shortening the pilings of a pier wouldn't change the structure on top or the ocean below. If the figures making up the conglomeration are cubes then the zones run in three directions, if they are hexagonal prisms or rhombic dodecahedra four directions if elongated dodecahedra five directions, if truncated octahedra six directions. The total number of different zones in a conglomeration of figures can be found by adding the number of layers stacked in the different directions.

Considering the total shape as a composite of layers of zones rather than as a sum of individual parallelohedra suggests a method of construction; place regular figures together in the best arrangement possible and then determine each different zone length by compromising between the ideal lengths for each of the figures through which it runs. In this way each polyhedra starts by speaking out for its desired shape in every direction in which it has a zone but ends by assuming a form which is the result of as many compromises.

Our second method is less democratic but perhaps in some cases easier to use. This is to build the agglomeration figure by figure, never making adjustments, just fitting the new figures to the old in the best places available. Zones then have their lengths dictated by the first figure in which they appear and the entire structure has a kind of heirarchy determined by the order in which it is built.





↑ sewer pipe and lag screw joint

↑ edge members spliced out of cull 2"x4" scraps

I climbed up on Clark's hug & Richard's dome. Richard was digging a cellar. He was radio.

it was still strong

They weren't using concrete footings - they had railroad ties

Clark, Gene, Joann Richard. More than anything I was stunned by Drop City. who were these people?

Saturday

Visit Drop City April 66

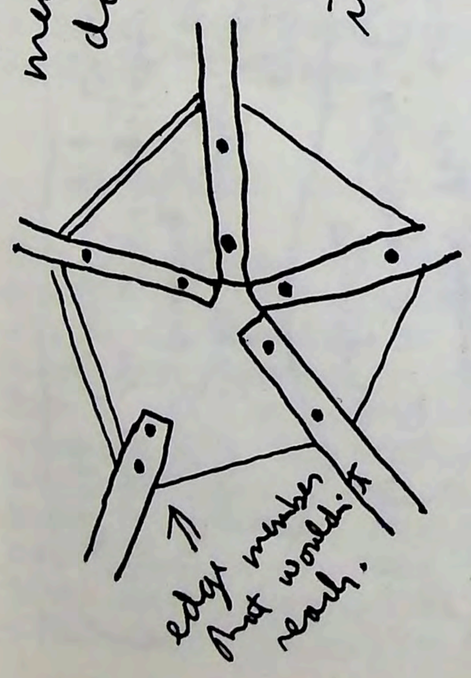
Monday

Raven and Charles allen on slab & poured

you don't need to know much you just need to go ahead and try it out. But then you do have to do other things.

Seeing Drop City specialy the mistakes and weak materials gave me great confidence

Forms & rebar mesh all in place to pour slab my first dome - reading science fiction up on the top of the building in albuquerque - then under construction. & huge Rick concrete slabs - layers of them seperated by pillars. this stack of tloors - no walls at first time - went up 100 feet. Standing at the slabs - no railing. of one of these huge a slight S.W. breeze, about 65° F 10:40 A.M. up 100 feet. Looking the city. Fragile green leaves the smells blowing right through the shit - if you could just leave Not beauty there.



edge member not worth it work.

that last member in Bernofsky's dome would've worked. So they reattached it right and it worked.

A polyhedral dome is made of faces that join each other along edges which in turn join at corners. The edges are more trouble than the faces and the corners more trouble than the edges. The problems of a three dimensional shape first distilled into two dimensional faces then one dimensional edges and finaly into zero dimensional corners.

A dome can be built by prefabing the panels on the ground and then hoisting them into place and attatching them together. An explanation then of building domes could parallel the steps taken in its construction----for instance

1/ Cut 60 18 guage 6"x6 x9.75" isosoles triangles

.
.
.

43/ Drill 3/8" holes every 24" perpendicular to the outside edges

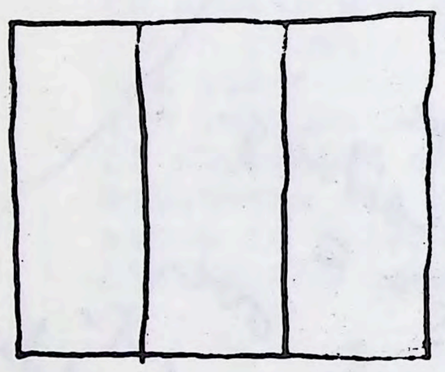
.
.
.

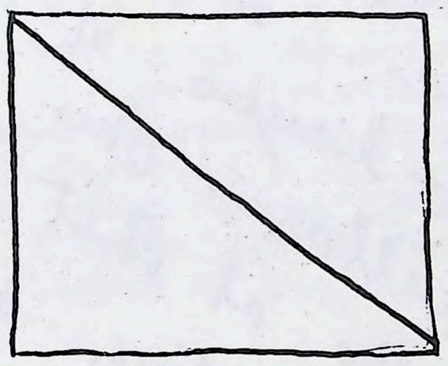
etc.

The structure of such an explanation is no better than a tower of childrens blocks, it collapses with the slightest error in any part. This paper will avoid that mistake while making others.

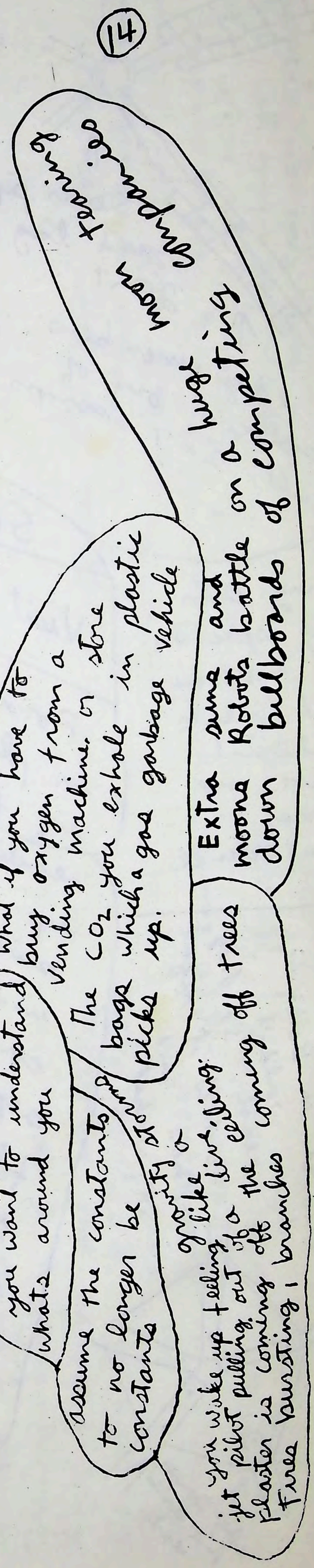
Faces

Make the faces stiff enough so that you can jump up and down anywhere on any one of them without it giving, a little tremble in a big face should be alright. This kind of stiffness we are all familiar with and the remedy for a face that doesn't have it is obvious-- put in bigger crosspieces. The other kind of stifness required is not so familiar; this is the faces' strength in resisting forces which would change the shape of its outline. A frame structure will not have this stiffness unless it is covered with a pattern of triangles





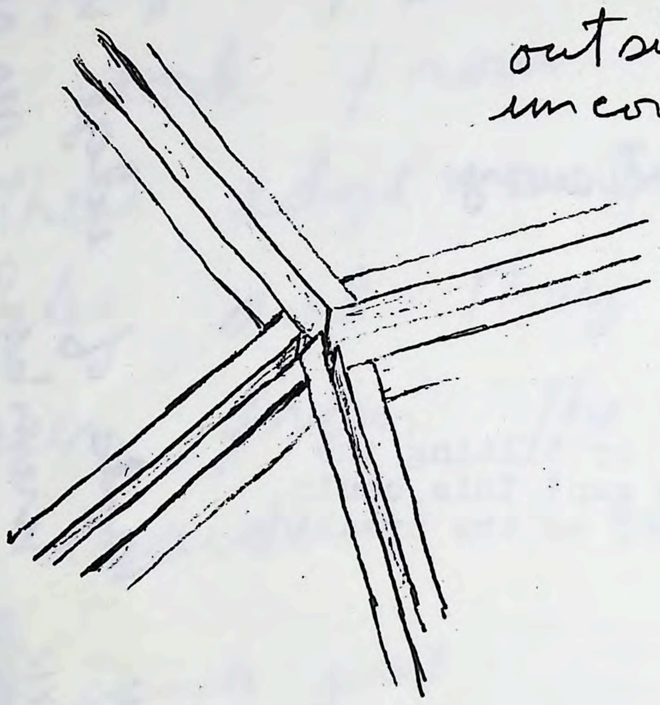
If a frame is to be covered with any kind of stiff skin such as plywood or tin it needn't be triangulated because the skin will p provide the neccesary stiffness. The problem of knowing when something is stiff enough occupies chapters and chapters of sophisticated engineering books. It's not an easy problem and I certainly can't discuss it with any authority. As you build things you develop a feel for what will and what won't stay up. Playing with models starts you off on this. The quickest and easiest way to develop this feel is by buiding and whenever possible building in such a way that you aren't convinced that the structure will be strong enough.



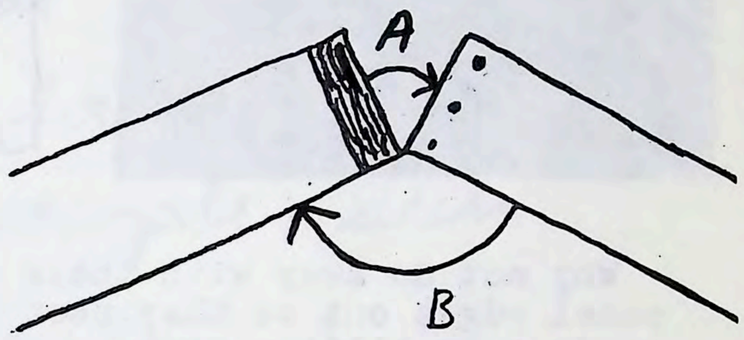
Edge members of prefabed panels.

If the frame of a dome is put up piece by piece, as we did at Manera Nueva each edge member of the dome need only be one piece of wood but if the dome is made of prefabed panels then any edge of the dome is composed of the two edges of the two panels that meet there. How these edges are made and how they are connected is a problem at the center of dome building.

If you are covering the panels with tin there is a simple way of making the panel edges and joining them together, ~~a method we used in building the cluster at Drop City~~. Each panel, ~~in that case there were squares, triangles and pentagons~~ is framed with lumber, ~~we used 2x4s where the edge length was 7.8 feet~~ but no attention is paid to the angles that exist between faces. The panels are framed with th the deep dimensions of the lumber always perpendicular to the plane of the face. The dome is built by joining the panel s with their inside edges matched

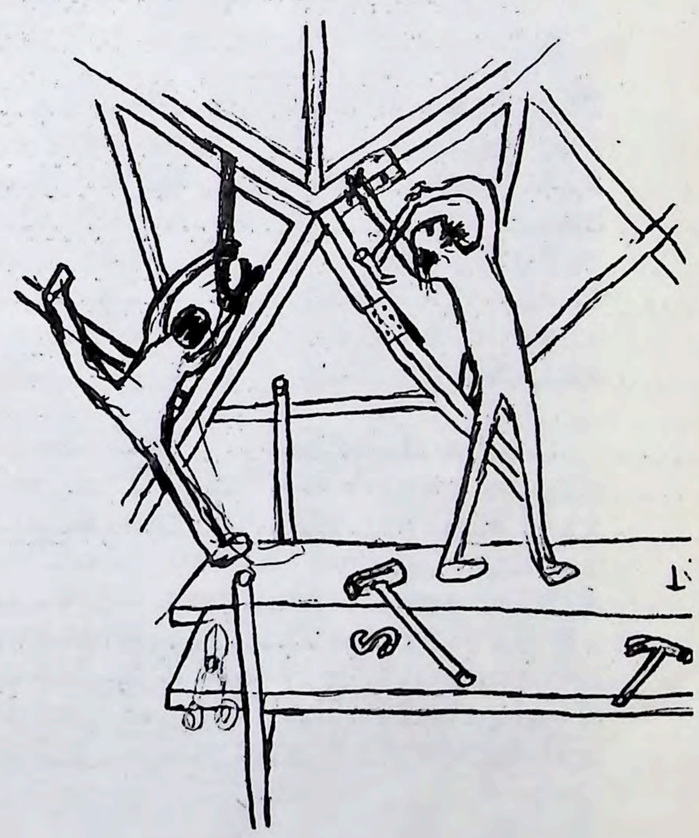


outside view
uncovered joint



13

It's easiest to first make this connection from the inside, gussett plates can be nailed to the adjoing already in place panels and then nailed to the new panel when it is aligned. The real strength in this kind of edge comes later when overlapping flanges from the uphill panels are nailed to their respective lower adjoining panels. This has to be done second because the first connection needs to be done quickly as their is usualy someone taking alot of strain to bring the edges in alignment, someone pulling on a wrecking bar, prying with a screw driver, hoisting on the end of a long pole or someone beside you on the scaffolding straining with his back. The overlapping flanges have to be made wide enough to reach the neighboring edge members and some thought has to be given to which edges of the different panels overlap and which are overlaped. There are no other calculations necessary for the edges of the dome. Nailing the flanges down makes an extremly strong seam, the whole dome becomes in effect a continous sheet of metal.



S.P. A drawback to covering a dome with big pieces of tin that are nailed securely to the frame and each other is that when the sun first hits the dome in the morning or when it comes out from behind a cloud the dome pops and creaks from the metal expanding and rubbing against the frame.

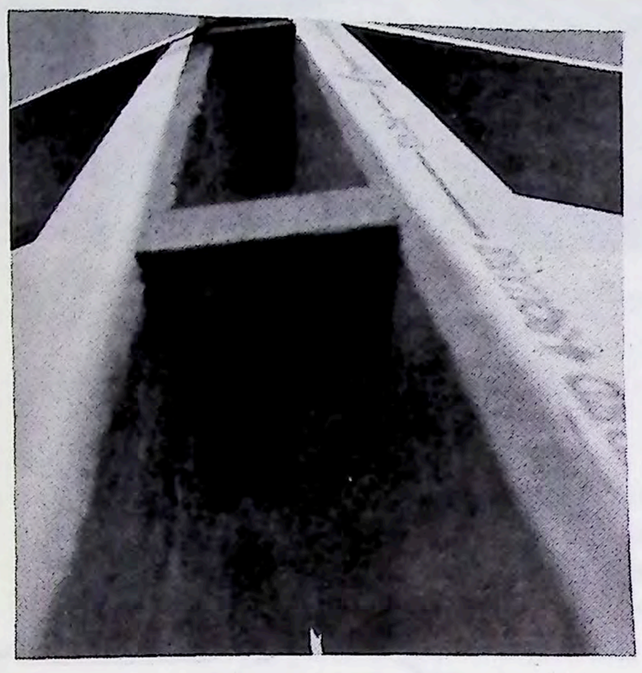
Di hedral angle and breaking angle

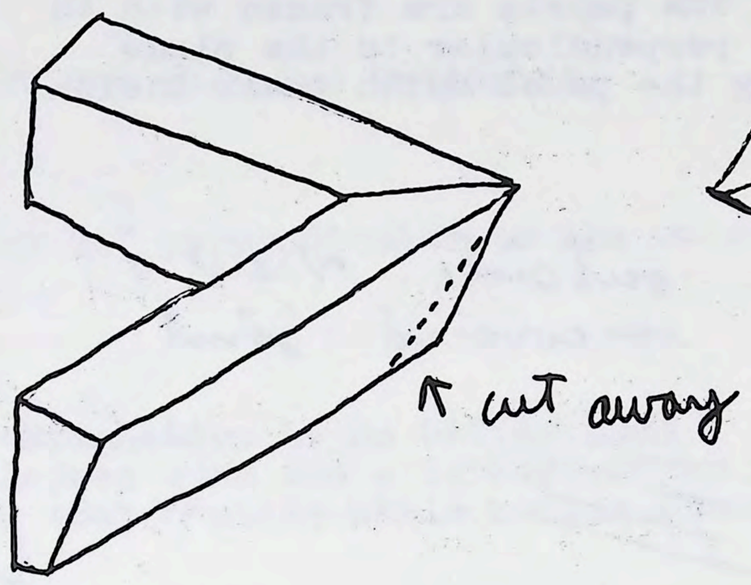
The wedge shaped gap (A) between the two panels in (13) gets bigger as one panel is bent farther away from the plane of the other, the angle at the tip of this gap is the angle through which one panel has been turned in relation to the other. In solid geometry they don't usualy refer to thas angle A instead they talk about its supplement, the dihedral angle- which is the angle B. As one of these angles grows the other shrinks, open the two panels untill they are flat , the pp angle A dissapears and the dihedral angle, B becomes 180 degrees. If you break open the angle A again you can see that every degree it gains angle B looses so their sum stays at 180. I811 call the angle A the breaking angle.

It's the easier of the two supplements A&B to work with. For instance when tin flanges are bent over and nailed down their tips abe bent through the breaking angle.

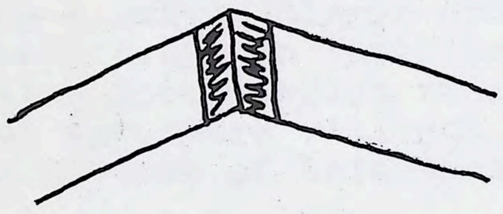
This same method of avoiding compound angles can be used even if you aren't using tin. The gap between the panels can be filled with wooden wedges, their tip angles equal to the breaking angle, and bolts put through the edge members wherever there is a wedge. illus.

This method is costly, time consuming and probably no stronger than a strip of tin nailed along both sides.



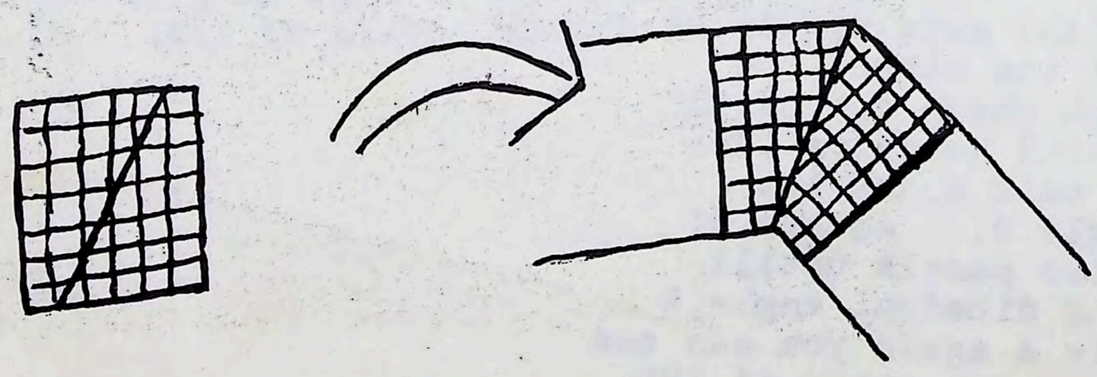


Why not do away with these gaps between panels by tilting the panel edges out so they meet in the center of the gap? This could be done by tilting each panel edge exactly one half of the breaking angle between the two panels.



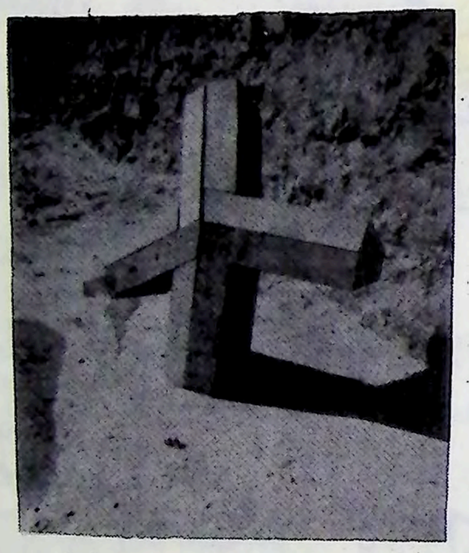
The reason not to do this is that it makes a lot of trouble. the ends of the edge members must be cut in compound angles to fit together, the inner and outer edges must be beveled to bring them back into the plane of the face, braces within the panel also require more complicated cuts wherever they join the edges and there is also the thickness of the panel -- if the braces are the same stock as the edges they will hold the inner and outer skins too far apart for the tilted edge members.

One solution to the problem of the edges of the panels is to rip a board so that its cross section pleases both the inside of its own panel and the similarly shaped neighboring edge. There is nothing complicated about this, the only problem is that you need a big saw. At each edge you find what the breaking angle is (if you are building a structure with any regularity there shouldn't be more than 3 or 4 different breaking angles) then tilt your saw blade half this angle and rip the stock into two congruent pieces one of which you turn over to form the arrangement as in ( )



kinds of edge members
when you build panels with them
have the inside faces of the edge
to the plane of the panel - this makes
the edge members themselves very simple
fit with their outside edges fitting together
of these edges also fit but one
must file or chisel away wood at
- the chisel

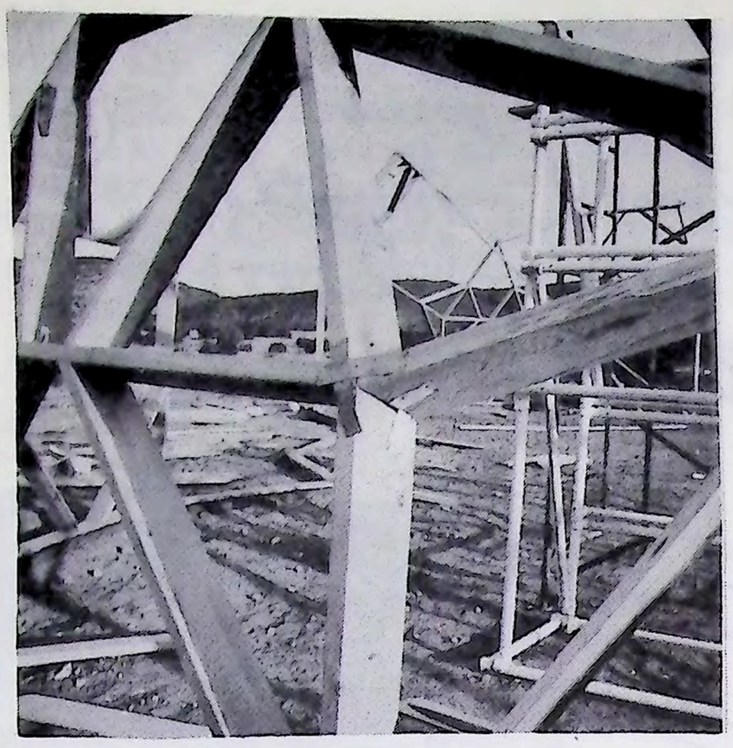
when members ripped like this are fastened Together to make The border of a panel the cuts made To join one end To another are compound angles in relation to the outside faces of the edges and thus present a dificult problem. the solution is to simply egnore the complexities of these relations — work from the right angled inside faces of these edge members you cut nothing but simple angles and they come out exactly right compound seen from the outside, simple seen from the inside

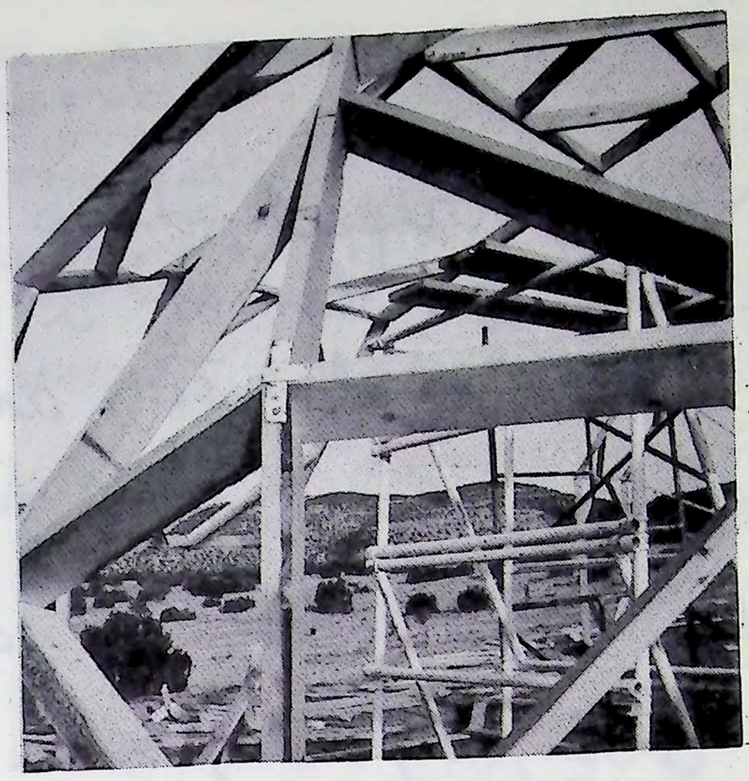


sample joint for a rhombo-icoso-dodecahedron. ←

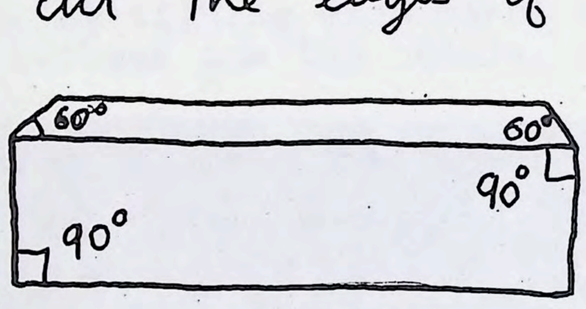
we built the panels for the gome at Llama by ripping 4"x6" this way. The Llama gome is 32' high and 46' from corner to corner. the panels made this way fit together just right one after another.

joints used at Manera Nueva Placitos, N M.

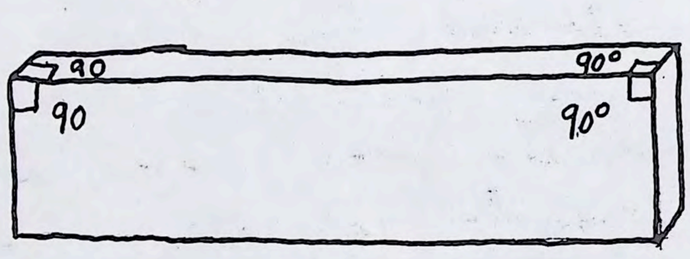




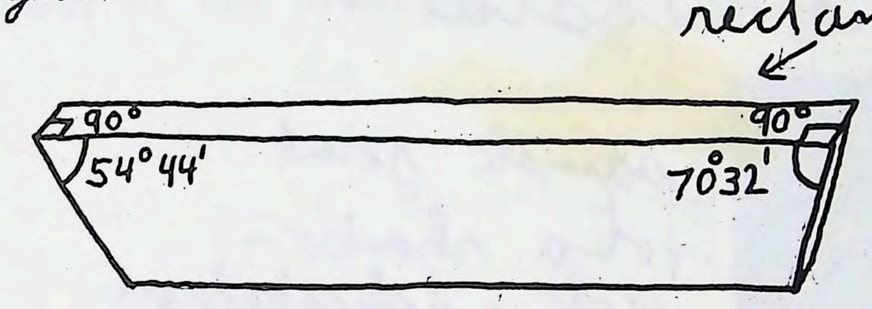
In framing this structure we were able to avoid cutting compound angles in the edge members by establishing a certain hierarchy of faces. Squares and triangles dominated the rectangles with which they share edges and rectangles dominate diamonds with which they share edges. The structure is exploded rhombic dodecahedra. An edge member between two faces is made perpendicular to the dominent face. Following this pattern we cut the edges of the Triangles



The squares



rectangles



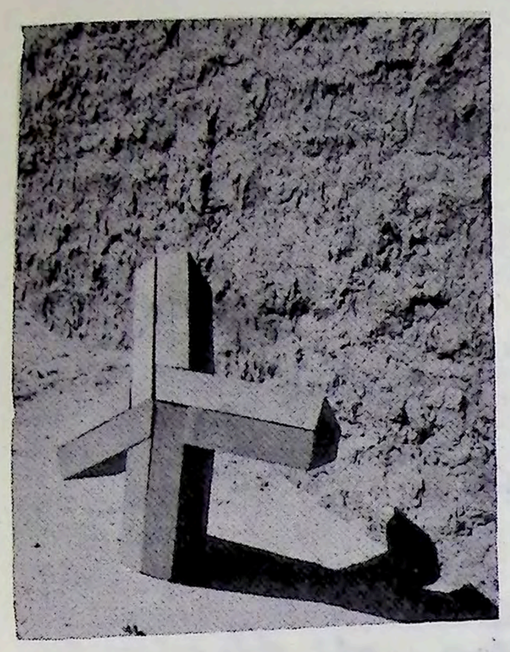
this end butts a square

this end butts a triangle.

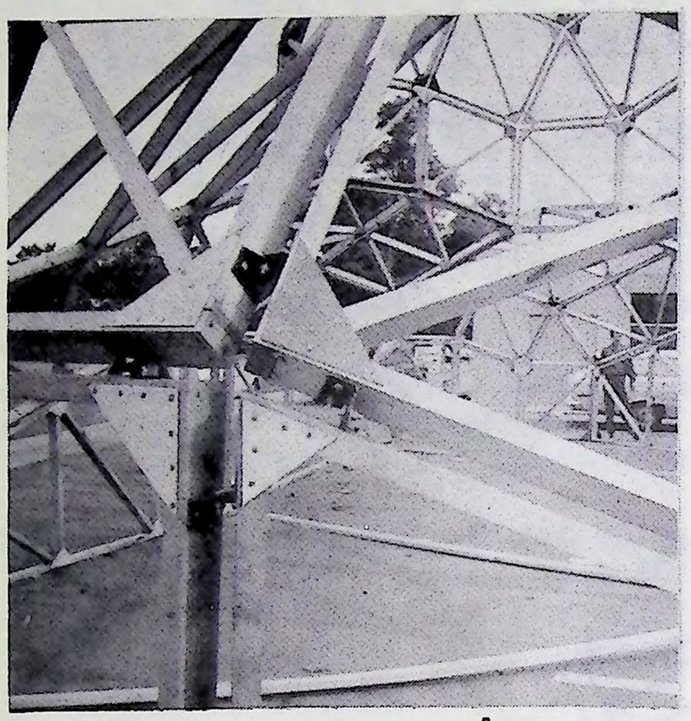
the diamonds are formed by the edges of the rectangles.

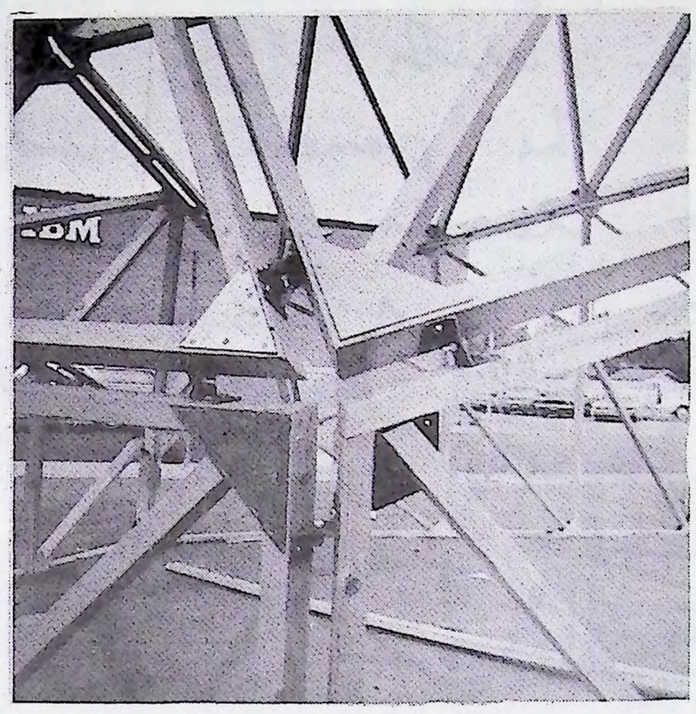
This needs 2 more drawings:
① showing a "square edge-joint dominating the rect. edge and
② a schematic of about 4 or 5 □, △, □ and ◇'s all coming together

A joint where pieces of wood or steel meet is not like a point where lines meet but it is always easiest to design polyhedra thinking of them as points, lines and planes. How can you reconcile thick pieces of wood with points and lines? You find a place on each kind of edge member to run a line so that these lines meet at a point somewhere in, on or above the wooden joint. When this is done you examine each piece of wood in relation to the meeting point of the lines. How far back is the end of the edge member from the end of its line? What angles are cut? I talk of this as if the joint were already designed before the edge member's relation with this sacred line were determined - but of course once you begin to establish these relations a new simplicity may appear.

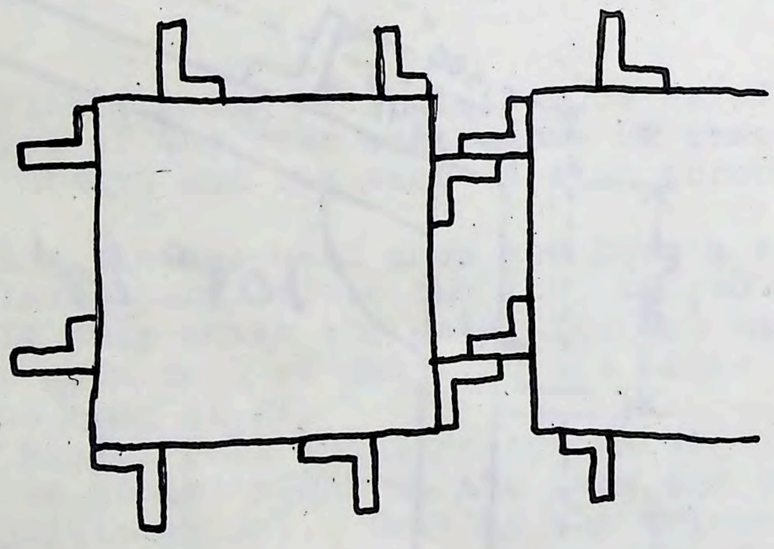


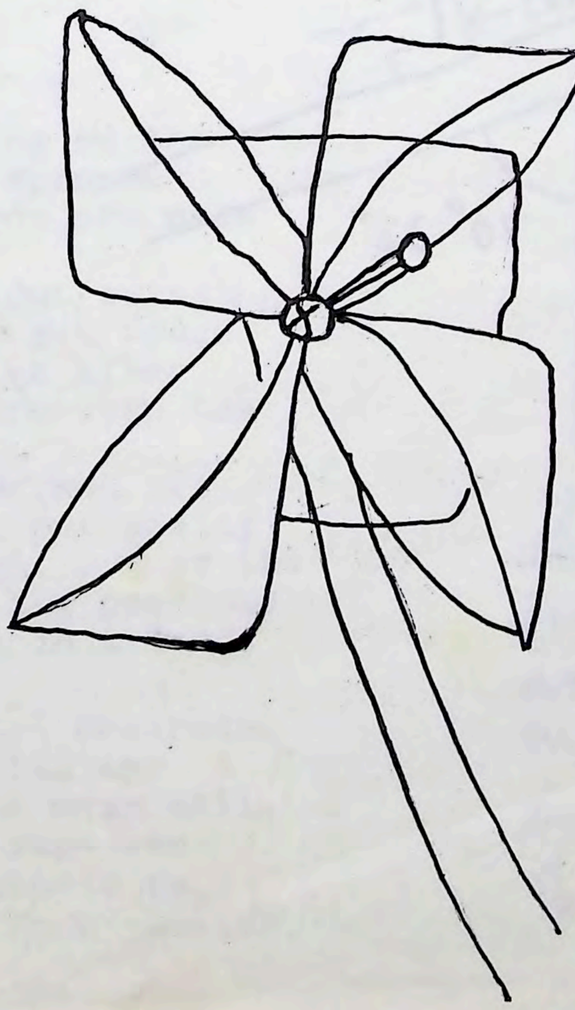
In this model of the joint we used at Llama the relationship between the wood edge members and the sacred line is very simple- the sacred line runs along the outer edges of the panels. the lines and edges coincide - the meeting point of the edges of the panels in the center of the joint is the same as the meeting point of the lines



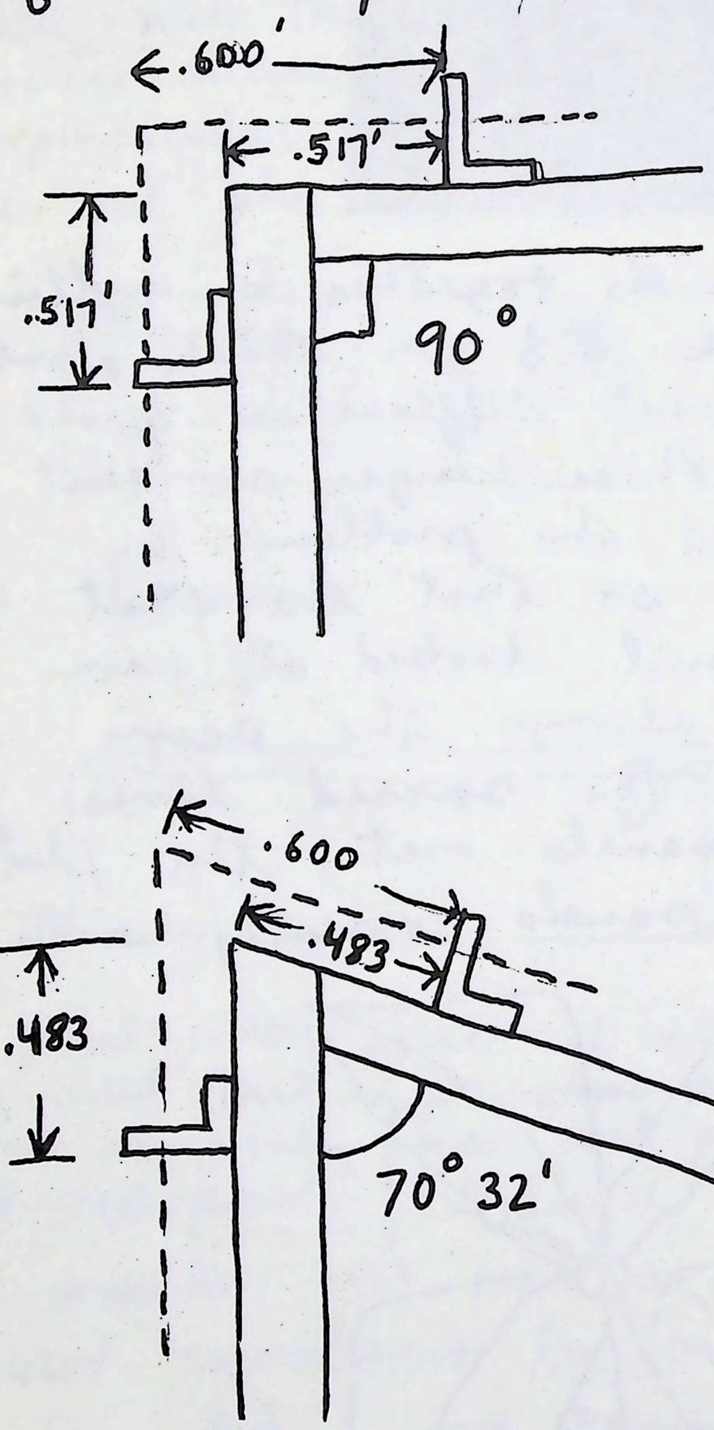


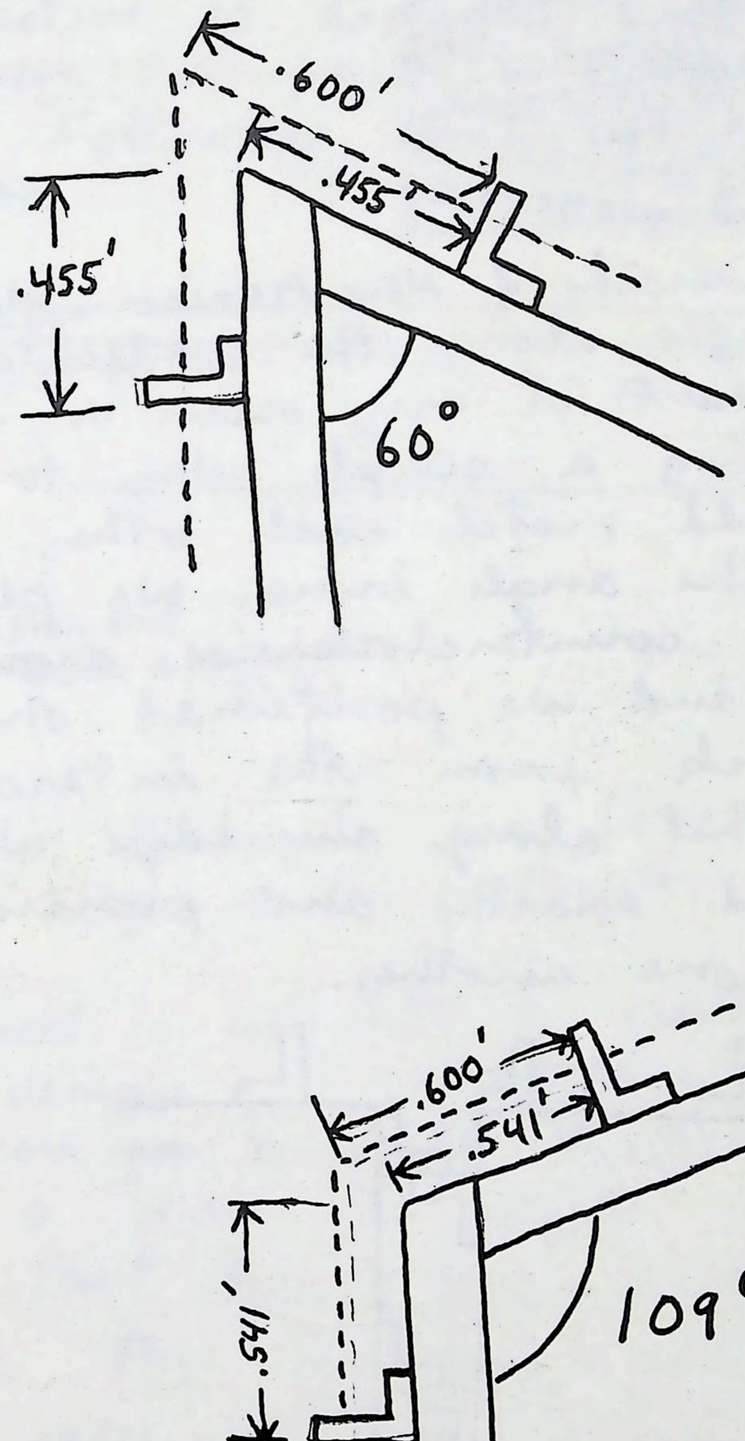
At the University of New Mexico we joined panels together by bolting angle iron hinges along the borders of the panels. If you think about this for a moment it may occur to you that great difficulties would arise in finding a simple way to arrange these hinges so that the panels would match each other. We solved the problem by pinwheeling the angle irons. We placed them so that the flat faces pointed counterclockwise around the panel looked at from the outside and we positioned these faces always the same distances back from the intersections of the sacred lines. this meant that along any edge when two panels met, the flat faces matched exactly and positioned the panels correctly with respect to one another.

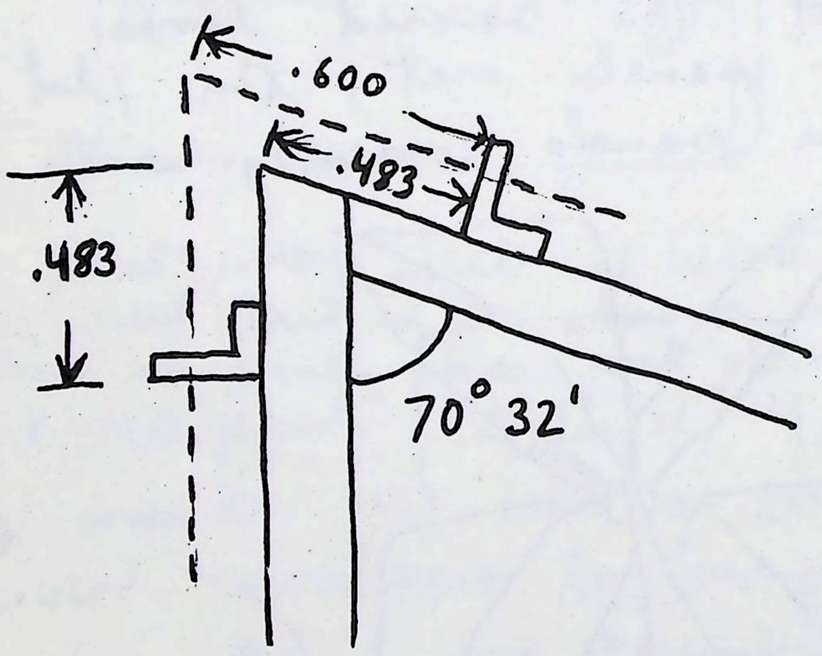


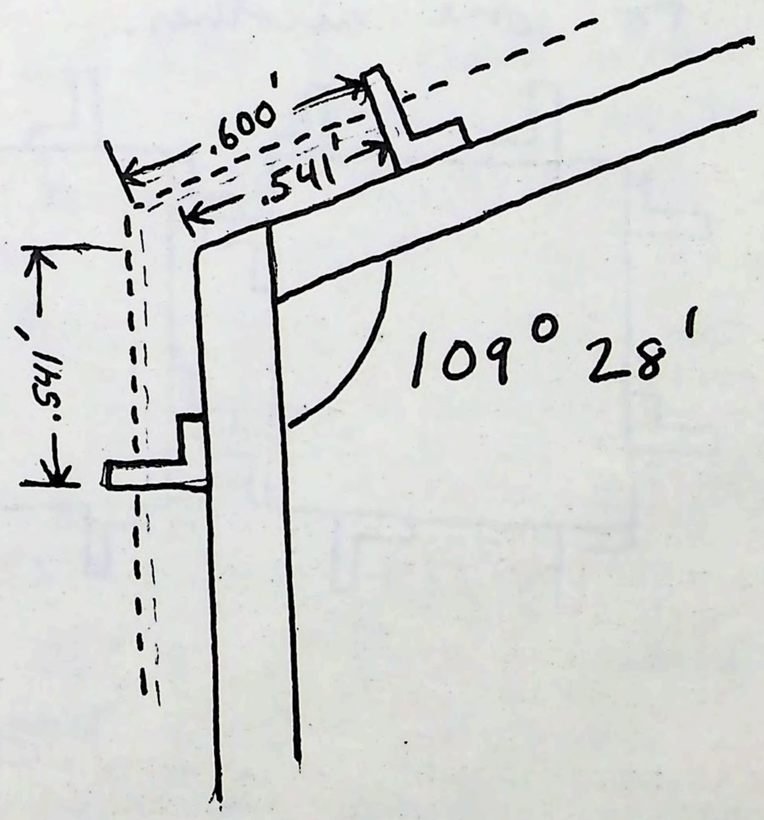


the angle iron was 1 3/4" x 1 3/4" x 1/8" and the 3/8" holes for the hinge bolts were drilled .083' (one inch) from the edge of the angle iron. The obvious place to run the sacred ~~edges~~ lines was through the centers of the hinge holes. With this relation between the sacred lines and the panels plus the decision to always place the leading face of the hinge .600' back from the intersection of the lines the following relations result between the hinges and the corners of the panels.









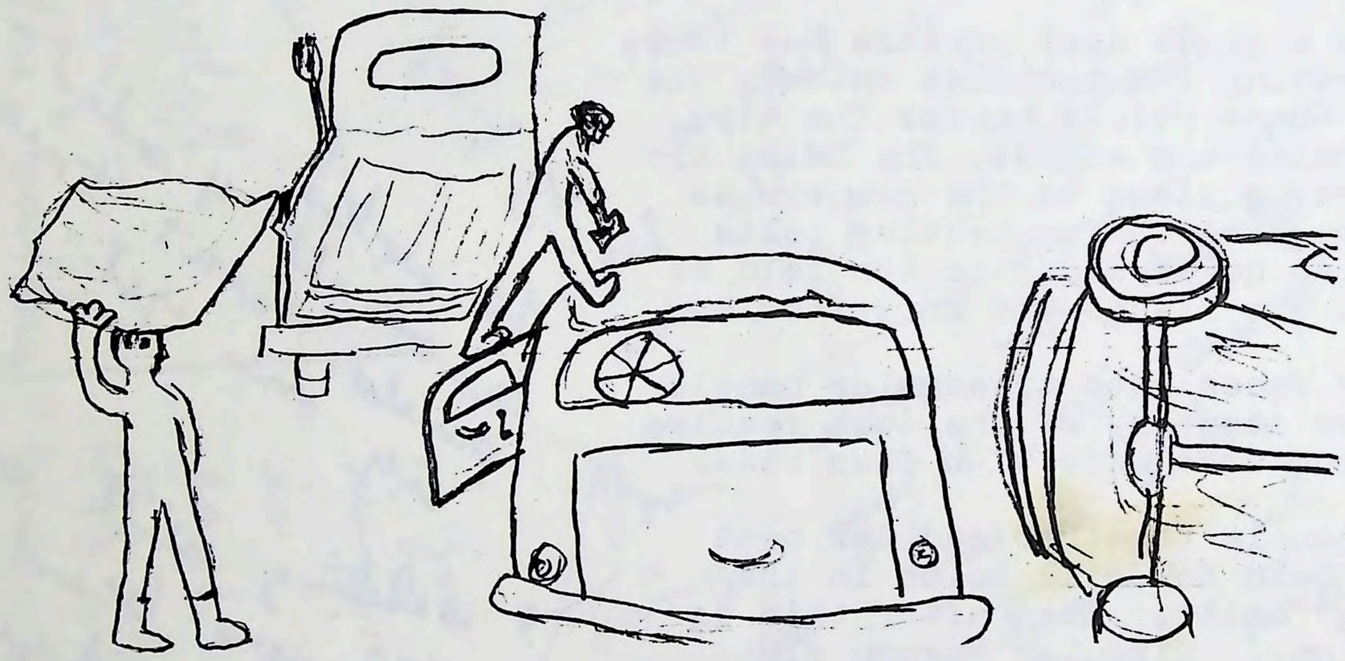
CAR TOPS

Car tops are a good building material. They are cheap, strong, have an excellent paint job and are available almost everywhere. The thickness of the tin varies from car to car some areonly about 20 guage (butter tops) others 18 and 19 guage. The tops can be cut into huge shingles and nailed onto a wood frame or they can be made int structural panels themselves which can be bolted, screwed, riveted or welded together to form a dome made of only car tops.

Most tops taken off a car with an axe will be between 45 and 52 inches wide and 50 to 70 inches long, a station wagon will give as much as 8 feet and a van or mini-bus even more. An experienced man with a good axe can easily chop 5 or 6 tops an hour and when the cars are packed close together so you don't have to touch ground you can go faster than this. Dave Park of General Salvage in Albuquerque has a stockpile of near 1000 car tops he has cut with various implements including a kind of giant can opener made from a spring leaf and driven with blows of a 3 lb machinist's hammer. Power saws with carborundumn blades, electric unishears, electric nibblers, acetylene torches, pneumatic chisels all of these will take tops off. The advantage of using an axe is that it's cheap and after some practice it can become a real pleasure to chop the top out of a car.

Chop along the sides first then the front and back. Throw open the doors- one foot on an open door and one foot on the car is a good stance for chopping the sides.

every man needs a gun but that's not
enough- what can you do with a little
gun today. We need bigger stuff
available to every law abiding citizen
There should be some very long phone
number that you could dial after any
area code that would trigger a matrix
of H bombs in that area. Anyone
given you a bad time you drive into
the next state and dial him out
The number could be kept secret
from youngsters, criminals and
people with poor judgement



On cars with missing back glasses be careful of standing on the shelf in back of the rear seat--some of these have gaps spanned only by cardboard and its easy to step through-- old fords are made this way.

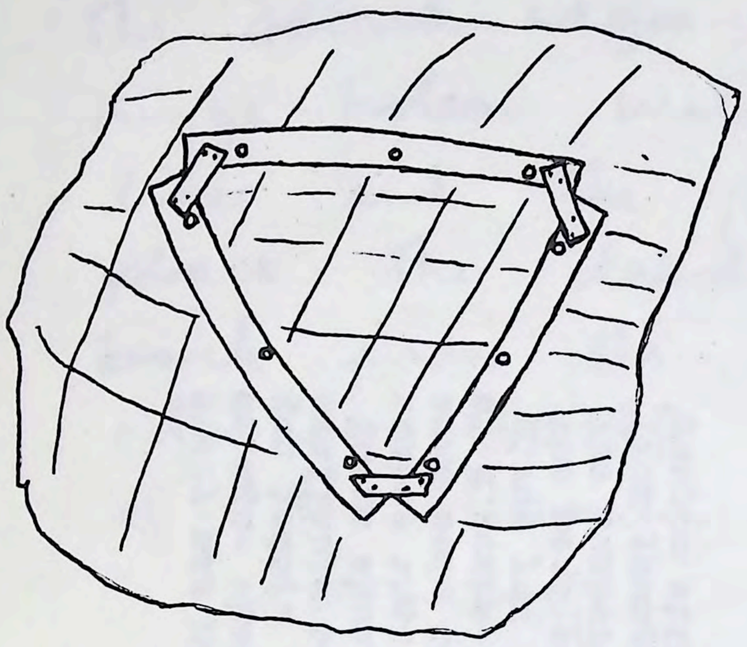
Don't swing the axe hard once you have a slot going. Cut swinging the head almost parallel to the top, if you hit flat, as you would a log you'll only smash the metal in. You have to first go after tops with a good deal of ambition, it takes a while before even the best get the hang of it.

Recently Mandel Bell and I rented an air compressor, marked off the shapes we needed right on the cars and then cut them out easily with a pneumatic chisel. Cutting the trimmed shapes right out of the junk yard eleminated at least two thirds of the work in the previous routine. It also meant we could haul twice as many tops in a load.

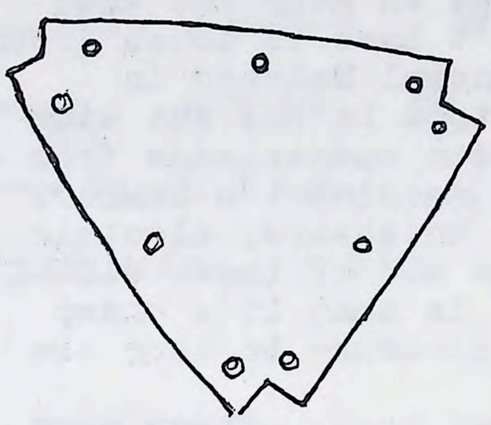
25 cents a top has been the going rate in New Mexico and Colorado. The tin can only be sold as junk and in many places junking car bodies is so unprofitable that the yards give them to who ever will haul them away. Not all junkyards will let you at their cars some junk dealers just don't like the idea of it. The best people to work with are the men who haul the bodies to a railhead or a smelter, they don't care what you take.

what is
? 11 to what
the blade?
the edge?
the handle?
you swing the
axe - so that
the head of the
axe is moving
more or less
in the plane
of the car top

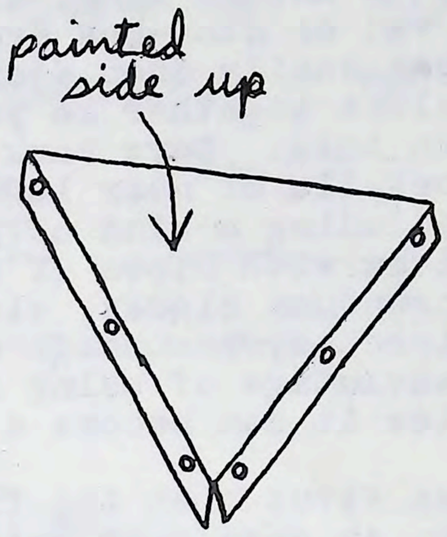
In the past the hard part of using cartops has been cutting out the panels. The tops are heavy and have sharp edges so every time you load or unload them or even just turn one around on a table you have work to do. I first marked out triangular panels using a flexible steel tape. The tops are compound curves(curved two ways at once like a sphere) so I measured the sides of the triangles along the curves. When they were cut out they weren't flat but when the flanges were bent in on a sheet metal brake all the measured distances straightened out and I did in fact then have plane triangles whos sides were the lenghts I'd measured across the curves. Since then we have succesfuly used patterns made of strips of flexible ¼" plywood. After the panel is marked it can be cut out with any tin cutting tool. None that I have used is ideal, the easiest cutting I have done is with a pneumatic chisel when the top was still anchored to the car.



flexible plywood pattern on car top

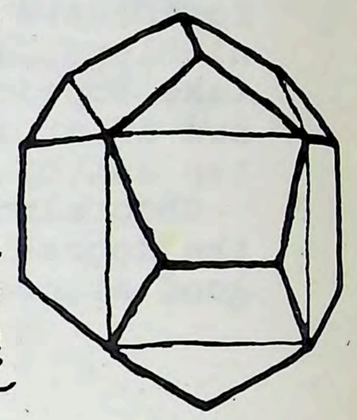


panel cut and drilled



panel, cut, drilled and broken

An enneacontahedron is the polyhedron produced by the stellation of the 10 diameters (vertex to vertex) of a regular dodecahedron. It can be inscribed in a dodecahedron - each edge in the enneacontahedron is formed by the intersection of two faces but edges can be drawn from the vertices of the dodecahedron to form the 60 triangular faces of an enneacontahedron. The 12 pentagonal faces of a rhombic dodecahedron are the same as faces of an enneacontahedron.



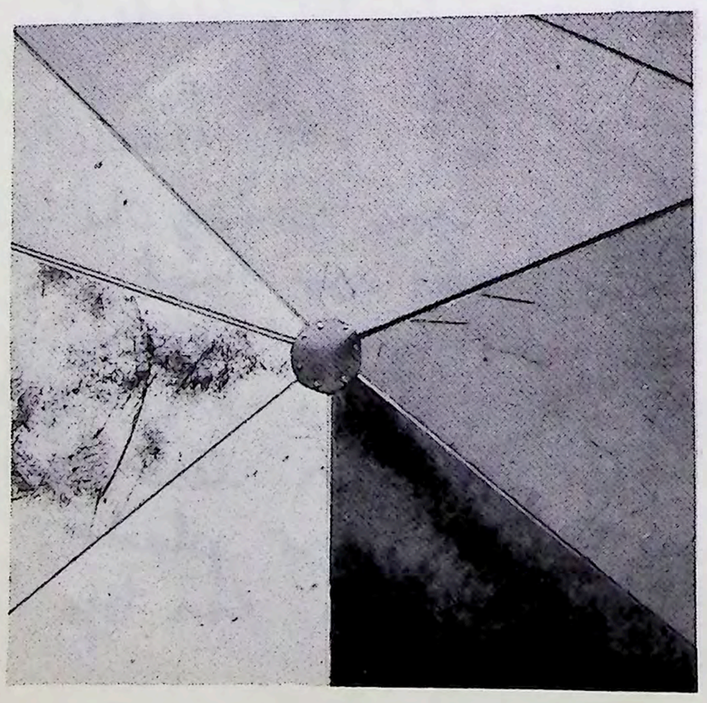
In making a structural cartop panel a great deal of care has to be given tc accuracy, particularly to getting the crotches between the flanges the correct distances apart, these points become the tips of the sructural panel and thus determine the edges. The holes are also important, the end holes shoul be as close to the corners as possible bring them back just far enough so the connecting bolts can be fitted through. They should also be as close to the fold as possible the farther down they are on the flange the more flexing the seam can do.

So far we have divided all the dome faces into triangular panels but I am not sure that the strength or accuracy of the dome require it. We are about to attempt some structures made with four sided cartop panels.

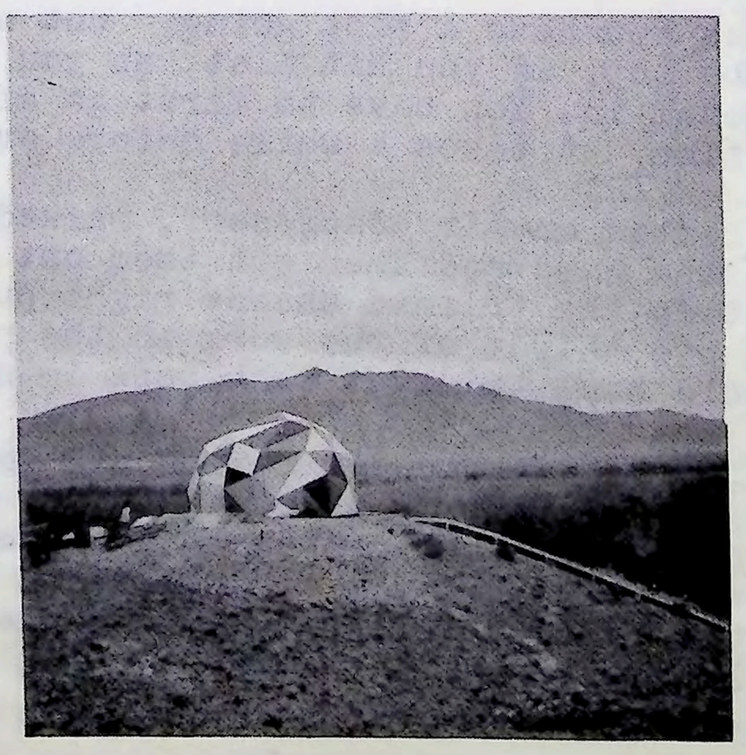
I still haven't tried welding the panels together and the best method of connecting them so far has been to drill holes in the flanges and bolt them together with ¼" bolts. Even after this is done the dome may be springy to walk on . Circular cartop plates put over every vertice and screwed or bolted to the tip of each panel will take out theis springyness. This idea was given to me by two hot rodders who stopped by the dome when they were out testing a beutifuly constructed dune buggy they had just finished.

this worked on small 4 sided panels. Haven't tried big ones yet.

→ welding with a continuous bead along the edges didn't work. Too many holes - set the tar backing on fire and it's slow.



← Zome made only with cartops. stretched enneacontahedron.



Build a model of a dome.

use a paper cutter or cut out patterns with a knife.

why build a model of a dome?

you can really cramp your fingers using scissors or cutting with the point of a knife

If you build a model you will quickly and easily acquaint yourself with many of the problems of dome building. The angles of the faces - The number of faces of different kinds - The pattern in which they fit together. As the model goes together you can feel where the strong and weak spots are at different stages.

How many pentagons? All are the same? When can you cut it? To make a good kind of thing? I'd is any good - why bother? Is there already one?

Then when you build the thing you'll be surprised because its so much like the model. Sometimes it will even look exactly like a model - of course it will look exactly like a

when you look at the model you want to get down low and look at it from an angle. Or better - building an airplane.

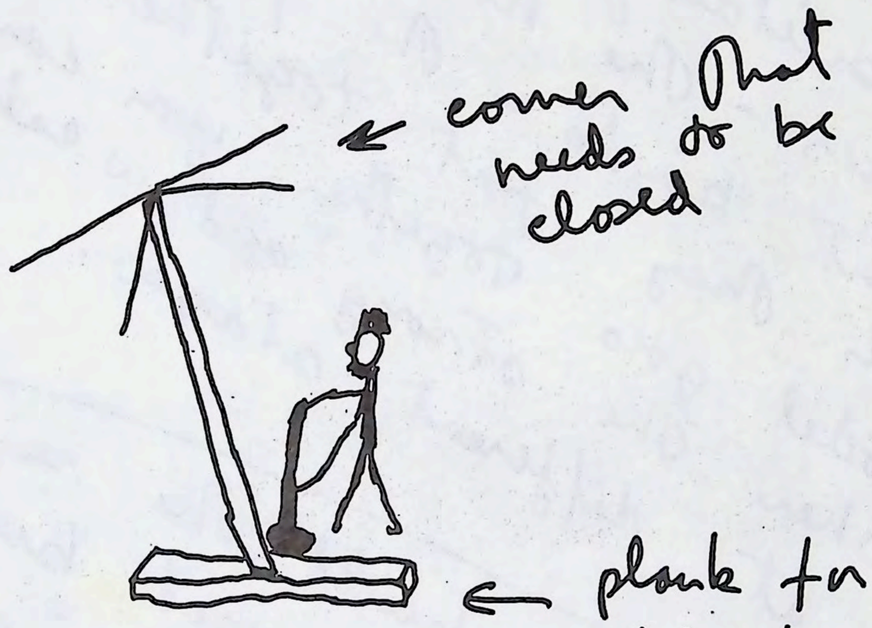
you find out just how important being accurate is - and how much each panel means to the whole of the strength of the business.

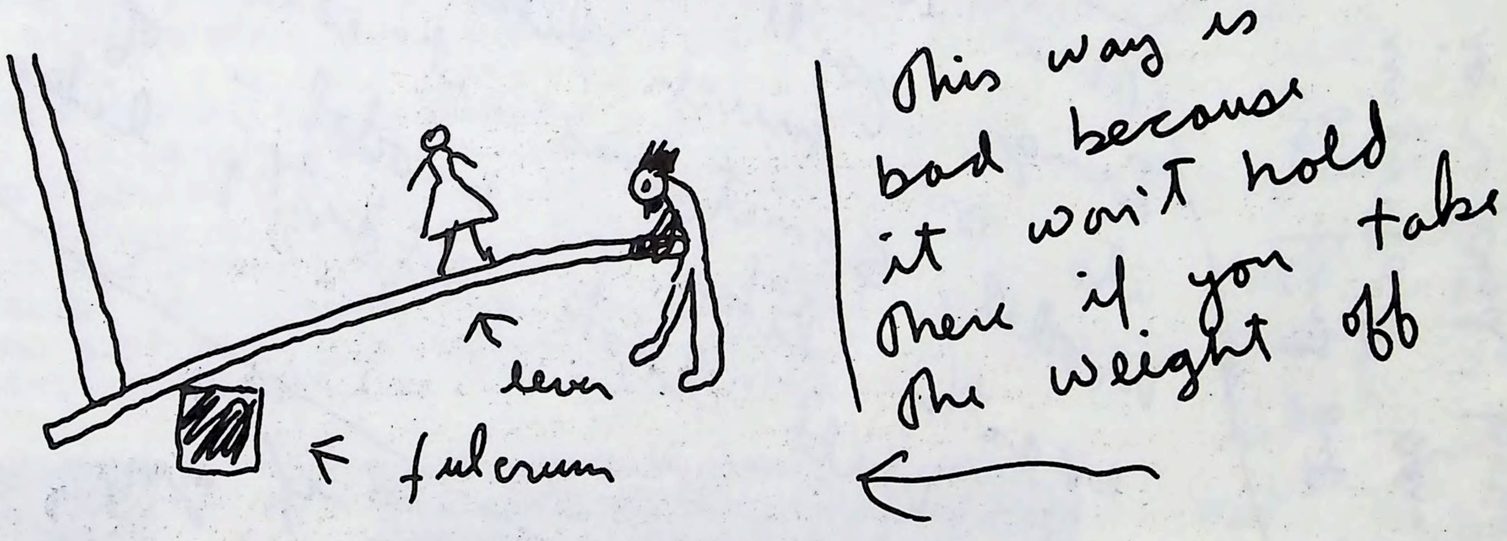
IT better get to look like the model... or somebody else's model or ...

if you get cardboard you have to be careful of the tape pulling the top layer of the cardboard off. The best stuff is thick stiff paper that won't peel apart. Bristol bond.

During construction you often have trouble getting something to fit. It can be the edges of two panels that won't come together, or the bottom of a dome that won't fit on the sill, or a diagnol that won't fit within a deformed face. Unless you are a capable perfectionist or very lucky these kind of things are going to happen. My assurance that this will happen shouldn't be taken as some kind of encouragement to goof off while putting in the footings or constructing the panels, if you do that you'll have problems of a whole different order. When the trouble starts you need tools like the following; sledge hammer, large clamps , block and tackle, large and small wrecking bars, drift pin, poles and levers.

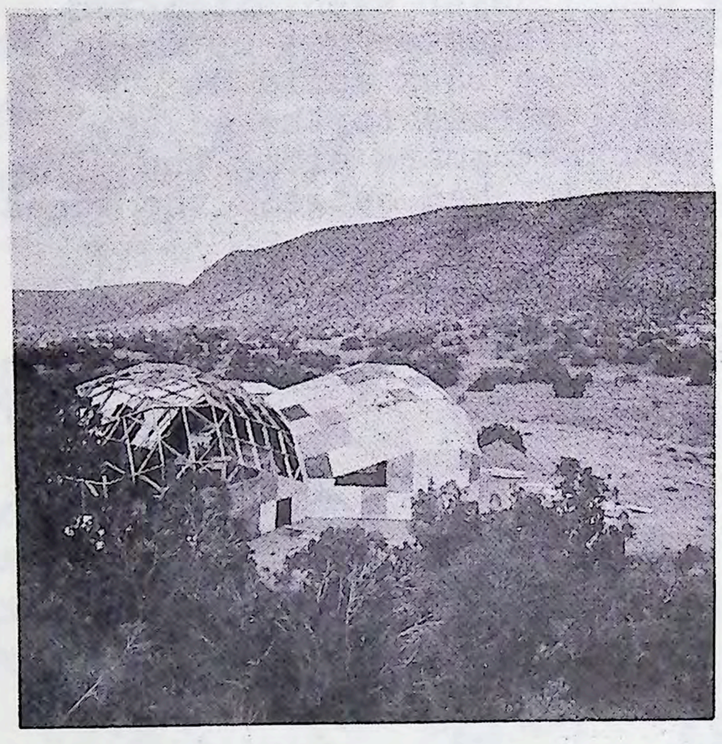
If two edges won't come together the open corner they are leading to needs to be pushed out, this makes the vertex sharper and there won't be room for the corner angles of the panels plus the open gap-- the gap closes as the corner is shoved out. The obvious way to shove a corner out is to use a pole sometimes a couple of people can put enough muscle on the pole to do the job but if this doesn't work there are other methods. Lay a plank on the ground leading in to a pt ~~directly~~ below the corner, put the bottom of the pole on the plank and drive the bottom of the pole under the top with a sledge hammer.





If two edges touch each other but don't match edge to edge, stick a small crow bar or a large screw driver between them and pry one in and the other out . We called this a "screw driver job"

Building the cluster of garnet domes at Manera Nueva we intended to first put up just the edge members but since almost all the faces had four sides the structure wasn't rigid enough and we had to put in occasional corner braces just to keep the edge members from collapsing in a heap on the floor. We completed the entire cluster ~~in~~ this ~~maner~~ way. it had very little strength and I was afraid to even trust my weight on the triangle at the top of the kitchen dome. Next we put in all the braces , this both changed the shape, bringing some erant zones into alignment and brought more rigidity. You could climb anywhere on the cluster, it swayed and sagged in places but never deformed dangerously. Then we put in cross pieces and nailed the car topshingles on dome by dome. During this stage Berry Hickman discovered that covering one dome greatly increased the rigidity of the neighboring domes. Evidently there had been a good deal of play across the fusing walls. At this writing three of the four domes are covered with car tops and the fourth and largest of the domes has most of its perpendicular zone covered. This dome has 750 square feet, the zones are 7,10.5 and 17.5 feet long and the explosion is 7 feet. It is 28 feet across and 34 feet long, the top triangle is 19 feet above the floor. Every edge member, every cross piece and every corner brace is made of pine 2"x6" which the mill had been unable to sell as #2 because of round bark coverered edges and other defects, we obtained this stock at 5 cents a foot. Even though the rigidity of the faces of this large as yet uncovered dome depend on short corner braces



illust.

it feels completely solid. I planned the construction of these domes depending on the corner braces only for enough rigidity to alow us to climb on the domes while we nailed on the car tops. I think that with the car tops on, the corner braces are almost completely redundant. this bracing consumned a lot of time and lumber and now that the tops are on it's useless perhaps now it should be called a retired part of the structure.

Building the cluster of domes at Drop City was also very instructive in that they became rigid step by step and because of identifiable actions on our part. It is necessary to seperate the changes ~~in~~ the structures undergo as the panels are fastened in place and those that occur when the shape is complete but fasteners and braces are still being added. The growth of a dome panel by panel is a marvel, watching it take its shape and strength is something at once very strange and very familiar, as if you were watching the growth of a life form from another planet unusual because of its foreign ness familiar because it seems alive. But This b~~eautiful~~ process if it ends on the addition of the last panel in a rock solid dome does not reveal what was necessary and what was unneccesary in the construction of the panels or the manner in which they are connected. If rigidity were to come before the adition of the last panel it may show that you have over built but this is an unlikely occurance.

(24) a note on the shiftyness of mylar film

THE WORD ZOME.

Steve Durkee invented this word. We were talking about these structures and agreed that they really were not domes because they are not symetrical. Stretching the zones of a zonahedra makes it asymetrical. Durkee said "they are zomes" I was very excited by this word - it sounds right. the word doesn't change any buildings but I kept waking up that night with the word going through my head. the next day at work Durkee and I kept saying things like - "well almost time to go zome"

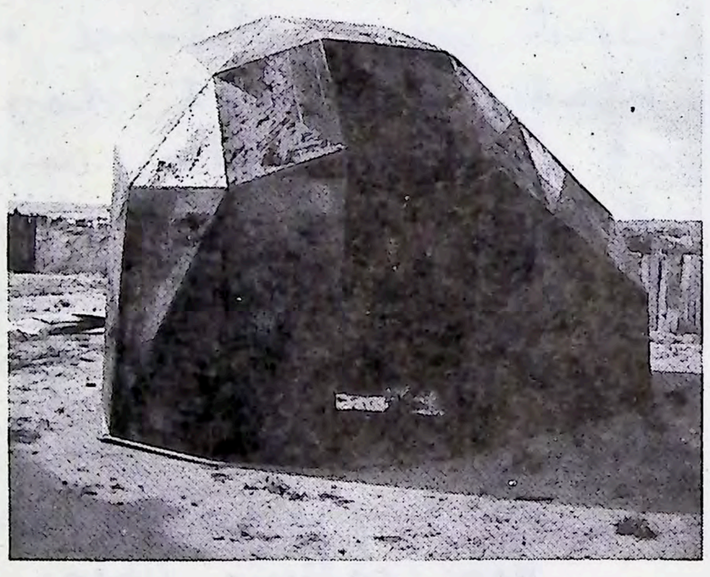
I have also seen it as a protection. People kept calling these buildings geodesic domes and Fuller type domes. They aren't. But I have sometimes been shy about using the word because it sounds to myself as if I were advertising something. It may be that inventing the word is more important to somethings use than the form itself.

In the book 20th Century Engineering there is a picture of a planetarium built in Germany in 1922 - it has the form of a multi frequency geodesic dome. who invented this form? I don't believe it was Buckminster Fuller.

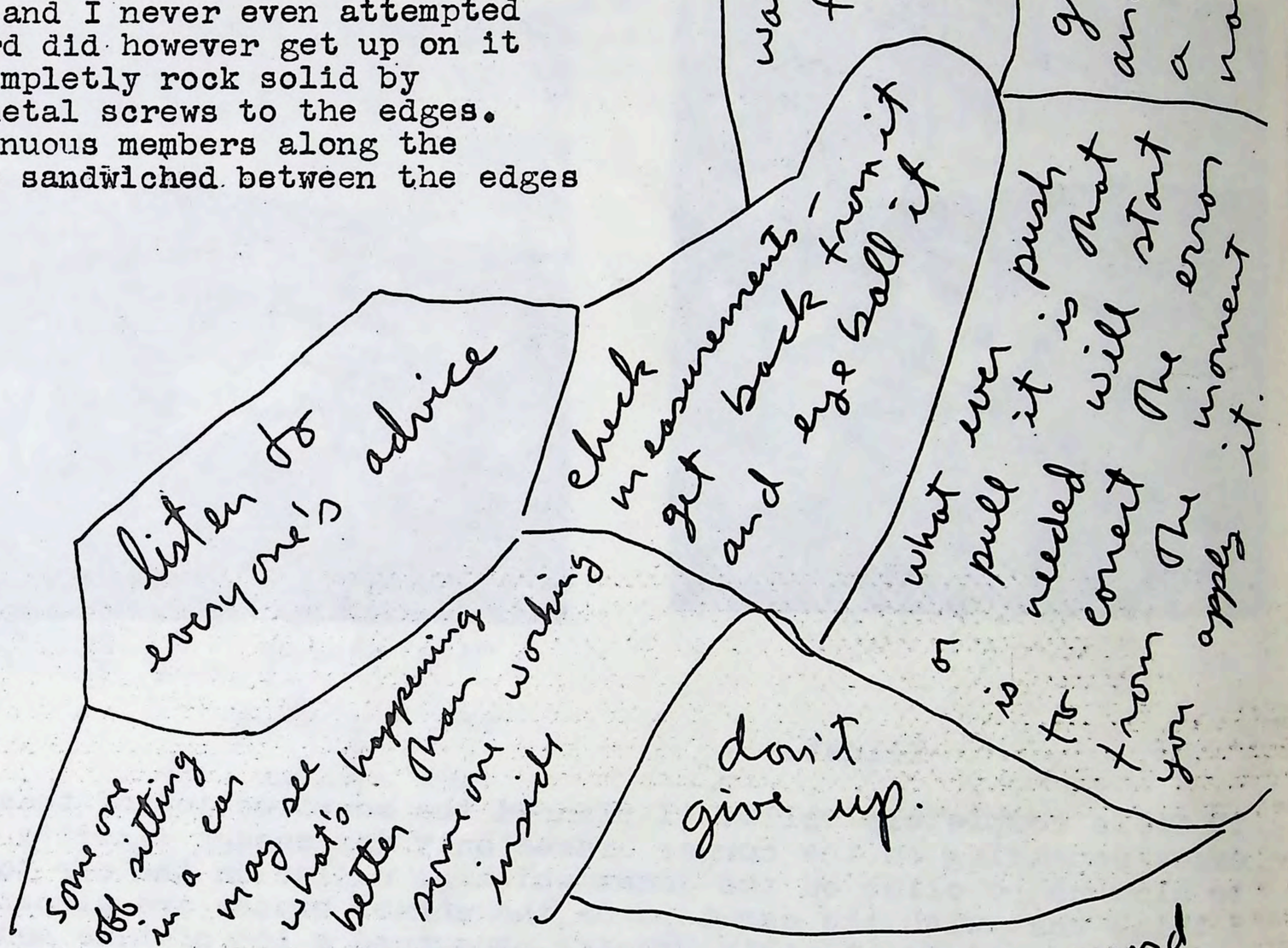
I first attempted against Clard's advice to sew the panels together with lengths of 10 guage wire strung thru holes we drilled near the corners of the panels. This proved too loose an arrangement and we abandoned it for car top gussett plates.

With the cluster at Drop City each of the three domes trembled when you walked on them when they were connected only with inside gusset plates. Worse the South West dome wiggled and shook, I found that this was because we hadn't put braces in the top square, it was distorted way out of shape and more important couldn't hold any shape. Bracing it instantly changed the wiggle to a mere tremble. The tremble later disapeared when the outside overlapping flanges were nailed down.

The first car top dome is perhaps the most surprising structure to find standing that I have worked on. After we put it up it seemed to me to be hopelessly wobbly and I never even attempted to stand on the top of it. Larry Lard did however get up on it at this time, and he later made it completly rock solid by spending days and days adding sheet metal screws to the edges. How this could be when the only continuous members along the 12 foot zone are 1/8"x2" steel straps sandwiched between the edges of the panels still amazes me.



→ on the kitchen complex october 1966



tool around with the model again.

At Drop City we couldn't get the second-to-last pentagon in. We took a day off. During this day a very strong chinook wind blew, the continual working of the building in this strong wind must have cooked the whole structure because the next morning the pentagon dropped right into place. At Manera Nueva we couldn't get a brace in a diamond. We tried everything -- poled the vertices pulled the corners together with a block and tackle tightened with a pickup truck, lifted the whole dome up to see if it wanted to sit down a different way. Nothing would bring it into shape. Finaly late in the afternoon someone brought a six pack and we all had a beer then on a hunch we tried rotating one of the domes a few inches - one shove like this and the diamond began to shape up. two minutes and the brace was in place. I walked up on the ridge between the site and the hiway I saw that the zones had finaly come into allignment

Money could have each transaction recorded on it - who had it when, what it was traded for. Cash registers could print this on the bills. Then perhaps it would be easier for us to understand our economy, who makes the money what it's spent on. Leafing through a pile of bills could be as interesting as watching the different names on the gondolas and box cars of a passing freight train.

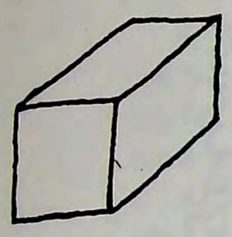
Everything must be fitted together somehow. If you leave out pieces the gaps expose the post faces you can never mend and will never mend to completeness.

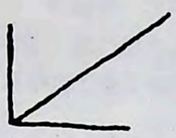
Born Los Angeles Calif Oct. 13. 1938

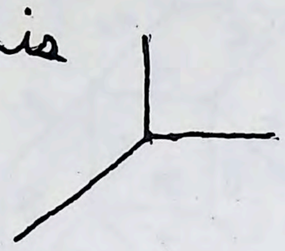
Lived in Civic Light Opera Apartments for a year. Went to Hollywood Professional School for 2 years. Then to Middle School Grade 6 - 8 Graduated from Middle School Track Captain - President - Treasurer - Class Representative

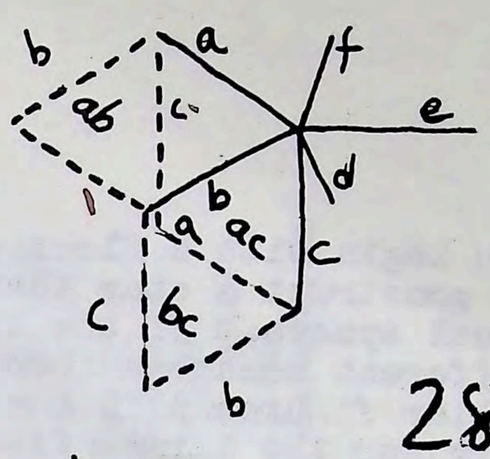
Lived in Beverly Hills 1 year. Went to Beverly Hills High School 1 year. Lived in Encino 1 year. Went to Encino Jr. High School 1 year. Lived in Van Nuys 1 year. Went to Van Nuys Jr. High School 1 year. Lived in Sherman Oaks

Each zonahedron has a star and its easy to see how to construct the star. What happens when we have some of the zones already represented by lines emerging from a common point and we wish to represent another of the zones- what side of the point do you run the line out of? With a cube



it could be this way 

or it could be this way 



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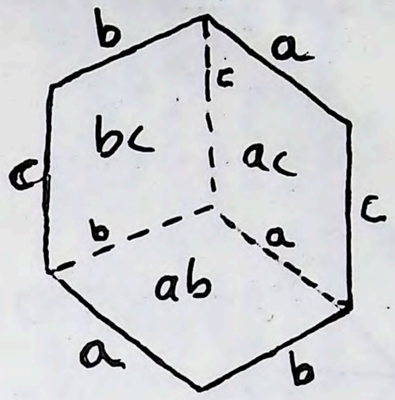


It doesn't make any difference, whichever is most convenient- the only things of importance are the direction and magnitude.

Just as every zonahedron has a star so every collection of lines going through a common point(or not going thru a common point - this is just a conveinence) has an associated zonahedron.

Sometimes if you wish to build a zonahedron to order it's easiest to make the star first. If the star never has more than two lines lying in a plane then every face of the zonahedron is a parallelogram. If there are three lying in one plane then the zonahedron has two hexagons- one on one side another directly across from it. Why should three lines in one plane produce these hexagons? Look at a star, every pair of lines defines a pair of similar faces one on either side of the figure- for instance the lines a and b define the parallelogram ab. I have labeled the dotted lines the same way as the lines they are parallel to. Since the lines of the star are parallel to the lines of the zonahedron the faces they define are parallel also. In the star above consider the three lines a, b, and c they pair together to form faces ab,ac,and bc. If I swing anyone of these lines into the plane of the other two there will still be the three seperate parallelograms but they will together edge to edge in the same plane to form a plane hexagon. (Don't expect to see this revealed by these primitive illustrations they only hint at it.) So if in a zonahedron you wish to have a hexagon, an octagon or whatever zonagon you simply bring the right number of lines into the plane in which you want the zonagon to lie.

Any two lines of a star define a parallelogram

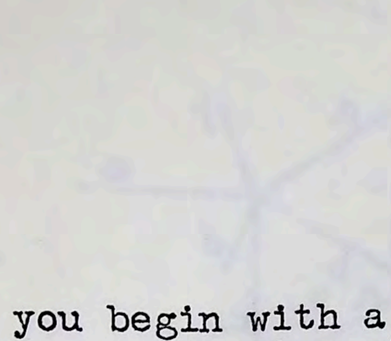
foot note

so if a star has n lines there are as many different kinds of parallelograms as there are pairs of lines in the star. This means there are $\frac{(n)\ (n-1)}{2}$ different kinds of parallelograms. When you consider that each parallelogram has a twin directly opposite itself across the zonahedra you see that there are then a total of (n)(n-1) faces.

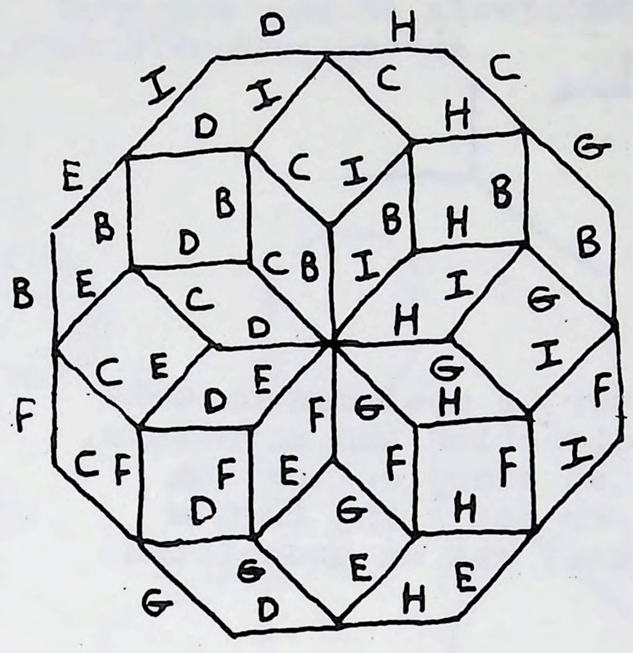
In calculating the number of faces in a zonahedra you must see whether all the different parallelograms are really different faces- if three lines of the star should happen to be in the same plane the pair of hexagons they form will swallow three pair of parallelograms so that the total number of faces would be (n)(n-1)-4 .

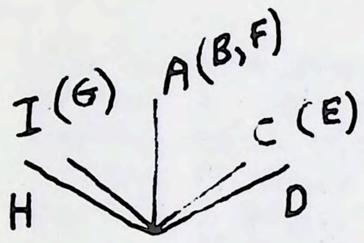
Any zonahedra can be dissected into (1/6)-n(n-1)(n-2) parallelepipeds (a parallelapiped is a solid with six parallelogram faces) one for every three of the n directions. These volumes are easy to calculate - so the total volume is also easy.

If you begin with a floor plan that is a tiling of zonagons you can construct a star that produces zonahedra which cap the individual spaces. If the tiling is a mixture of two or more different zonagons then the stars for the zomes covering the smaller figures will contain only some of the lines of the stars for the larger figures.

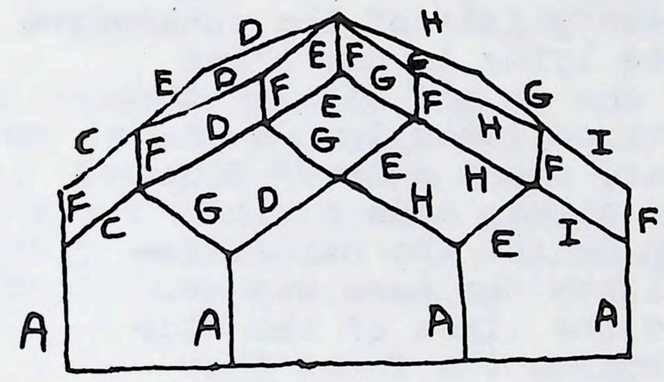


TOP VIEW

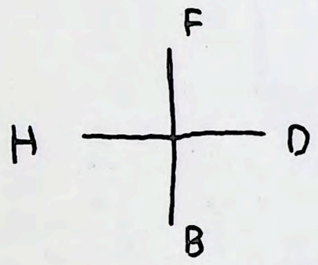




SIDE VIEW



letters in brackets are hidden



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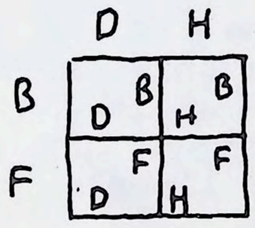

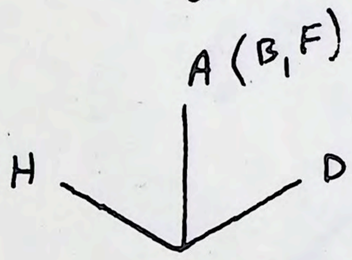

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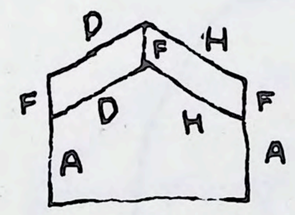
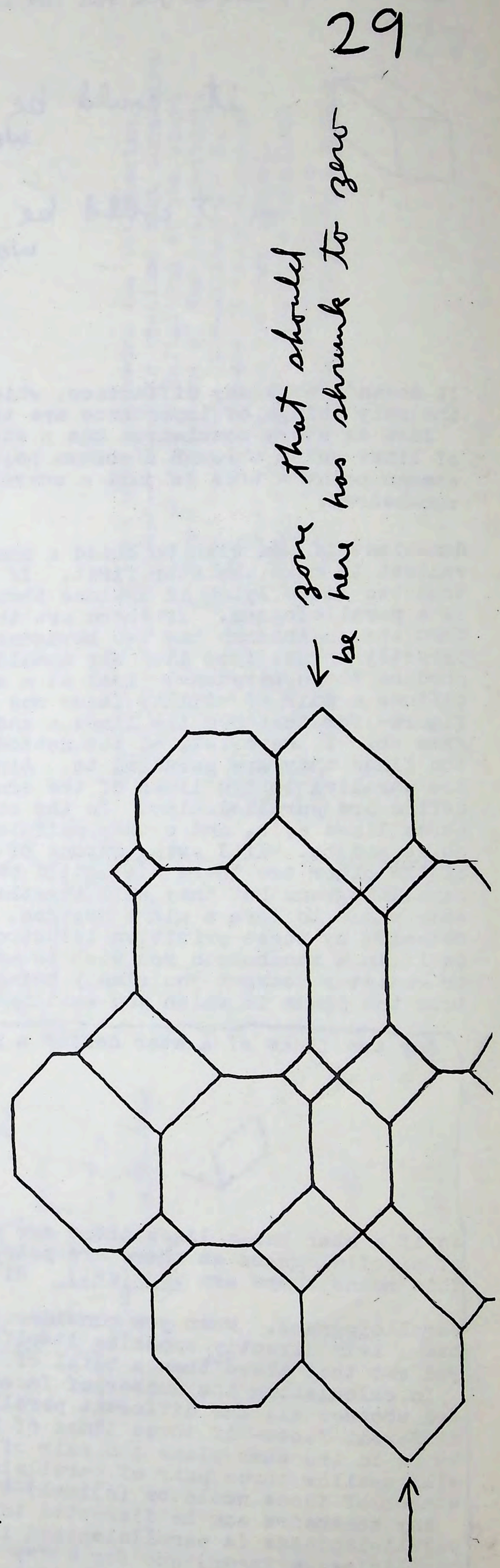


I'll give as an example a star for capping a tiling of octagons and rectangles - this particular star has four sets of three coplanar lines, they produce vertical hexagonal walls which are cut by the floor. These four sets of three coplanar lines are found in the star which has nine lines, one vertical, the other eightinclined at 30 44' to the horizontal and placed every 45 around the circle.

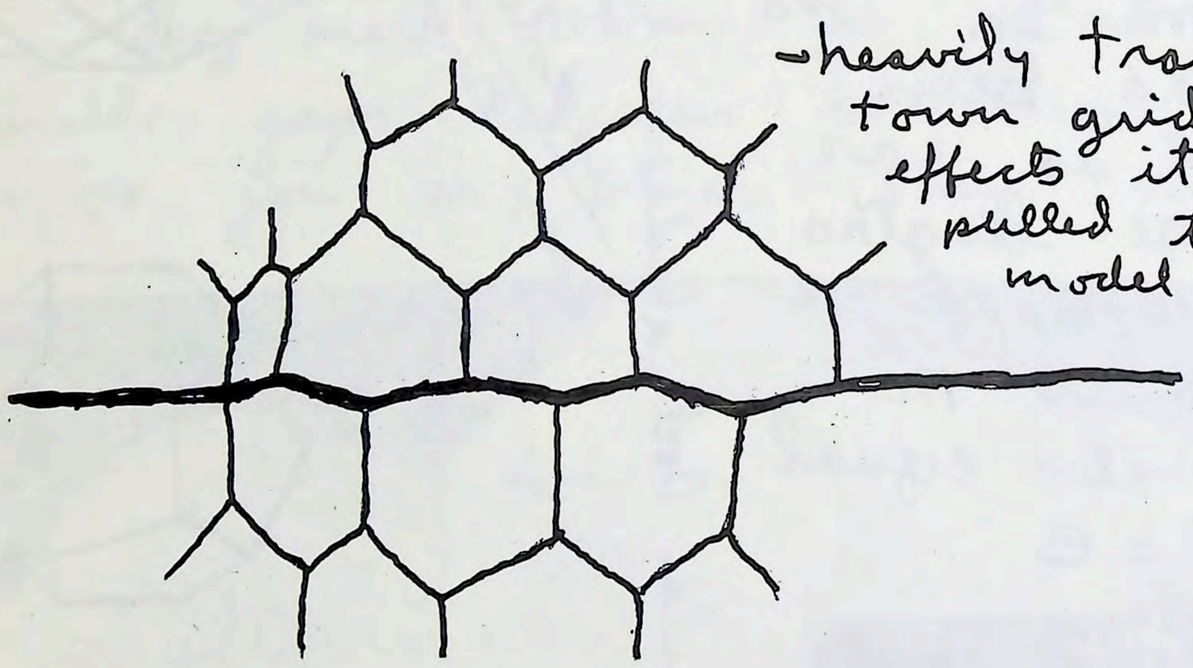
The reason in these stars that the lines are inclined 30 44' is that at this at this inclination there are only two kinds of faces. At any other angle there are three. If all the lines lie in the horizontal there are again only two kinds of prallelograms-- this can be seen in the top view of the big zome- the octagon floor is divided into squares and 45 - 135 parallelograms.

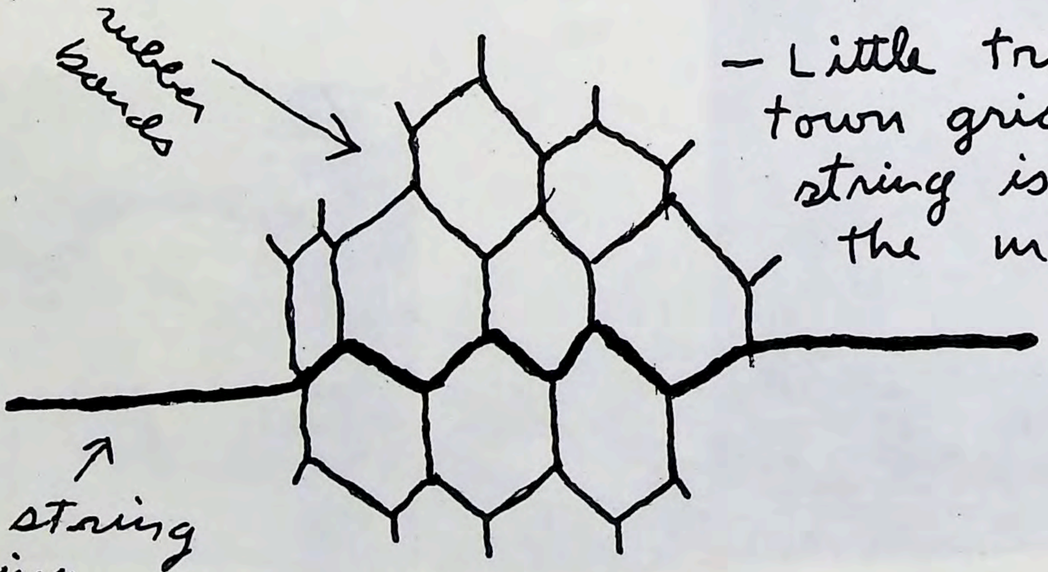


← zone that should be here has shrunk to 3

A designers plaything and eventual tool. A rubber web or net. Everything that must be built to be represented in the net. The rubber network is laid over a map and the floating assemblage anchored to the map where some event must take place. For instance a string or rubber strip or whatever represents a highway would be tied down to the map wherever there was a tunnel or pass or bridge already there. Everything that can be represented would be fitted in, each with an elastic nature that will somehow fight for the shape it wants. A parking lot could be a set of fairly stiff rubber tubes who's width was equivalent to 40 feet or however wide a parking lane with parking spaces bristling off to either side needs to be. Each section of this pliable but stiff tubing will seek to keep itself straight yet there is a vanishingly small probability that it would be a straight line, for like everything else its shape reacts to many other forces. Since parking spaces must be connected to the roads the thick strips which model the parking spaces must connect to thinner strips which model the roads.

Hidden preasure groups secretly controling designs -- they couldn't exist. Everything is out on the table. rubber tubes, springs, weights and pulleys, roller bearing needles, ballons, pools of imiscible liquids-- Let the wiggly mass pop out there over the map.

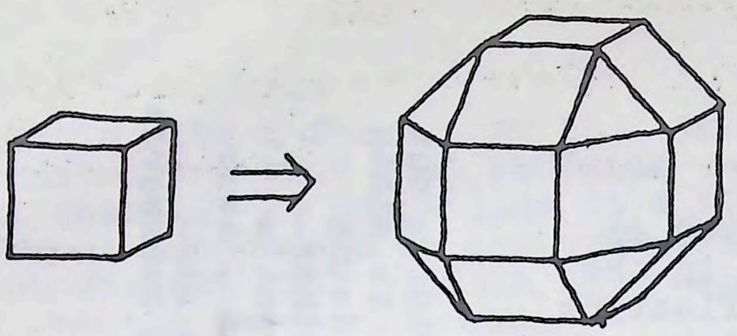




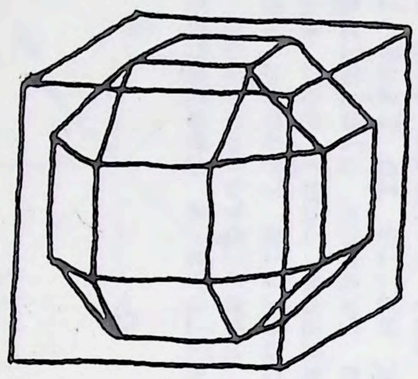
It might be a good idea for a time to have everything out in the open. To make it impossible for designers to claim they are doing one thing while in fact they are doing another. Acting for one reason claiming its another. If they can always invent a plausible reason for it. As I said earlier the cube is the best protection for this kind of activity because it allows a designer to work backwards or forwards.

Every part effects every other part. If you pull on just one rubber band all the others move- some only a tiny amount. Just as in our universe every planet, moon, star, comet or asteroid effects every other. But there we have definite laws-- I don't think there are any such laws for people- how we act or what we build for instance. In our lives our tongues and minds are such massive components that every time they go into activity to investigate, describe or communicate a whole new batch of matter is flung out in strange directions and the world is changed to a new world different than before you brought out the big guns.

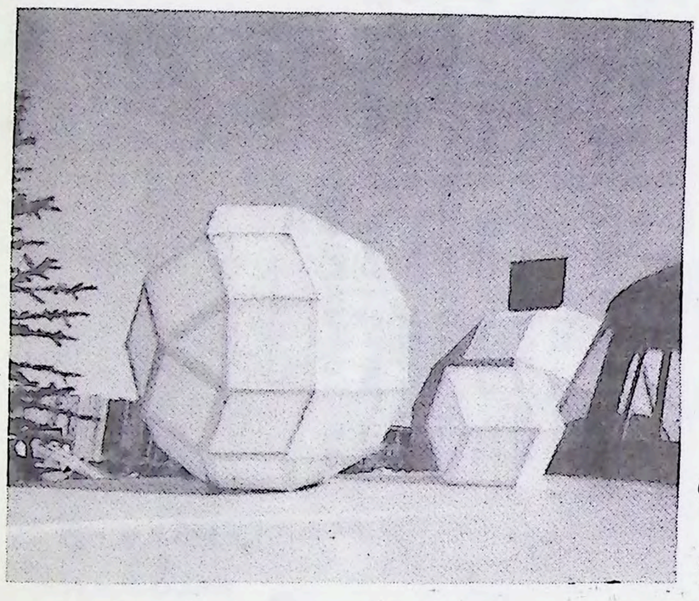
If a small town were situated on a hiway and the town was in a hexagonal pattern the hiway would be modeled by a string weaving in and out through the nodes of the rubber band grid-- when the forces were let loose one of them would be huge tension on the string but no matter how tight it was pulled it could never completely obliterate the effect of tiny cross streets.



this is a cube and an exploded cube You can see that rectangles appear over the edges and triangles over the corners

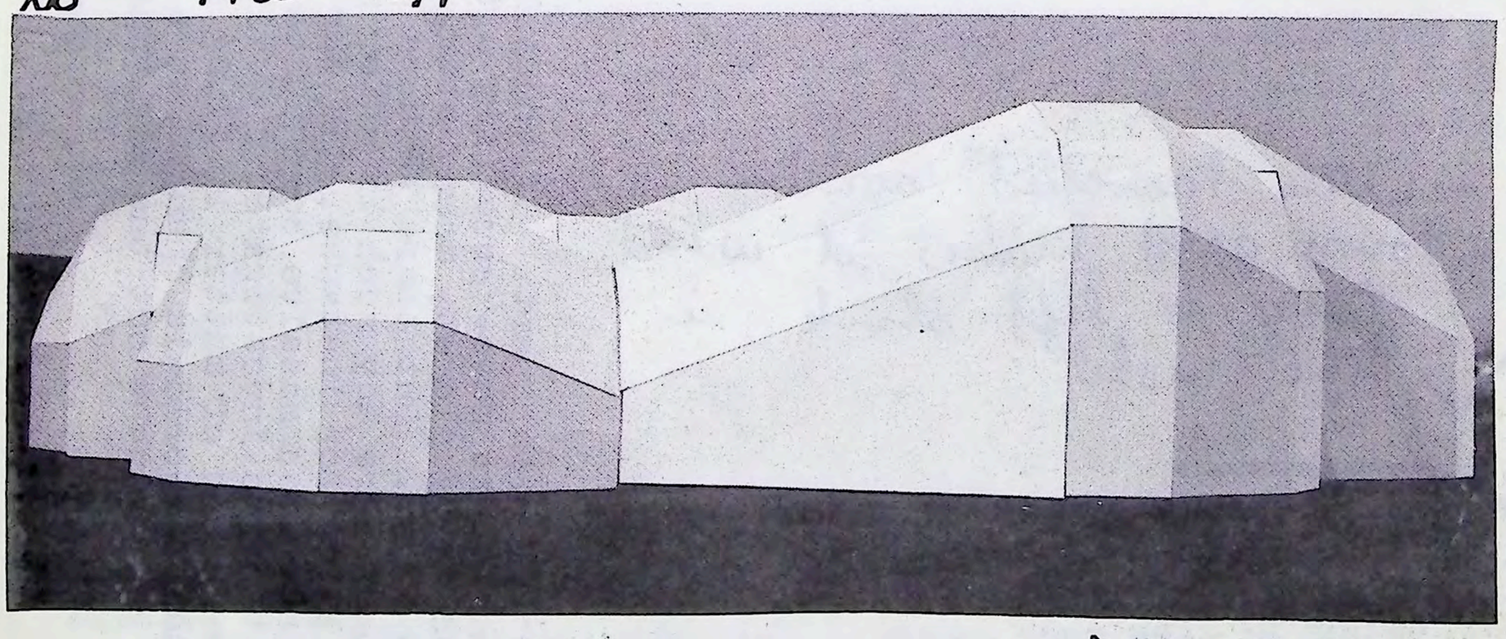


Here is an exploded cube inside a large cube showing that exploding a small figure or cutting away the edges and corners of a large figure can produce the same thing.

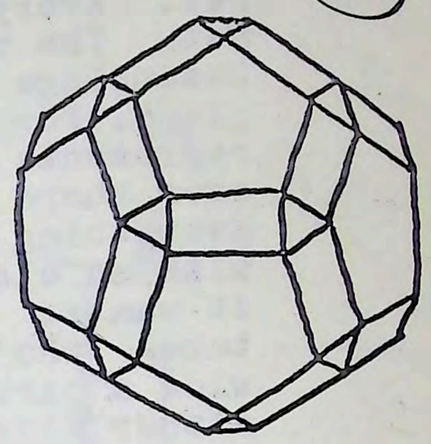


a rhombic dodecahedron and an exploded rhombic dodecahedron. In this case it has been exploded just as far as the edge lengths of the diamonds.

in this picture all the zones are the same length and they are also equal to the explosion. a=b=c=d=e



fused cluster of exploded rhombic dodecahedra. The zones have been stretched different lengths and the entire cluster is cut by the plane of the floor These are zones



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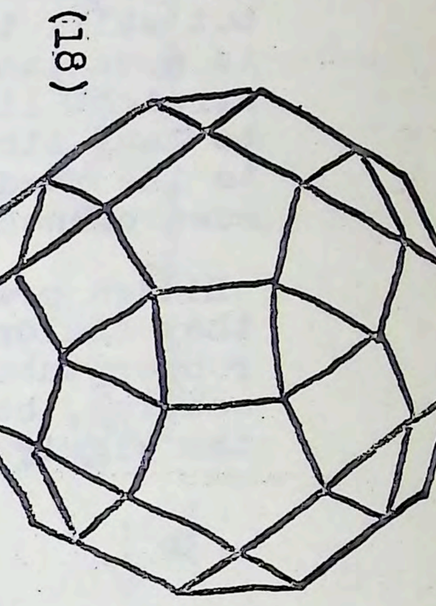

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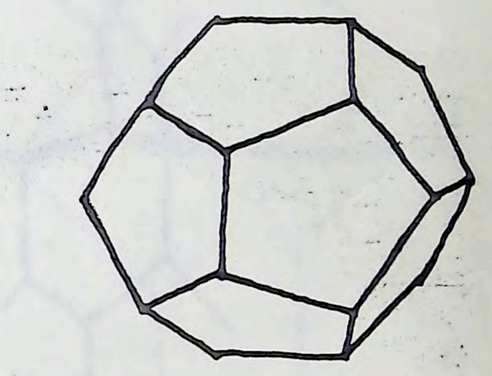
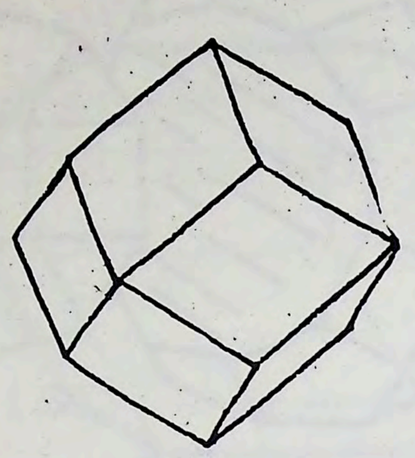


Regular dodecahedron exploded 1/2 edge length

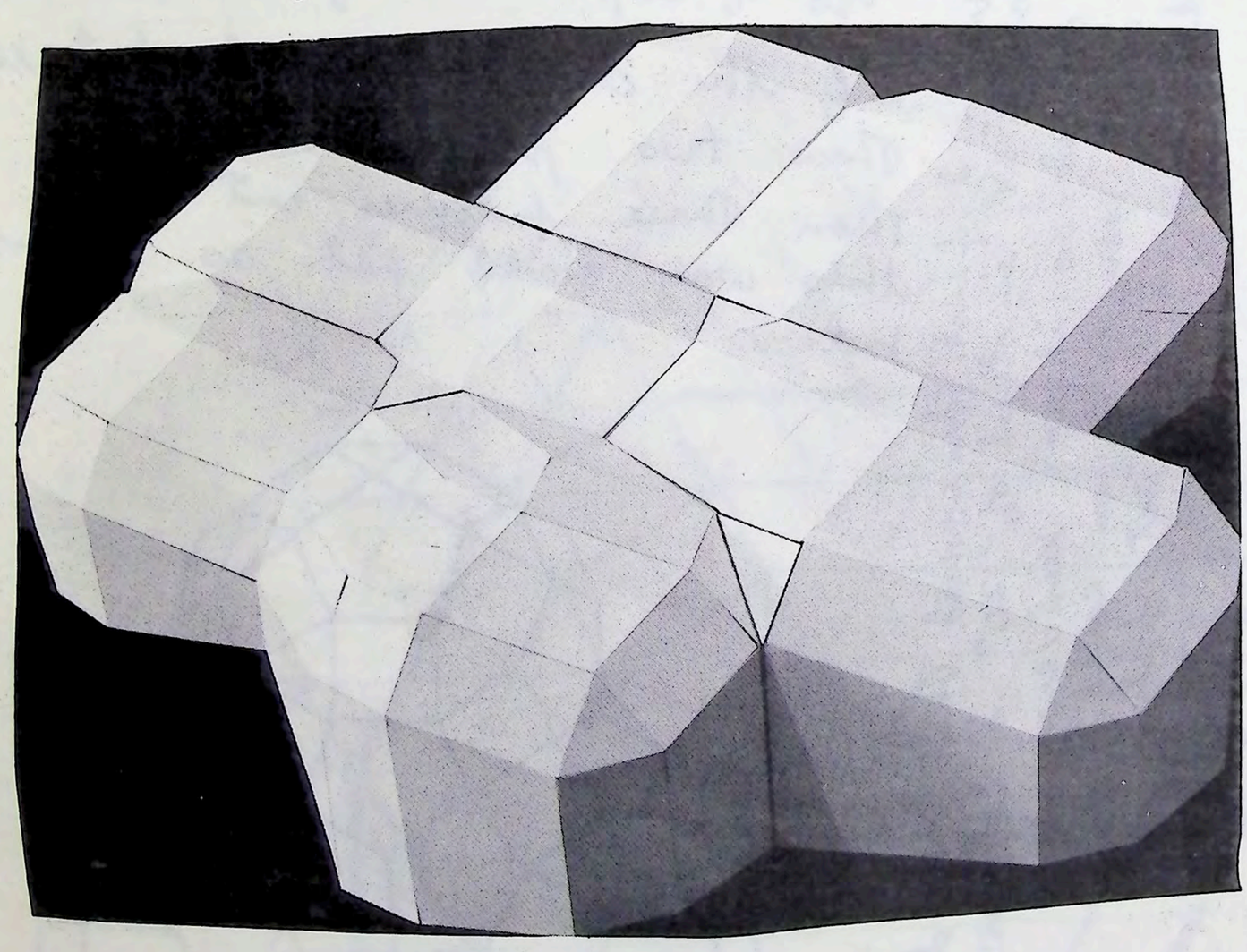
exploded 1 edge length

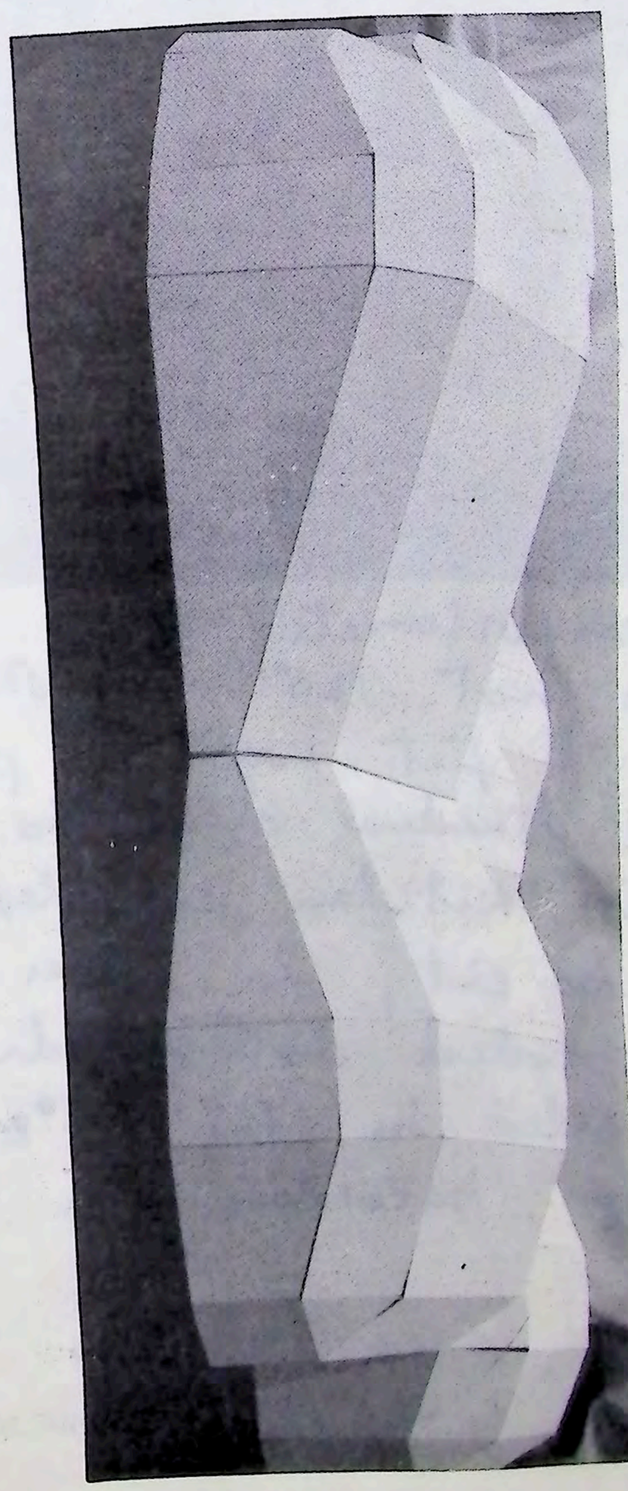
a model with the fusing ring outlined



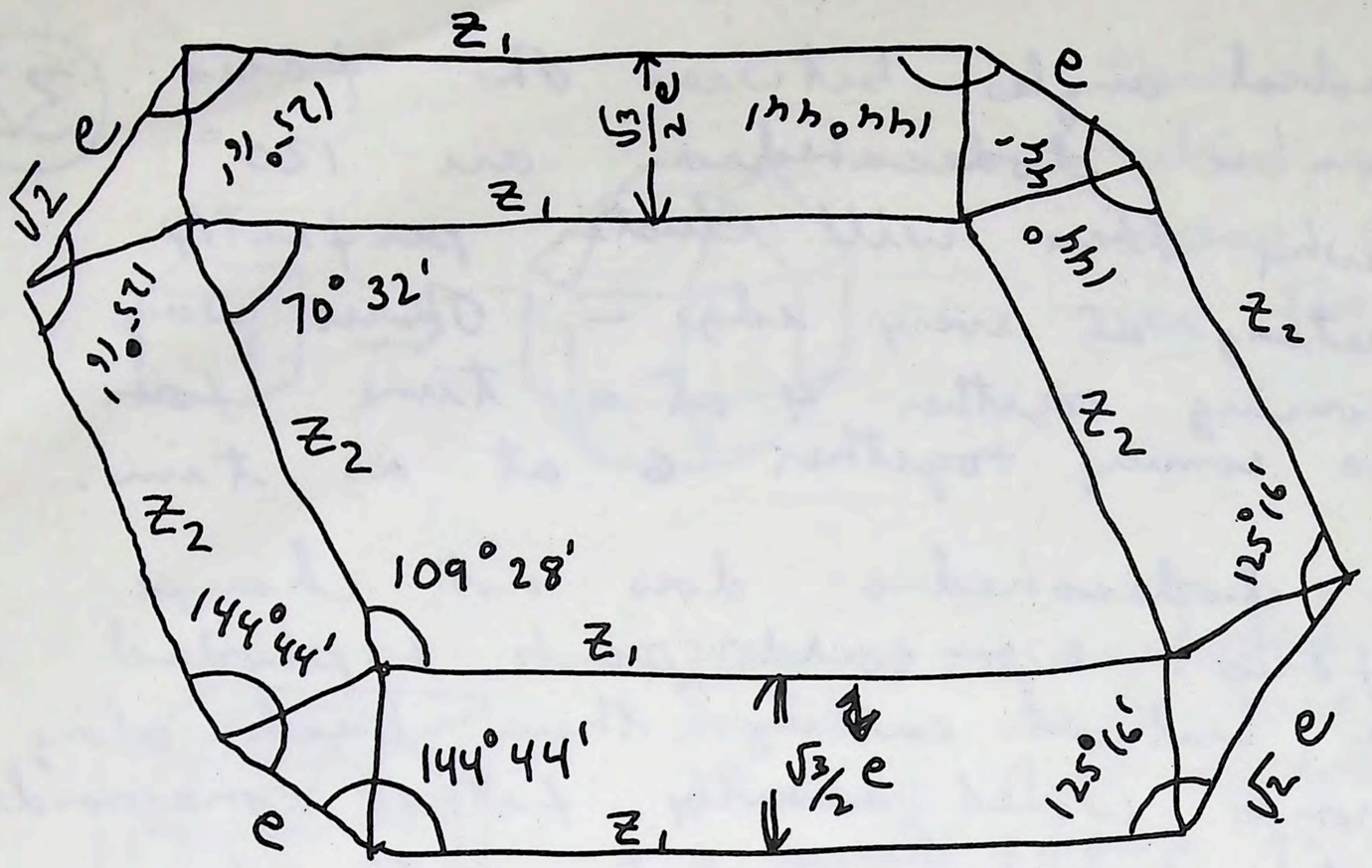
the dihedral angles between the faces of a rhombic dodecahedron are 120° this is why these will cluster perfectly. three meeting at every edge — three way corners coming together 4 at a time four way corners coming together 6 at a time.

exploding these rhombic dodecahedra does not change the angles between the faces. We could pack exploded rhombic dodecahedra together without cutting them back along the fusing rings. Diamonds would exactly fit to corresponding diamonds but there would be spaces between the figures as with a box of marbles or eggs. Cutting the exploded figures back along the fusing rings turns them back into the simpler rhombic dodecahedra shape - do this 12 times and that's what you have. the advantage in ~~buildings in~~ exploding them and then cutting them back where they meet others is that you don't have small unusable gaps between buildings but where they don't have to join to others they swell out like bubbles.

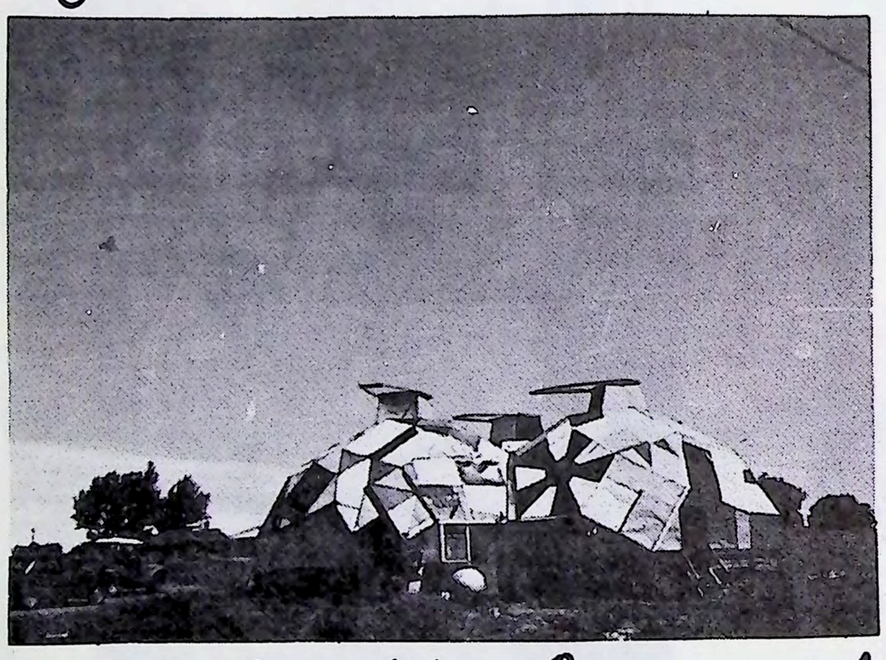




I have made huge nets of rubber bands and strings. I first did this on the wooden attic floor of my wife's grandmother's house in Switzerland. During the same time Audrey and I were experimenting with blowing soap bubbles, watching how agglomerations of soap bubbles adjust to different forces is very beautiful. There is an excellent book on soap bubbles by C.V.Boys Dover press. this man also built a solar powered water pump on the Nile at the end of the last century.



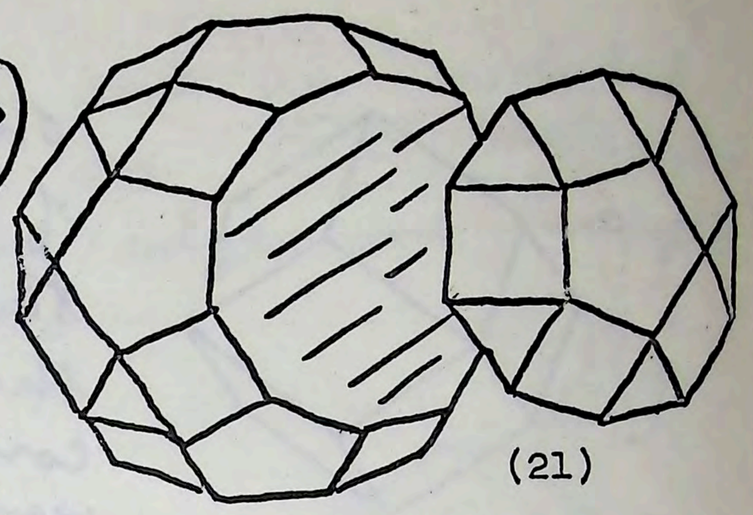
Fusing ring of an exploded rhombic dodecahedron. This ring cuts behind the diamond where the zones marked z_1 and z_2 cross. The ring follows edges except where it cuts across the two squares which lie outside the acute angles of the diamond.



unfortunately these angles are not 120° and the figures don't fit together perfectly. the dihedral angle is 116° 34'. the kitchen complex at Drop city is three fused exploded dodecahedra. We filled in the 3°26' slice gaps between the domes.

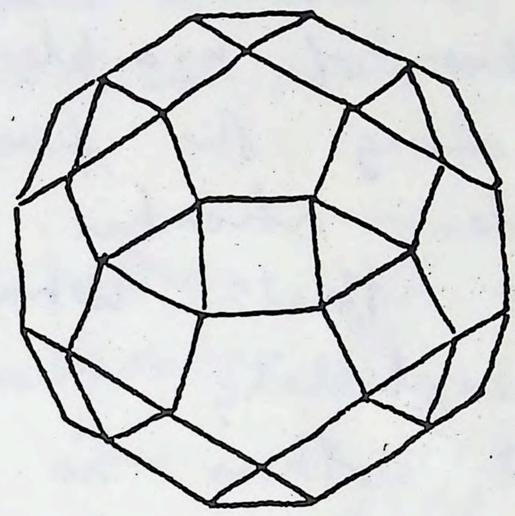
When I first discovered that this dihedral angle was 116° 34' instead of 120° I couldn't accept it. It seemed as if our universe were flawed. If the angles were 120° you could build perfect endlessly in space. These figures fit perfectly.

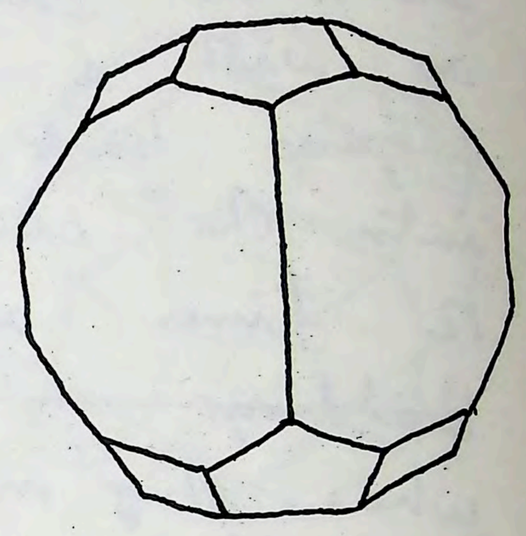
(33)



(21)

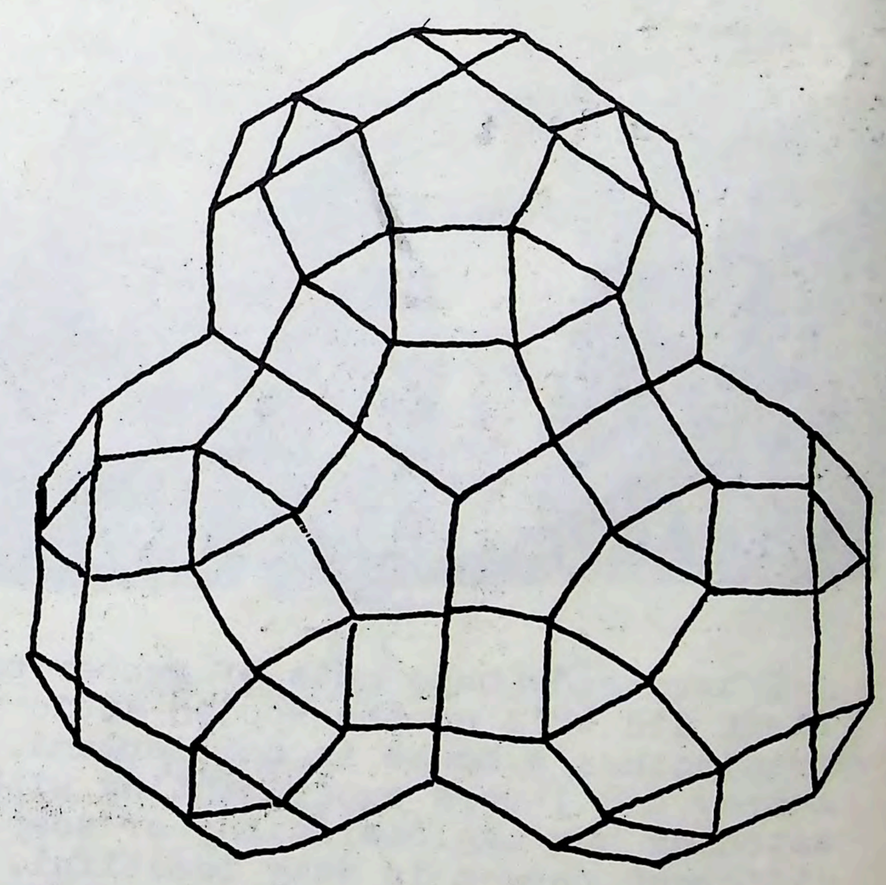
decagon fusing ring of the exploded regular dodecahedron.





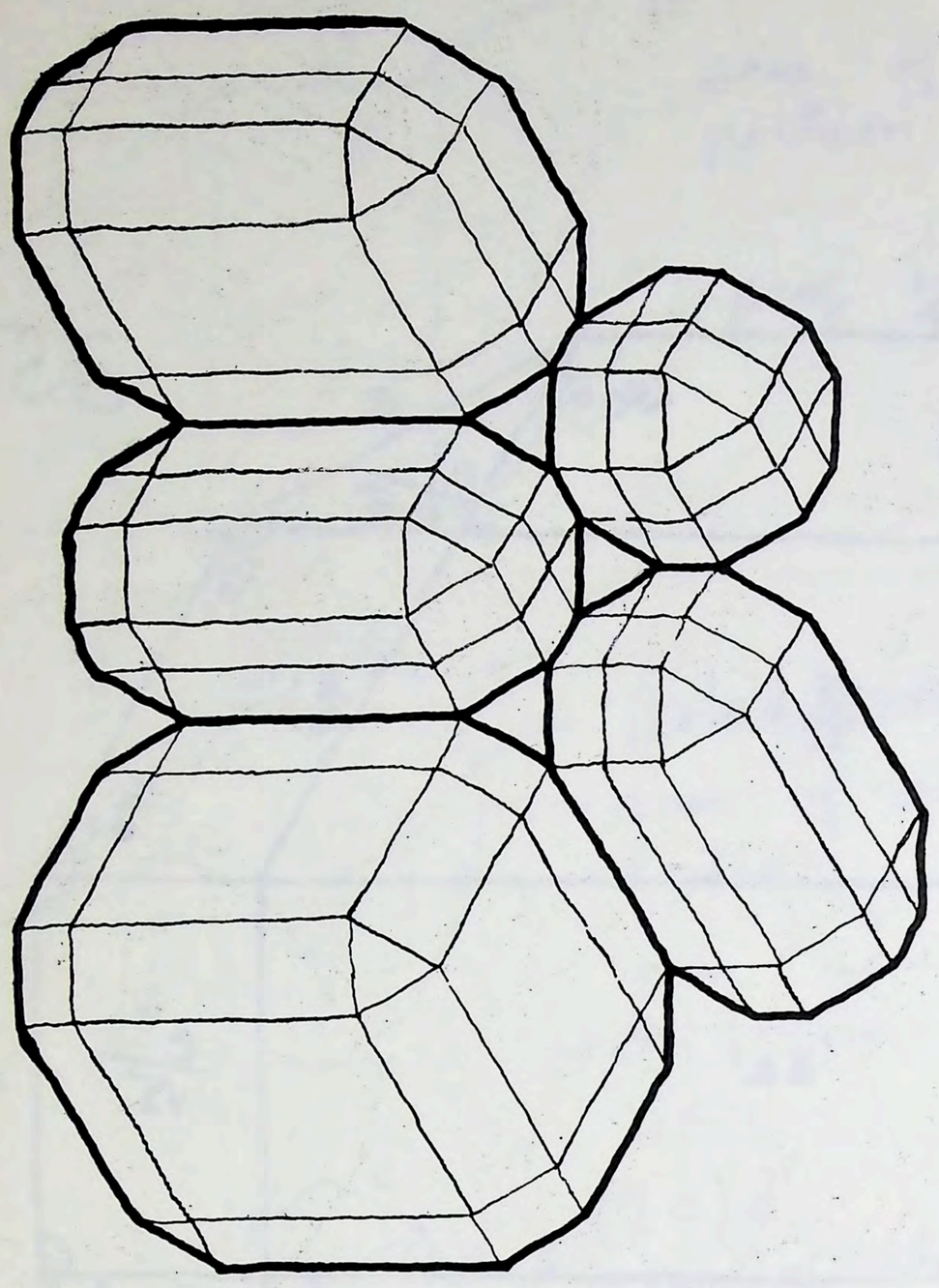
two overlapping rings cut off of exploded regular dodecahedron

If the dihedral angle between these two planes were 120° then three figures cut back this way could fit as shown below



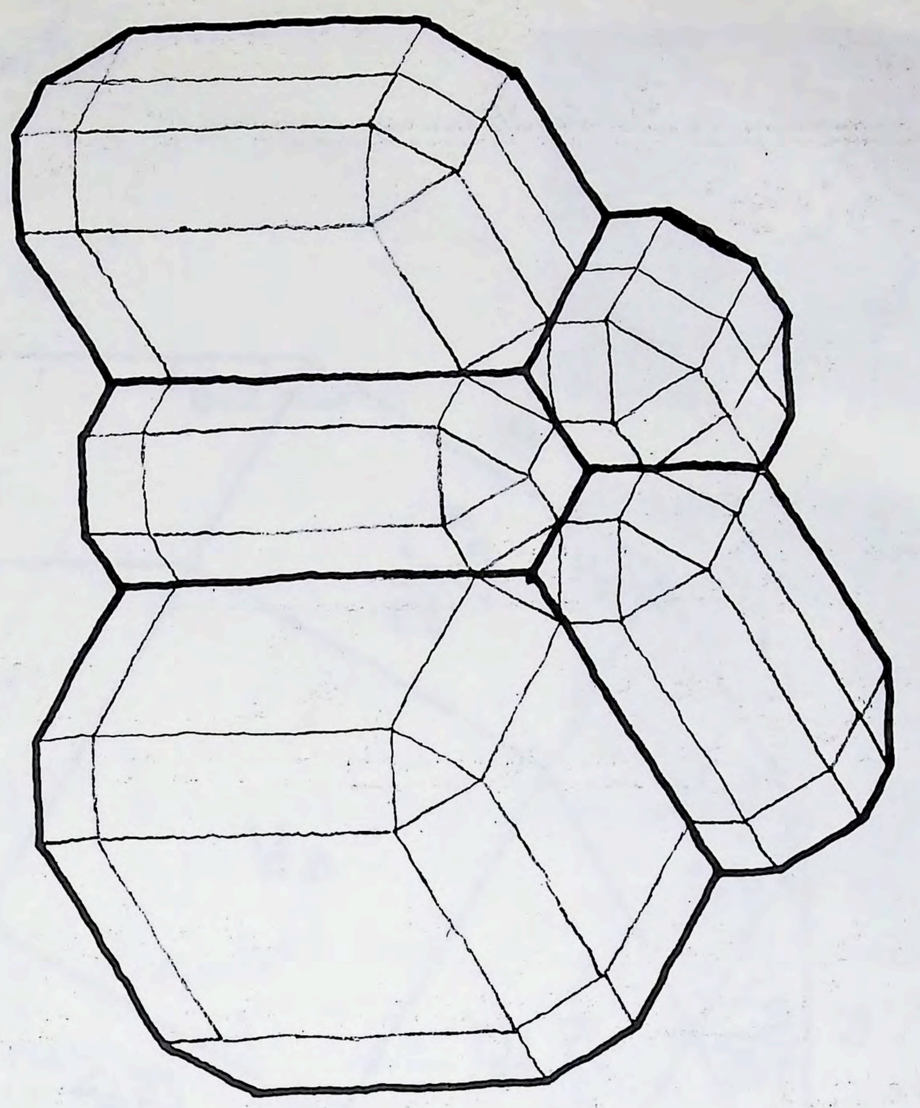
these figures are slightly distorted to make them meet.

KISSING

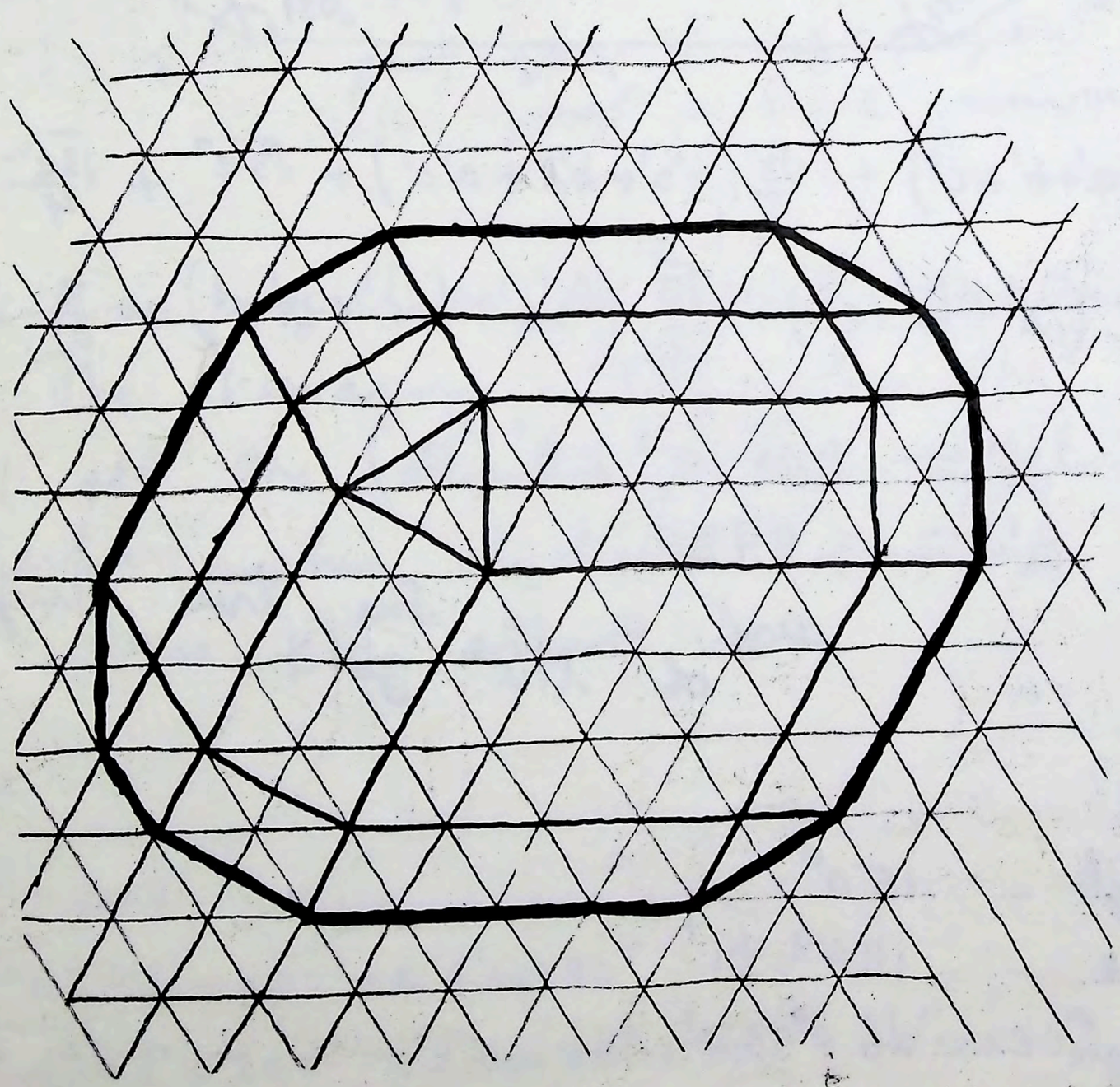


Top view of cluster of exploded rhombic dodecahedra

FUSED



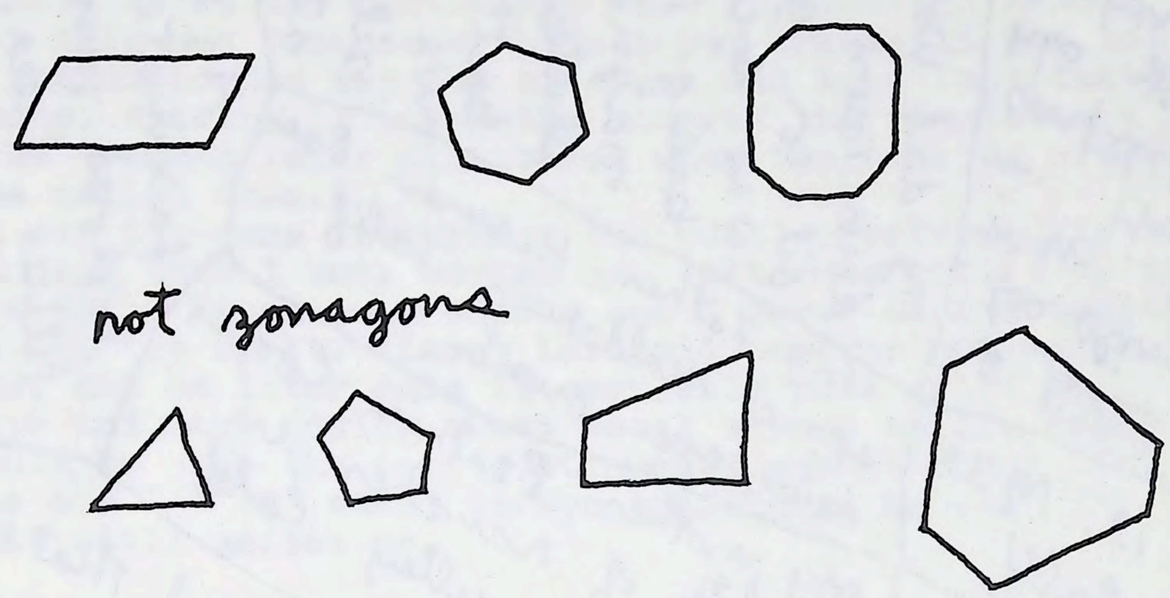
top view of cluster of exploded rhombic dodecahedra



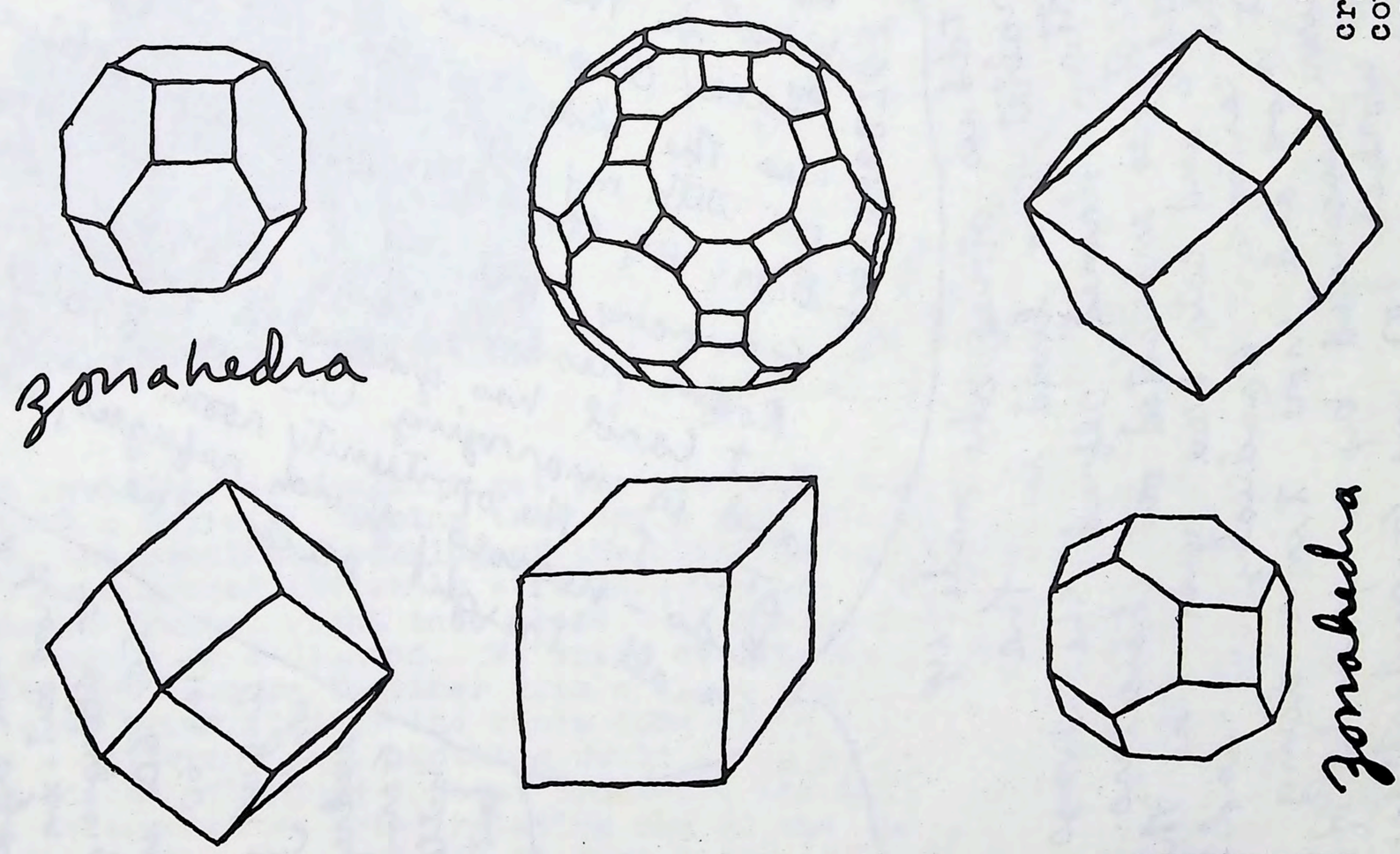
It's a very simple matter to draw floor plans of these figures using triangle grid isometric paper.

ZONAHEDRA

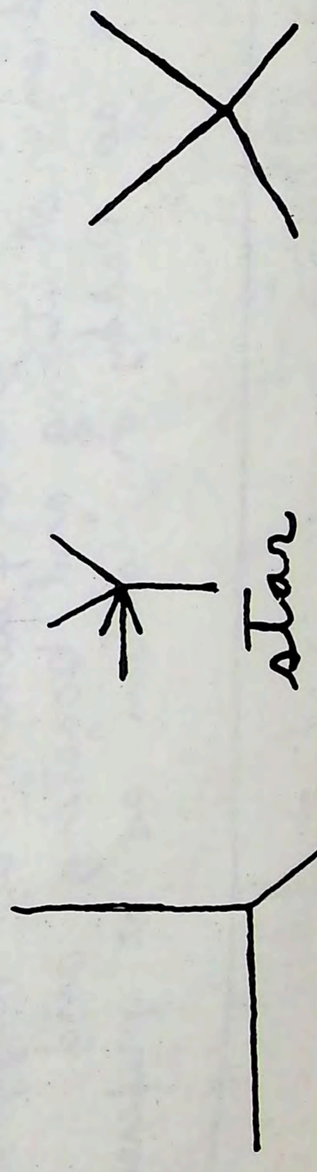
A zonahedron is a convex polyhedron all of whos faces are zonagons and a zonagon is a polygon whos sides are in equal and parallel pairs. Zonagons can be stretched to form different shapes without altering angles.



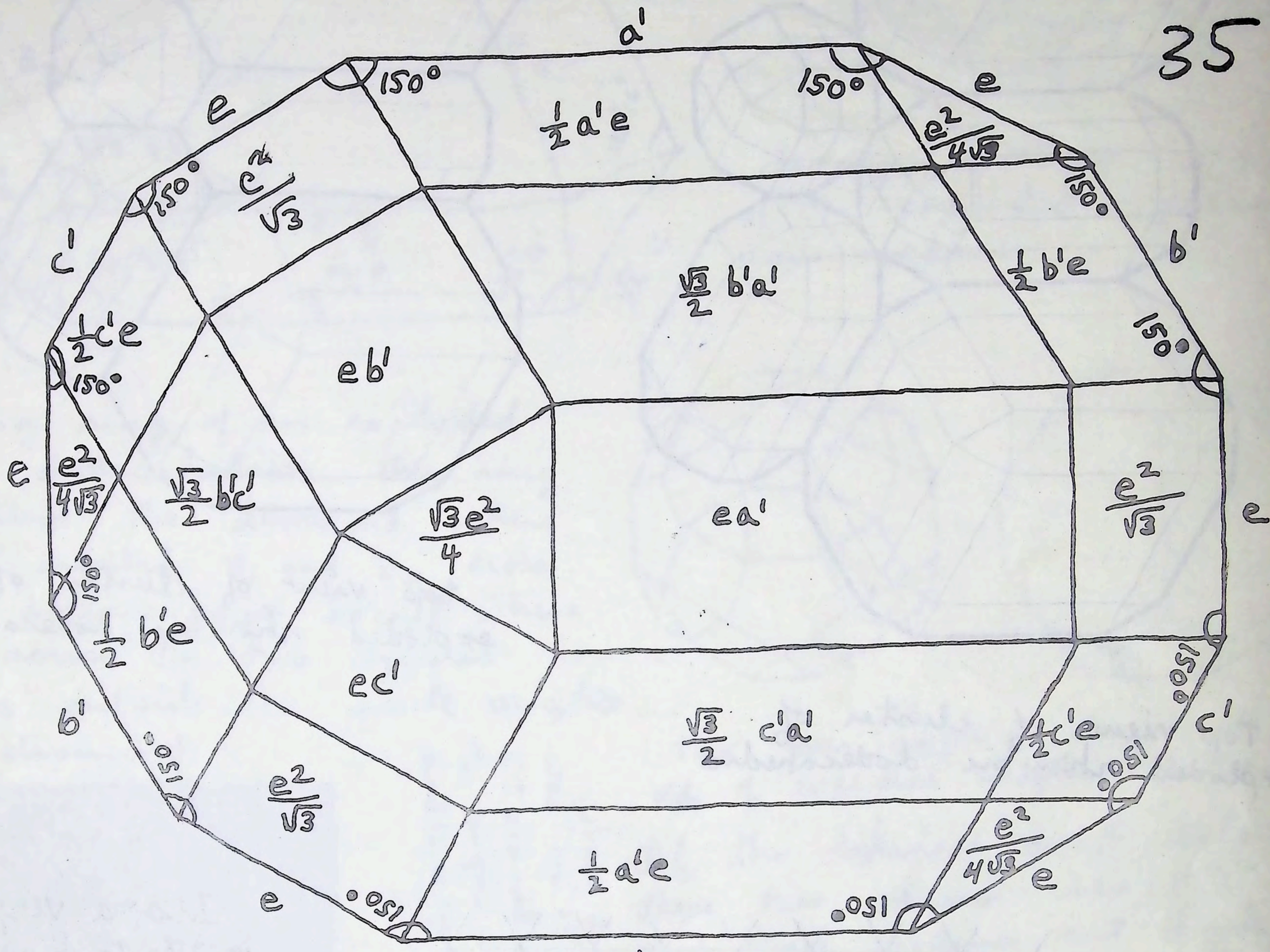
A zonahedron is formed from zonagons joined edge to edge. A zone of the zonahedron is a band of parallel edges which circle the figure. Every edge is part of a zone because you can always cross a face to another parallel edge. There are exactly as many of these girdles of parallel edges as there are different directions to the edges.



The first man to work with zonahedra was the Russian crystallographer Federov. He never realized that zonahedra could be defined with the simple definition at the start of this page. He worked at the end of the last century. More recently zonahedra have been investigated by **P.** Donchian who predicted that they were 3D projections of four dimensional figures-- this has now been proved. I first read of zonahedra in H.S.M. Coxeter's excellent book REGULAR POLYTOPES and in his contribution to W.W. Rouse Ball's book MATHEMATICAL RECREATIONS & ESSAYS.



The star of a zonahedron is a bristle of lines passing through a common point, one line equal and parallel to each zone of the zonahedron.



$$\text{Total area} = 2e(a'+b'+c') + \frac{\sqrt{3}}{2}(b'a'+b'c'+a'c') + \sqrt{3}e^2 + \frac{\sqrt{3}e^2}{4} + \frac{\sqrt{3}e^2}{4}$$

$$= 2e(a'+b'+c') + \frac{\sqrt{3}}{2}(b'a'+b'c'+a'c') + \frac{3\sqrt{3}e^2}{2}$$

where $a' = \cos 14^\circ 28' (a)$

$a' = .9428\ a$

and a is the true length of the zone

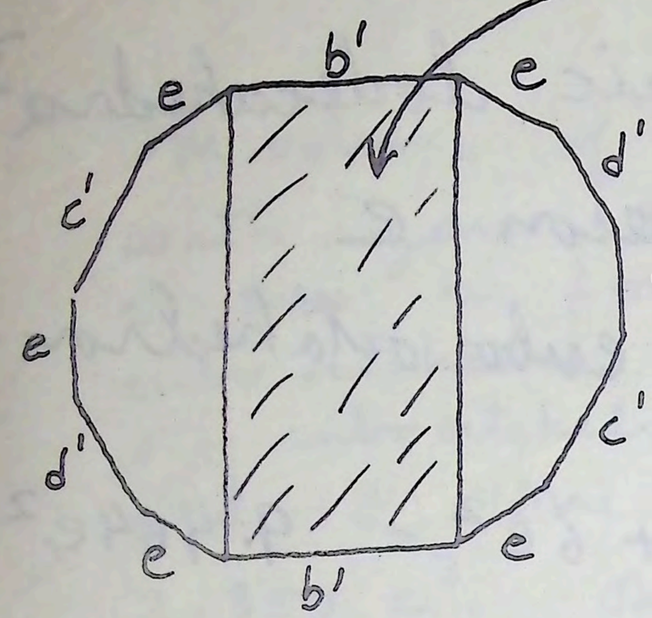
dihedral angles

rhomb - rectangle - 150°

rectangle - square - $144^\circ 44'$

rectangle - triangle - $160^\circ 32'$

(A)

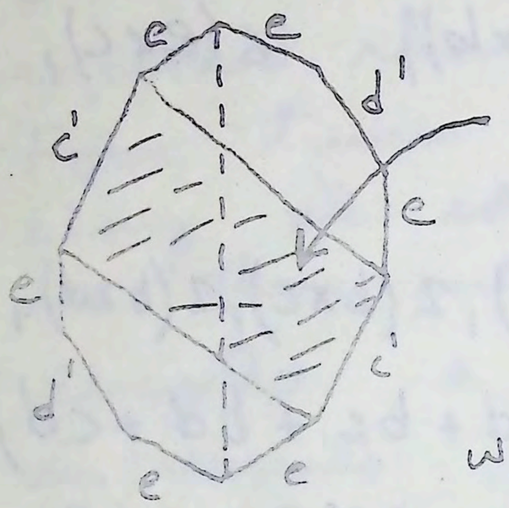


$[2e + \cos 30°(d' + c')]\, b'$

area of shaded portion

proj zone a

(B)

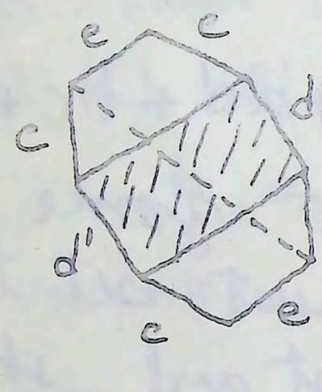


$[2e + \cos 30°(d')]\, c'$

area of shaded portion

proj zone b of figure with zone a removed

(C)

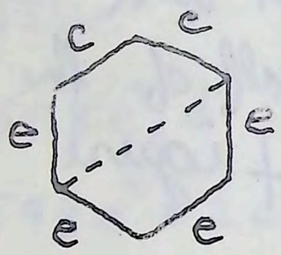


$(2e)\, d'$

area of shaded portion

proj zone c of figure with zones a + b removed

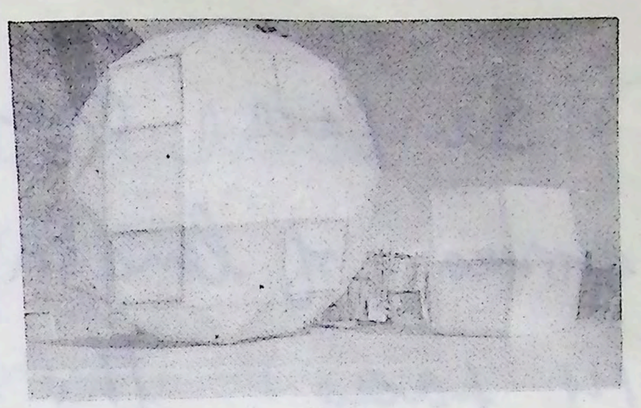
(D)

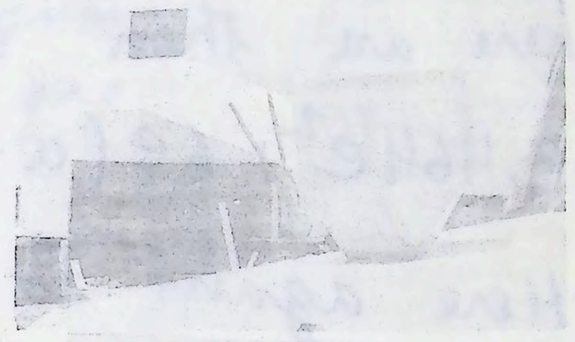


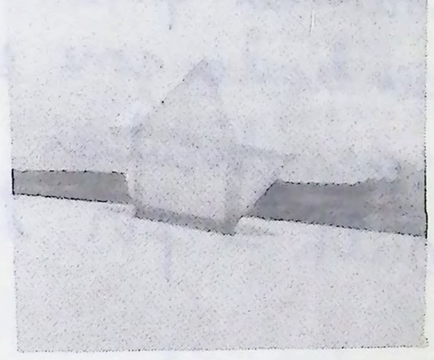
area hexagon

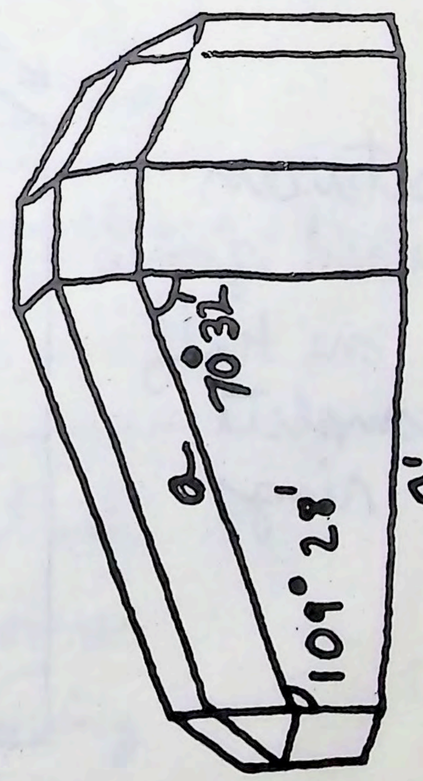
$2.598\, e^2$

proj zone d of figure with zones a, b & c removed









The area of a projection is equal to the area of the hexagon - (D) plus the areas of all the shaded portions below the projection plus its own shaded portion. Thus the areas are

(D) $2.598e^2$

(C) $2.598e^2 + 2ed'$

(B) $2.598e^2 + 2ed' + 2ec' + c'd'\cos 30°$

(A) $2.598e^2 + 2ed' + 2ec' + c'd'\cos 30° + 2eb' + b'd'\cos 30° + b'c'\cos 30°$

Surface area of exploded rhombic dodecahedra

zones of length a, b, c, d and explosion e
14 faces, the faces of the residual cubo octahedron
are dependent on/y on e

surface of cubo octahedron $= 8(.433e^2) + 6e^2 = 9.464e^2$

there are 24 rectangles $6(e \times a)$, $6(e \times b)$, $6(e \times c)$, $6(e \times d)$

surface of rectangles $= 6e(a+b+c+d)$

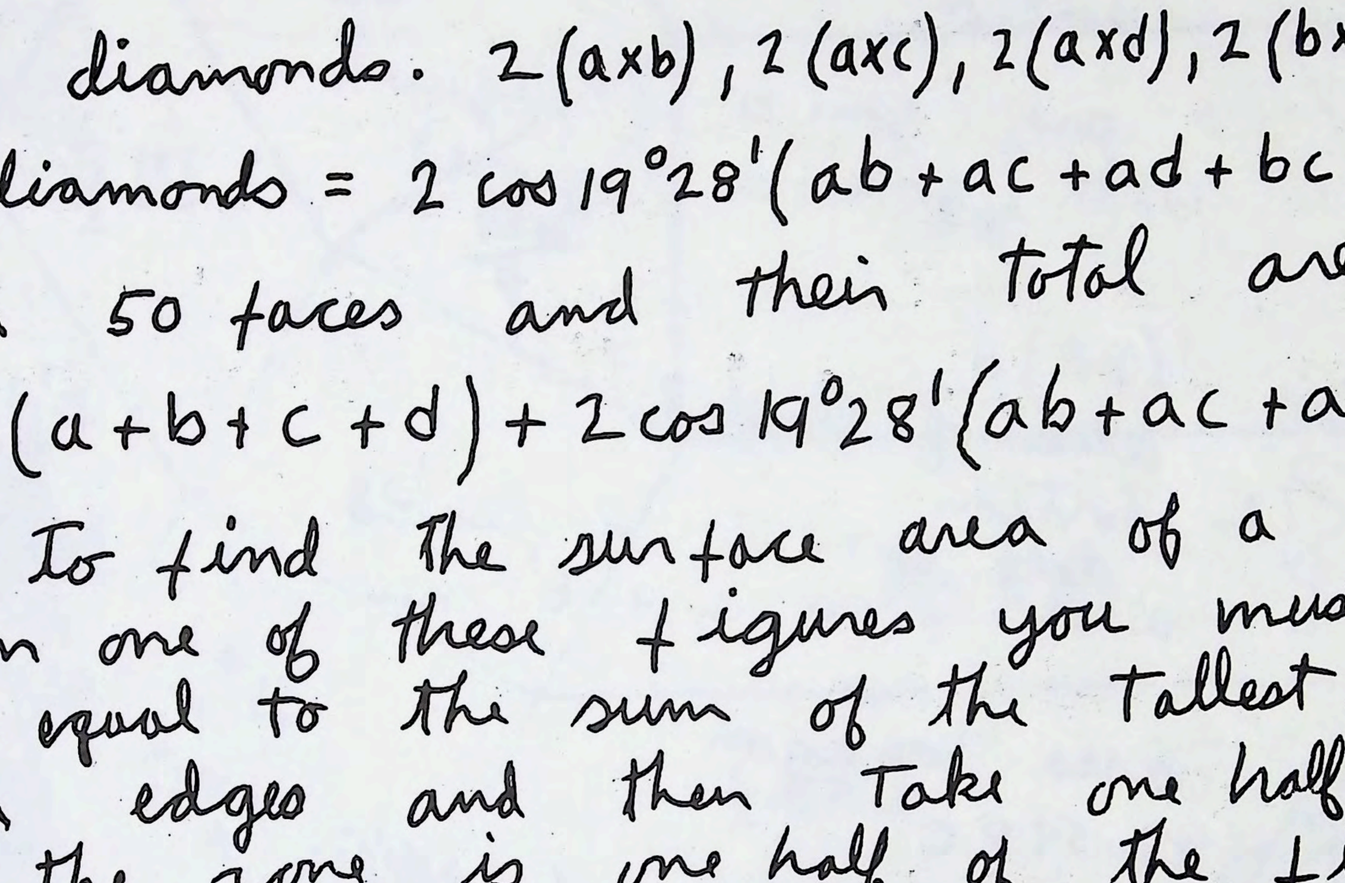
there are 12 diamonds. $2(a \times b), 2(a \times c), 2(a \times d), 2(b \times c), 2(b \times d), 2(c \times d)$

surface of diamonds $= 2\cos 19°28'(ab+ac+ad+bc+bd+cd)$

There are then 50 faces and their total area is

$$9.464e^2 + 6e(a+b+c+d) + 2\cos 19°28'(ab+ac+ad+bc+bd+cd)$$

Here again To find the surface area of a zone produced from one of these figures you must set the perpendicular zone equal to the sum of the tallest and shortest perpendicular edges and then Take one half of the final result - for the zone is one half of the figure



Wall between Two fused zones this is one half of a complete fusing ring

the volume of an exploded rhombic dodecahedron with zone lengths a, b, c, d and explosion e can be found by forming it from a cubo octahedron of edge length e. The volume of the cubo octahedron divides into eight tetrahedra and 6 one half octahedra. this equals $2.357\ e^3$. The cubo octahedron grows to the exploded rhombic dodecahedra in four steps. Four times the growing figure is divided along its edges into two equal parts which are then pulled apart the successive zone lengths. a, b, c and d. These four increments of growth are easy to calculate for their cross sections are the figures (D) (C) (B) and (A) and their depths are d, c, b, a.

VOLUMES

$2.357e^3$ - cuboctahedron

$(2.598e^2)d$ - (D)

$(2.598e^2 + 2ed')c$ - (C)

$(2.598e^2 + 2ed' + 2ec' + c'd'\cos 30°)b$ - (B)

$(2.598e^2 + 2ed' + 2ec' + c'd'\cos 30° + 2eb' + b'd'\cos 30° + b'c'\cos 30°)a$ - (A)

and the total volume of the figure is

$$2.357e^3 + 2.598e^2(a+b+c+d) + 1.886e(dc+db+da+cb+ca+ba) + .7698(cdb + cda + bda + bca)$$

the volume of a zone can be calculated by finding what complete figure the zone is ½ of. This is a matter of determining the length of the zone which has its edges cut by the floor. This zone length would be the sum of the tallest and shortest perpendicular edge.

I sent Fuller a letter almost
I was trying long
what I was back to
what me time
waste the Hz
Takes letters.
& interested

Why Fuller
Geodesic in
on Germany
built in
Kenneth Snelson
tensegrity
The it is
and yet
a
and Fuller
Structure.
Snelson
Shitty to

Talk
name
Hz
But think
invented
you have

heard of
& telling
about end
said his.
were

I bought Fuller's untitled
Epic Poem on industrialization
in London Oct 1963. I had
never heard of Fuller and didn't
know what the strange looking
structure was on the cover. I
believe this is the best book Fuller
has written. I have re read it many
times as I read it I felt as if my
mind were learning to swim. Does
anyone else understand it as
well as Fuller — if so why can't
the rest of us sing about it as
he can?

But what's all this Omni Directional Halo crap
I can't understand it. Or why does he
apply his "Fuller synergetic Treatment" to a
polyhedron why not a geometric transformation
without his name in it?

sounds like
a hair oil

R. Buckminster Fuller

Fuller can
me
Think
what in
will
among
must
it.

learn
tell
my
up
thinking

have
meeting
much
ideas
got
him
more
than
I'd
about
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well

of Modern art

In the last few days I have been working on using the octet truss to make panels for the exploded rhombic dodecahedron zomes. altho it's obvious I had never noticed that the dihedral angle of a tetrahedron was the same as the acute angle in the diamond of the rhombic dodecahedra - and the dihedral angle of the octahedron the same as the obtuse angle. Because of this the regular octet truss can be made up to form parallelograms with just the right angles for these zomes - and the octet truss will also make up triangles, squares and rectangles so every panel can be made up of regular octahedra & tetrahedra But how do you join the panels?

This summer Dave & Bill Karuschke are working with the Libre Community in Colorado building some clusters of zomes. Beny Hickman is planning a 26' dome size built with only one kind of panel and one dihedral angle at Manera Nueva. Ed Heinz is working on new designs at Drop City. Nancy Buckey and some other people are planning to build a geodesic dome whith each Triangular panel bordered by a 1"x3" and filled with rigid plastic foam which will act as the exterior and interior skin plus insulation. I am working on heating and cooling systems - so far without much luck.

I hope this Fall to teach a ~~course~~ class at U.N.M. in which we build a structure and experiment with solar heating. If the course is given it will be open to anyone who is interested.

If people are interested in this booklet I hope to hear about mistakes and hard to understand sections so that I can redo it later.

Steve Baer
P.O. Box 422
Corrales New Mexico

When you are putting up a dome panel by panel you often have to use poles to support the wobbly sides as they close in towards the center. When we were putting up the second to last panel in the shop dome we had three poles in strategic spots to hold the wobbly overhanging panels from collapsing. The poles were nailed at the top so they wouldn't fall away if during a moment's strain the load were lifted up and off of them. The panel was an 8'by 19' and extremley heavy. We put it up with an inadequate crew, two men and two women. We struggled for an entire afternoon the last few inches Albert Maher pushed from on top of a spool resting on top of the cab of his pickup which we had driven into the dome. It was touch and go a clamp might slip, Albert might collapse, the poles might buckle. Each one of many failures seemed equaly probable as getting the monster joined to the neighboring panels. A huge shove, some quick work with the crow bar and clamps--Albert eased off and it still held, I took a few more turns on one clamp and added another one-- it was a sure thing, we had it in place!

It felt as if the panel had been lifted into place by some incredible wave we had created that now washed back as we put down tools and Albert got down off the cab. But there was one last thing to check-- the poles, were they dangerously bowed under this new load. The entire sensation in my head began for a moment to turn inside out when Holly yelled "look at them" but then I saw what it was- the dome was finding its shape, it had lifted all three heavy poles off the floor, they were hanging from where they had been toe nailed at their tops, swaying slowly. Three important pillars transformed in one moment into three dangling slow swinging pendulumns.

Are we working at a new society- load sharing intelligently put together, one that will someday reveal the load bearing pillars of today's arrangement as totaly unnecessary.

Will these pillars of society as they feel the structure trembling to lift up and away attatch themselves hoping to hold it down, hoping to keep the status quo. Will that be a joke- something pretending to carry while being carried/?

Books -

Lyusternik - Convex figures and Polyhedra
Dover Press - inexpensive $1.50 clear introduction

Fejes Tóth - Regular Figures MacMillan
good illustrations- clearly explained - some of it very advanced - I haven't read much of it.

Cundy & Rollet - Math Models - Oxford Press
good illustrations - hints about building models - lists dihedral angles and duals of semi regular Polyhedra

Coxeter - Regular Polytopes
MacMillan - explains zonahedra
has excellent historical notes
good illustrations - quite a difficult book

A.D. alexandrov - Konvexe Polyeder Akademie Verlag Berlin very clear and complete book by a great Russian Geometer Not yet translated into English

Keith Critchlow - Architectural Design, oct 65
Critchlow illustrates packing of pairs of figures which I believe he was the first to discover. also excellent illustrations of conventional packing