Collana diretta da Bruno Munari

Quaderni di design

MODELLI DI BIONICA

Capire la natura attraverso i modelli

a cura di Giorgio Scarpa

13

Zanichelli

BIONIC MODELS
by Giorgio Scarpa

Design Notebooks 13

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Zanichelli

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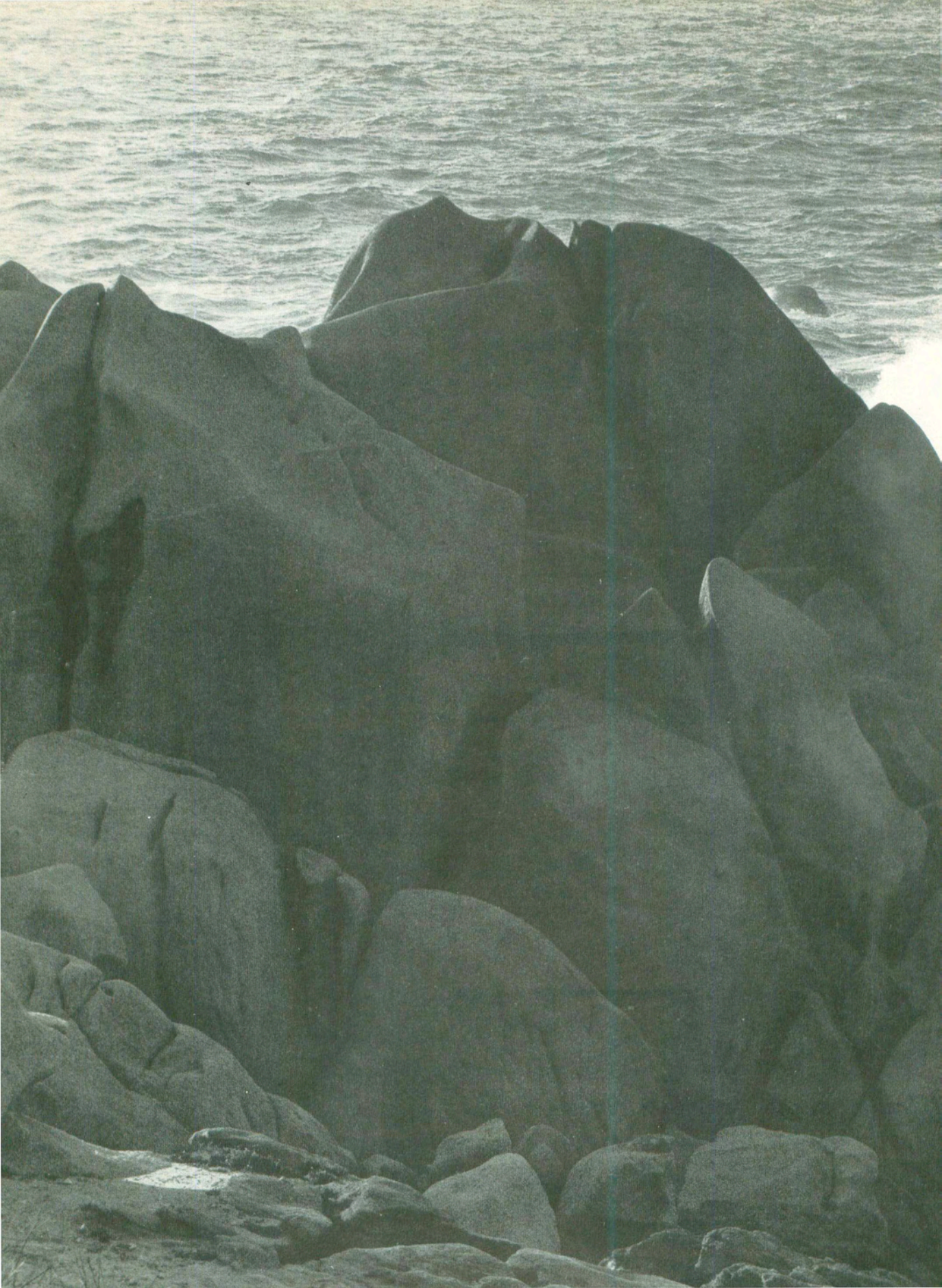
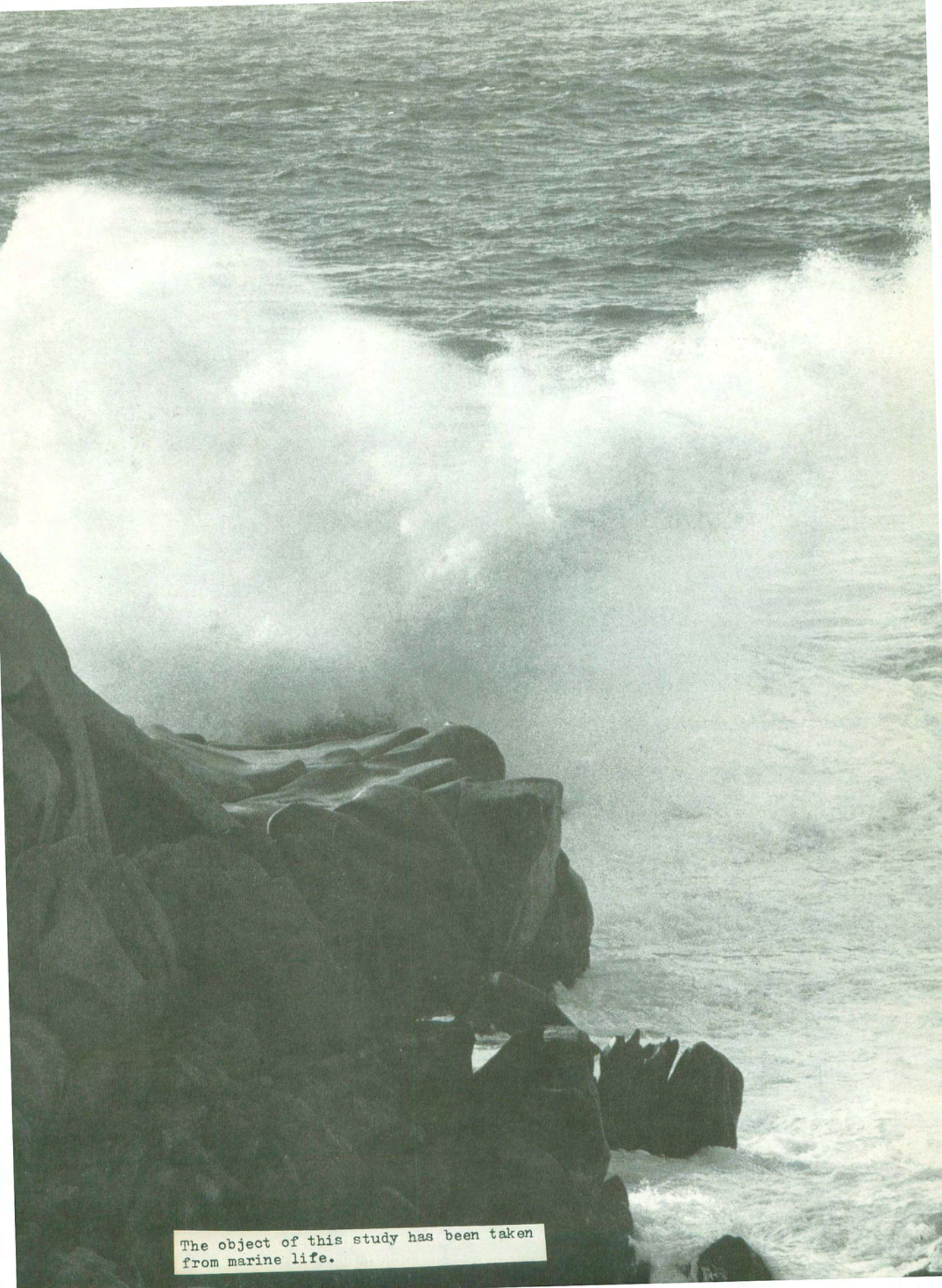
BIONICS

The word "bionics" - its greek root bios means "vital element" - indicates the study of biological prototypes and of functional principles which operate in natural systems. The purpose is to apply the knowledge gained from this study to the design of artificial systems.
To do bionics means to study living systems in order to find out how they work; to learn how to apply what we learn from the living systems towards the solution of technical problems.
The study of bionics can also be seen as a particularly interesting tool which helps us to look closer, to observe things longer and with more profit. To evaluate visual perceptions and information in a less approximate way.
It enables us to become more conscious of tactile perceptions, to enrich and stimulate our knowledge of natural phenomena.
In fact, in asking what we can learn from a moving, jumping, trailing or swimming animal, from the shape of roots, or an egg shell or fish... there is already an implicit answer: more attention, consciousness, interest for the strangeness and beauty which can be found in natural phenomena.
One might ask if there actually exists a subject of study called "bionics", with its own standards based on interpretative schemata of the phenomena it deals with.

Made up of commonly accepted rules among the scientists who, with their experiences, constantly discover new things in it, interpret it and make it an object of communication open to anyone.
We can then say that the study of bionics is still in its beginning, those who are studying bionic problems are at the beginning of a tiring exploration for which we can't forecast a time schedule. Neither can we forecast the results of their research. The few ones already available represent the first marks inprinted on an almost unknown terrain.
But despite these difficulties, we must say that the answers to the problems which we did not know how to attack, seem today a little closer.
It seems nearer, for example, the ancient man's struggle to be able to substitute organs, tissues, parts of the body which no longer work, with replacement parts which derive directly from bionic studies.
One example is the possibility of studying the structure of the human bones by means of space technology, in order to construct working models.
The aim of this research is to construct replacement parts for the human skeleton which would have such characteristics as to keep to a minimum the variation of the structural functional equilibrium, if they are being used as substitutes for the original parts.
To improve the therapy for critical burns, experiments are being conducted in order to construct new types of synthetic skin which has similar functional characteristics to the human skin.
Electronic eyes are being designed, devices to bring back the lost sense of hearing are being studied. Artificial heart, arteries, tendons, arms, are being constructed, and arms controlled by computers, too.
The movement of the human hand is being studied in order to supply the computer with a universal hand which will be able to grab any object.
In current research, the mechanical analysis is based on the decomposition and analysis of all the elements that make up the movement of grabbing an object.
The starting point is the study of all possible forms which can be manipulated by the hand, in order to define the optimum grabbing points.
Jumping machines are being built, some keep their balance only if they execute jumps similar to that of a kangaroo. Walking machines are derived from the study of the typical locomotion pattern of insects.
The construction of these prototypes is made possible by using tools such as high-speed cinematography and microchips.
For example, high-speed cinematography makes possible the observation of the gliding movement, with no balance problems, as performed by the six or more legs insects have, half of which can be used to provide a continuous stability on three points at any given time.
Microchips allow the control of these "legged" machines.
Experiments conducted with these devices help understand the dynamics of walking, running and jumping movements.
Another example: insects, which have a body protected by a series of skin layers called hexa-skeleton, offer interesting information to the study of bionics.
The analysis, the study, the artificial reproduction through the use of models,

of this rigid protective covering which can be thick, but becomes thin and flexible around the articulated membranes, allowing all the various movements, can represent an interesting source of design ideas.
Models for bionic studies are plants which must resist to mechanical forces of various nature. They grow - strengthening themselves from the inside - precisely in the direction of the forces which act upon them.
In the never-ending process of multiplication and diffusion of vegetal species, the ways and means, the mechanisms employed by nature in dissemination, represent maybe the most fantastic and unpredictable component of the whole reproduction process.
The study of some surprising properties which are typical of seeds' dispersion mechanisms can help collect new and stimulating information.
It might be that a device derived from rigourous physical studies, which is capable of concentrating light and work as a solar energy collector, is a discovery which nature itself has already made 200,000,000 years ago.
A light collector with similar characterics is in fact found in the eye of an ancient sea anthropoid, the limulus, or horse-shoe crab. An animal that is, in some respect, much like a living fossil, closer to spiders and skorpions than to crustucians.
Of course one must draw a distinction among the innumerable objects which are offered by nature to the bionic study, and closely evaluate the problems which might derive from a hurried, overoptimistic choice.
A leaf, a seed, a shell, a sprout, are easy-to-find objects of study. They can stimulate curiosity and therefore represent a starting point in beginning to know some of the innumerable aspects which characterize natural forms.



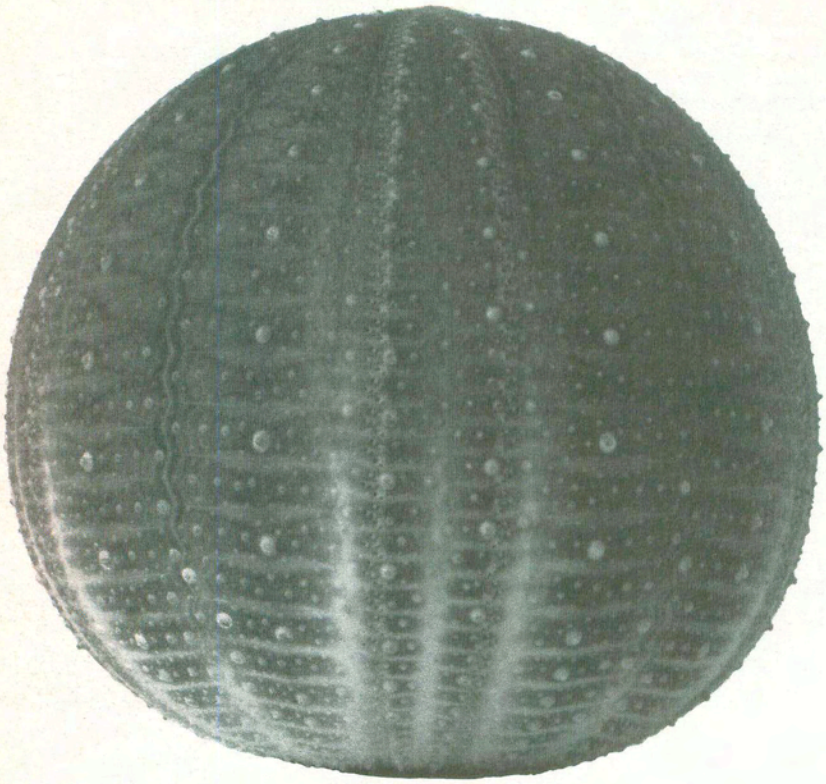


The object of this study has been taken from marine life.

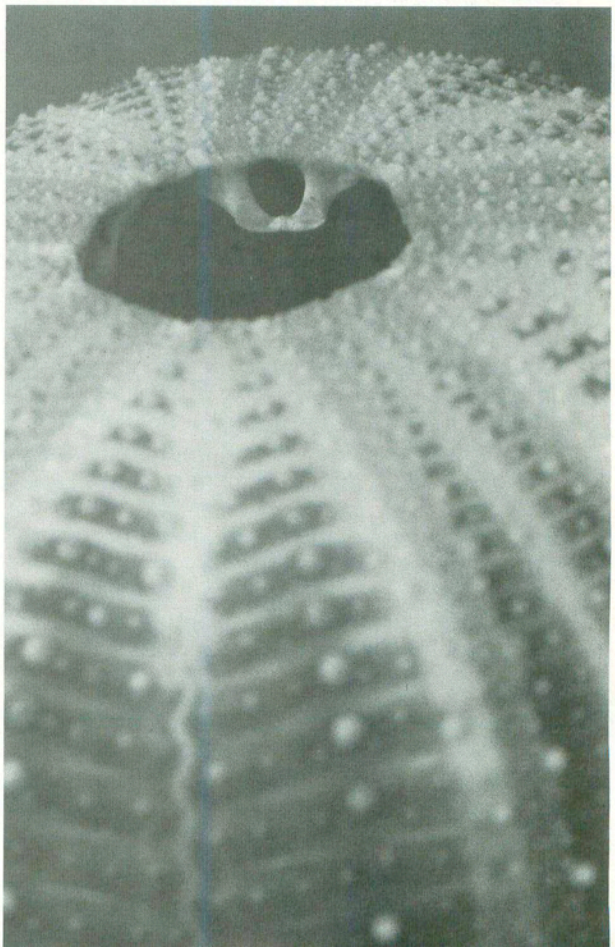
Echinus esculentus (sea urchin)

THE PROBLEM

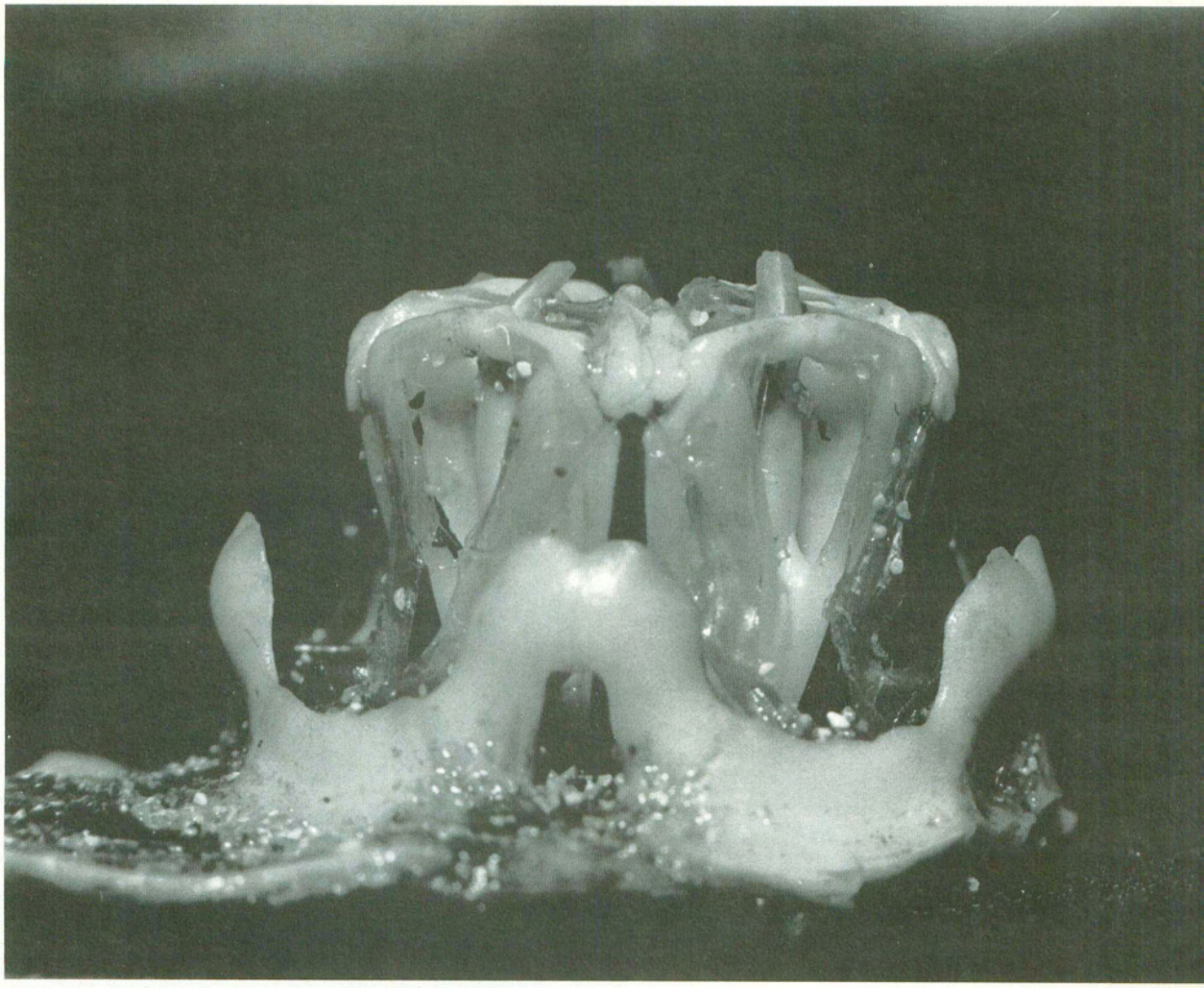
At first there is a problem which has to
be faced, defined, and if possible,
eventually be solved.
The elements of uncertainty and perplexity
can be numerous and diversified.
First of all, we must thouroghly understand
the difficulties, then focus on the objectives
we would like to achieve and try to
clarify why we will make certain decisions.
The analysis of the problem must help us
in finding , in evaluating and modifying
the possible solutions; it will help to
look for, experiment and, when necessary,
pick new solutions.
Yet, in this initial phase, it is hard
to have a clear perception of the nature
of the problem.
We are not even sure that there is only
one problem or more and which ones they
are. It is not easy, therefore, while
facing a problem, to figure out where one
must begin, what to keep and what to
discard.
We try to find the starting points, the
most efficient ways to procceed, discover
things which can lead us in a promising
direction.
There is no single direction based upon
which one must procceed, to begin to build
some form of knowledge related to the
object of study. Also, we can never be
sure that what we see and think of the
object coincides with a real problem
related to the object itself.
A problem whose solution we value as
important can loose its significance
when we modify our approach towards it.
On the contrary, unexpected developments
can come out of an apparently uninteresting
problem.
Some relevant aspects of a problem can
be hidden by a small difficulty which
blocks off an important passage for its
solution.
Often, one must study a problem for a very
long time, before being able to solve it.
There are no short cuts, special ways,
magic sticks which enable us to quickly
arrive at the solution.



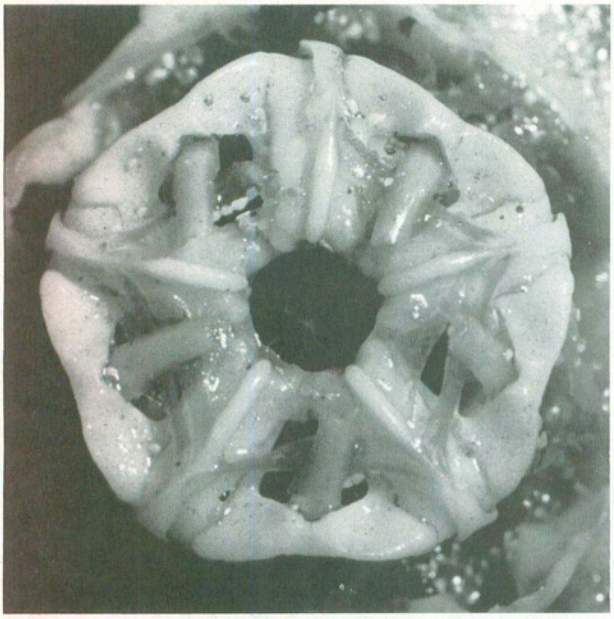
Sea urchin shell with no spines.



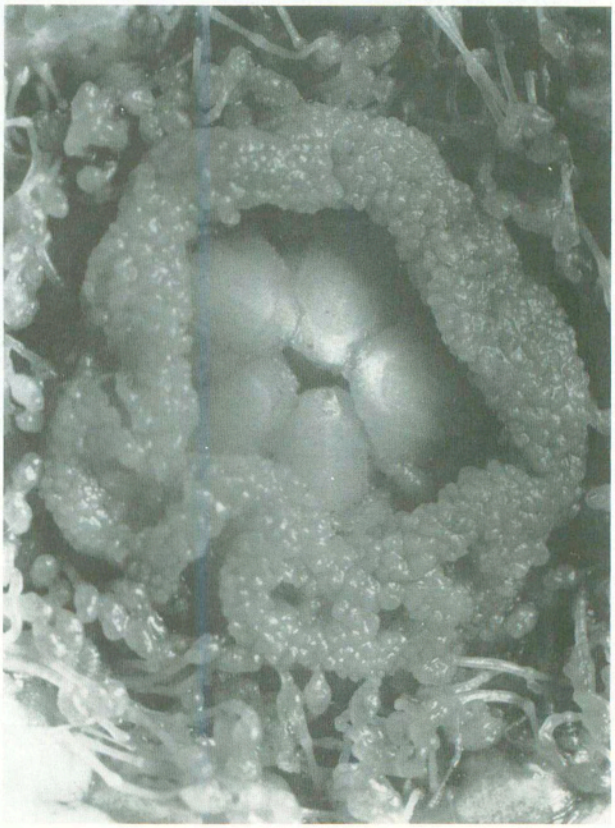
The same shell upside down. The mouth opening is visible.



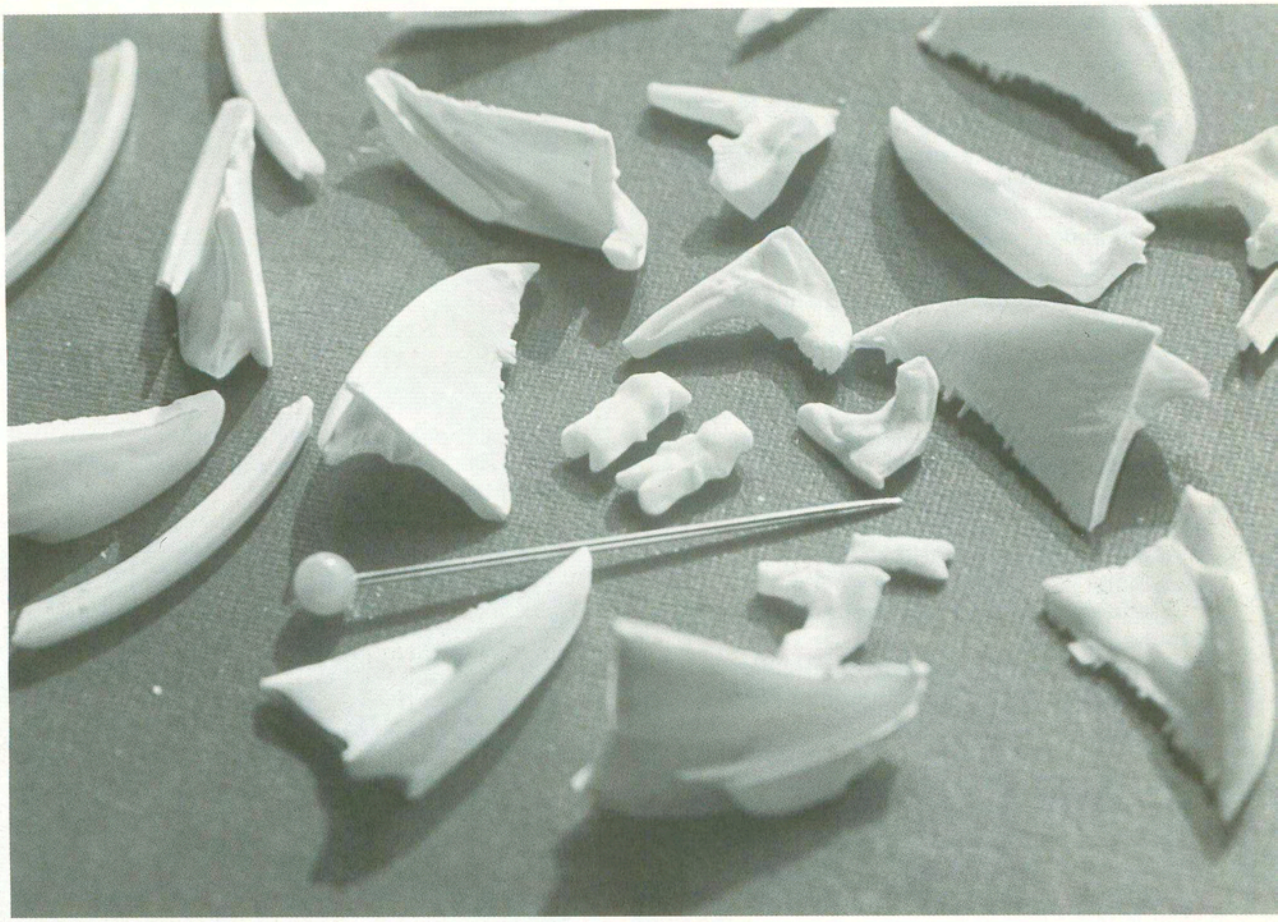
The complex calcareous structure which enables the sea urchin to swallow food and dig holes and niches in underwater rocks.



The structure shown on page I3 is seen here from the top.



The structure as seen from the bottom. Five partially overlapping teeth are visible in the center of a membranous area surrounding the mouth.

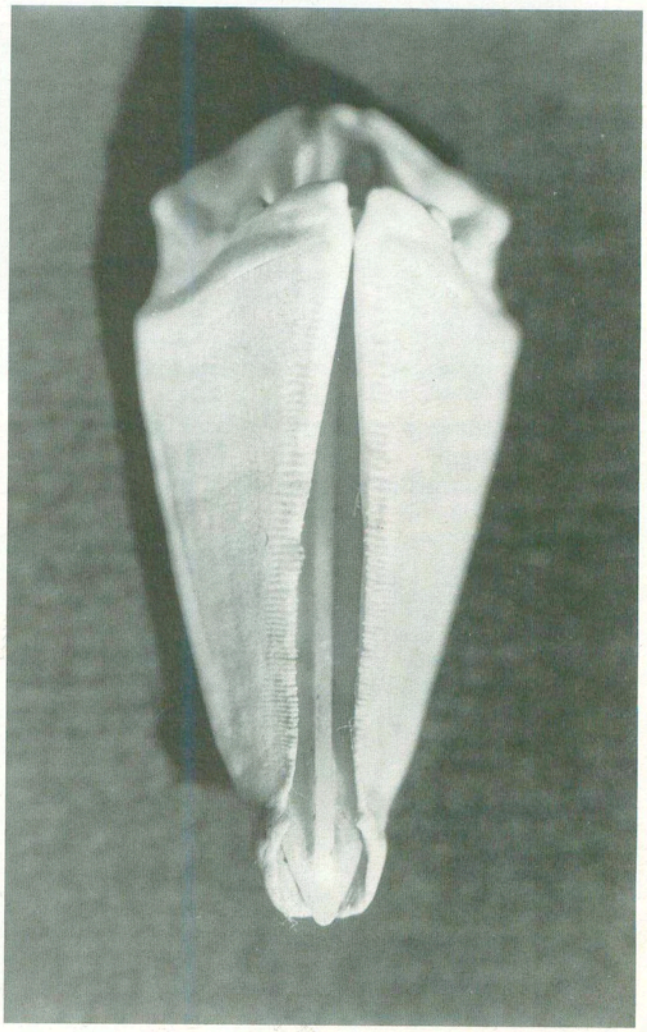


Calcareous pieces which form the skeletal structure. The pin shows the dimensions of the parts.

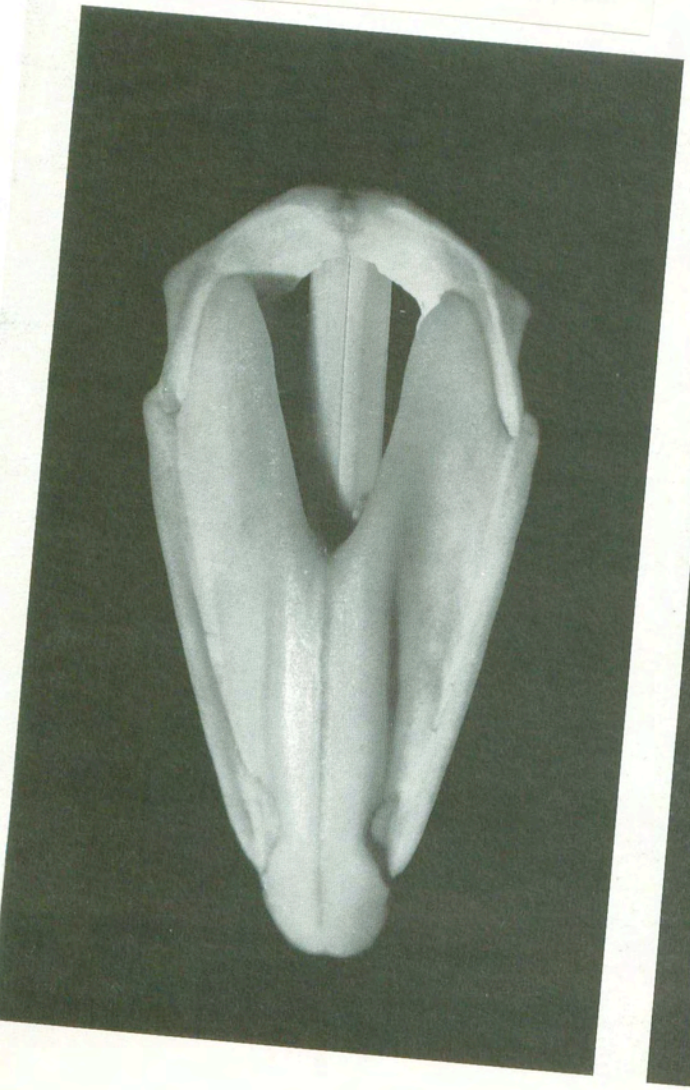
FIRST OBSERVATIONS

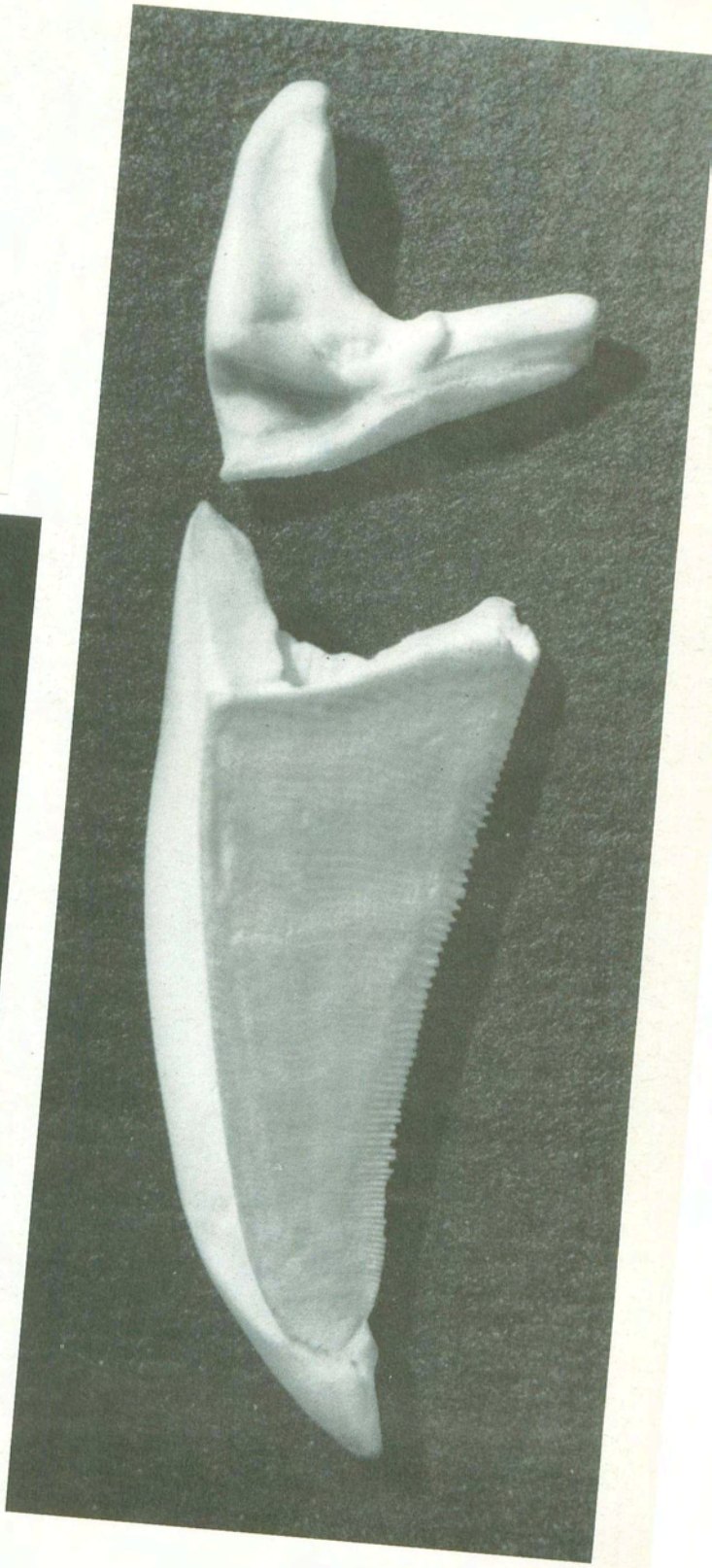
The mouth of the sea urchin opens in the center of the lower extremity of the shell. It is composed by a membranous surface, by numerous and various forms which surround a skeletal structure called "Aristotele's Lantern", which is connected by muscle bundles to the inside of the shell.
This "Lantern" functions as jaws.
It is a complex structure composed of calcareous articulated pieces.
The various pieces can be easily examined: they are solid, do not deteriorate, do not alter over short periods of time. On the contrary, the soft parts which connect these pieces tend to deteriorate and quickly modify their original form and characteristics.
The lantern is tightly connected to the muscular structure and is dependent from it in its movements.
It can be easily observed that the muscular structure, which is correlated to the movements of the whole mouth apparatus, is a highly complex system. The movements are barely visible from the exterior of the shell. We would have to be inside the sea urchin in order to catch the essence of these movements.
The collecting of sea urchins on the sea shore can take place at various times, sometimes by chance. The sea urchins are then classified and stored in glass jars after they have been carefully cleaned.
During the washing of the lanterns, some elements might detach from the rest and show that they are made of smaller parts.
The pieces are counted.
The analysis of the forms begins.

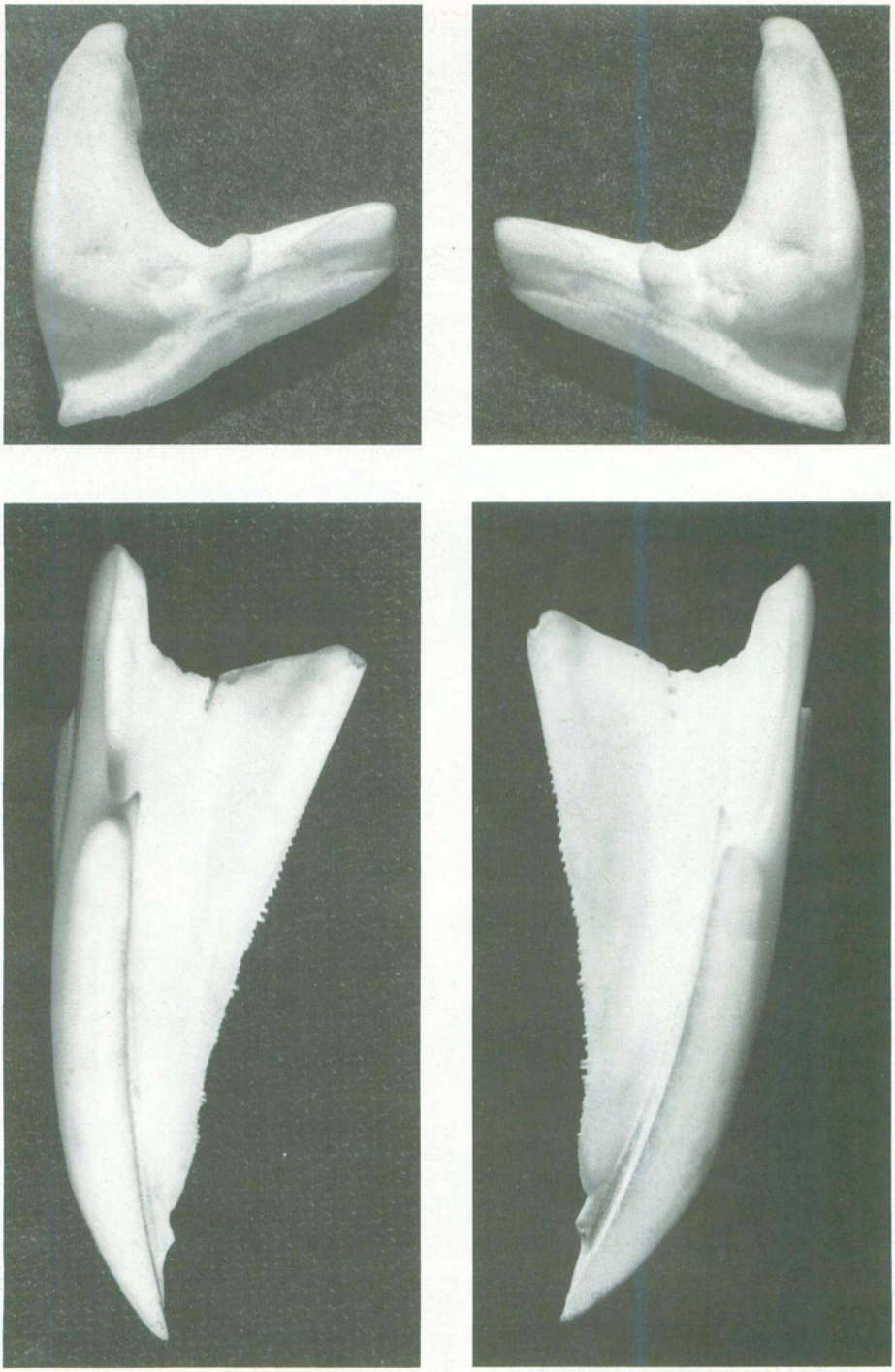
One of the jaws seen in front view.
A tooth housed in the inside is partially visible.



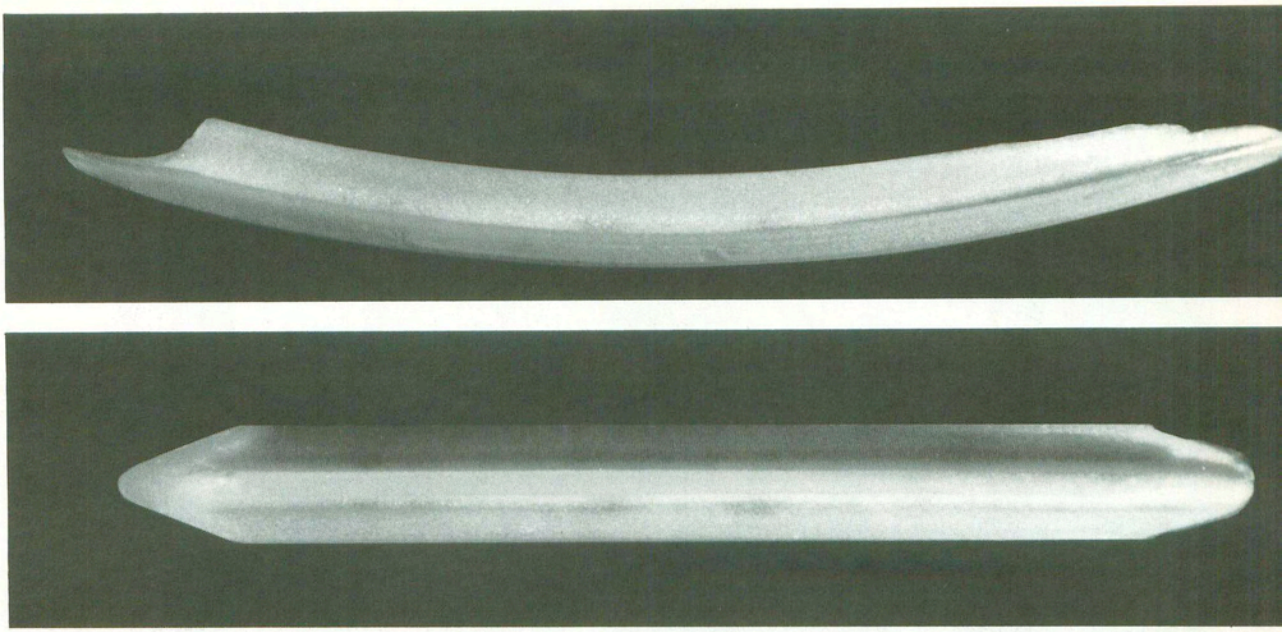
The same jaw seen from the opposite side.



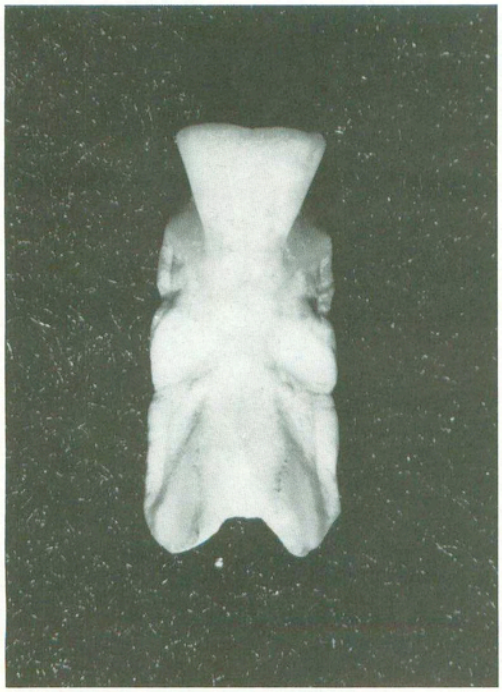


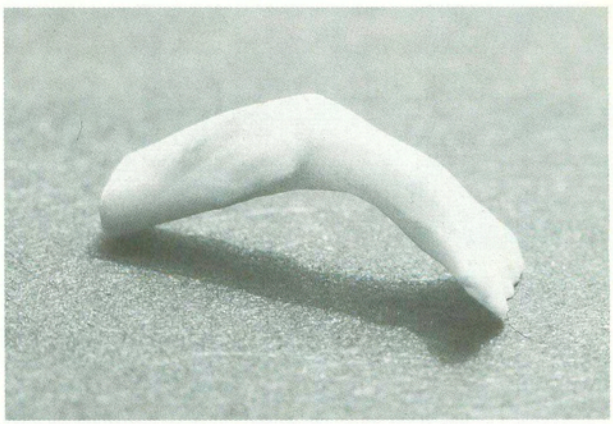


Each jaw can "break up" spontaneously or be decomposed into four parts.

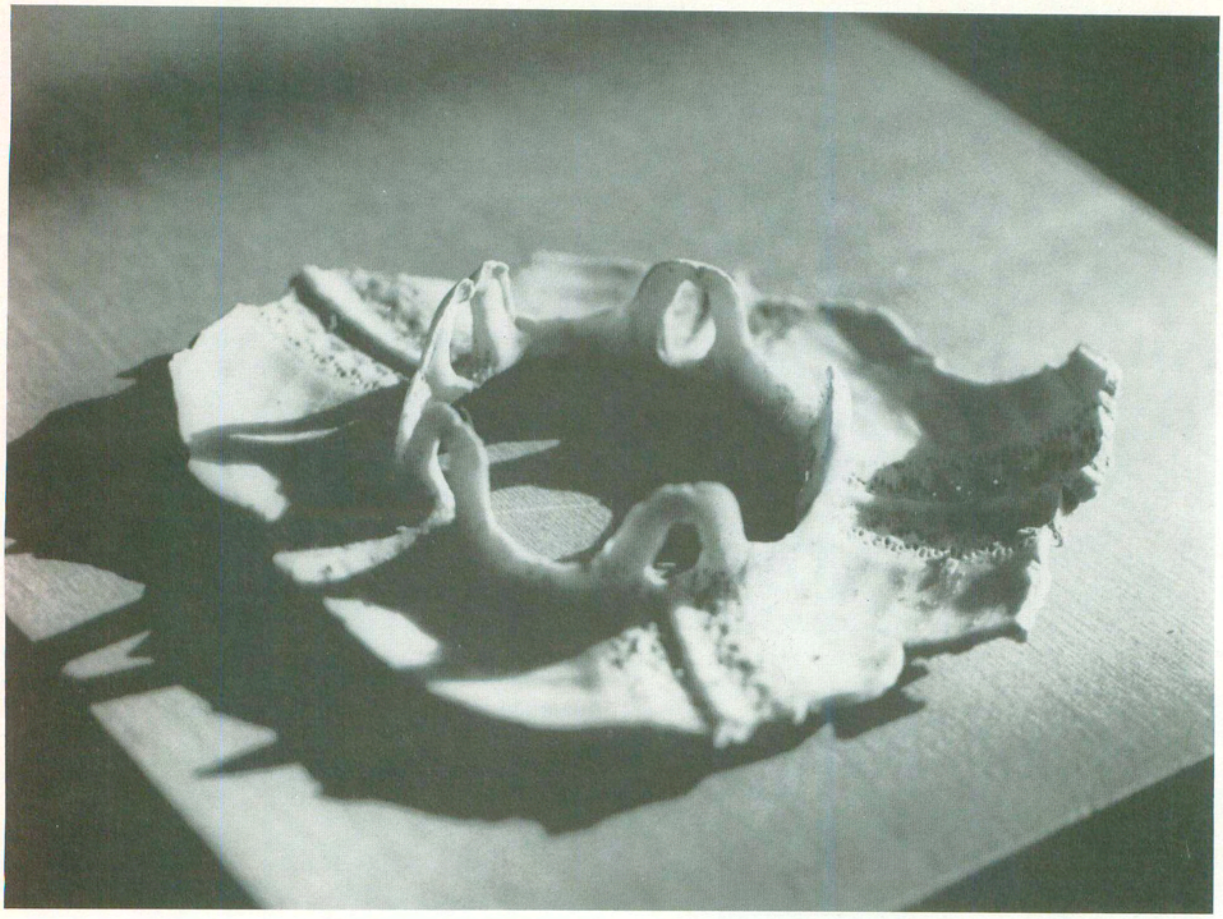


One of the five teeth belonging to each jaw, seen in front and side views.

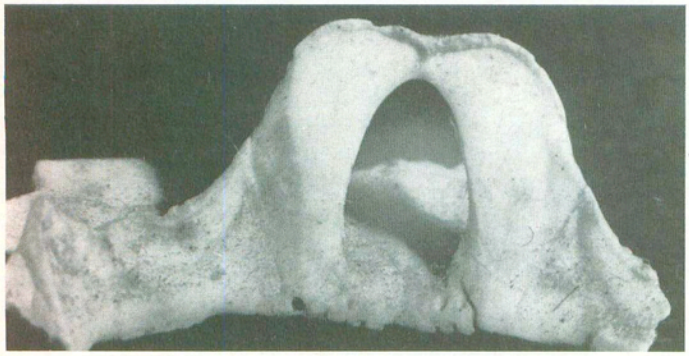




The forms shown above are found in the upper part of the lantern.



Inside the shell, a crown-like structure, surrounding the mouth opening, holds the muscular structure to which the lantern is connected.



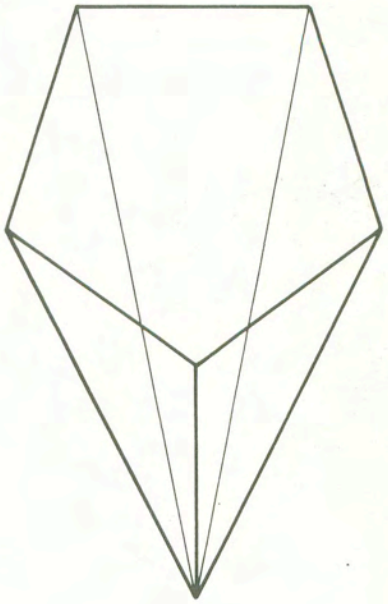
One the five "ridges" to which the muscles are attached - forming the crown - seen here from the front and the side.

THE VISUAL ANALYSIS

First of all we must be able to see easily, and with clarity, every part of the object we are examining.
In Aristotele's lantern, as in the one pictured below, many interesting details are visible, despite the small dimensions, even with a naked eye.
The use of a magnifying lens or of a camera, helps in making more precise and detailed observations and also in discovering aspects of the forms which would otherwise go unnoticed.
The use of macro-photography, which allows noticeable enlargements of the observed parts, is an especially big help in this kind of research.
Whether we look with a naked eye, or with a magnifying lens, or through the view-finder of a camera, what we see appears to be quite complex.
It is difficult to establish relationships, find the essential elements, compare the forms which we see in the object.
The difficulty lies in being able to see the object as a whole.
If we succeed in seeing the object as a set of parts, which are there in a given number, layed out in a given arrangement and in relation to each other, what appeared to be complex starts to get a little simpler.

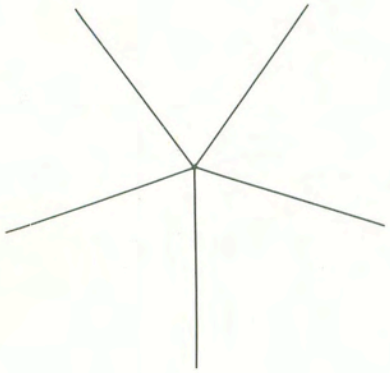
In order to understand the forms, the functions, the behavior of the elements which form an organized unit or integral whole, we can try translating what we visually perceive of each component, into a series of lines, surfaces, and volumes.
The analysis of each part and of the whole formed by the various parts, clarifies why it is possible to see the parts and the overall structure as agroup of more or less geometric figures.
The deciphering work must then proceed in the direction of extending the relationships which can be established among the various components of the object.
This is done in order to attempt translating what we think of the object, what we imagine and remember, what comes out of our reflections, into the mathematical and geometric language.
We begin by studying one by one all the pieces which make up the lantern. We try to put them back together to see if it is possible to discover in what specific way are the forms complementary and inter-dependent.

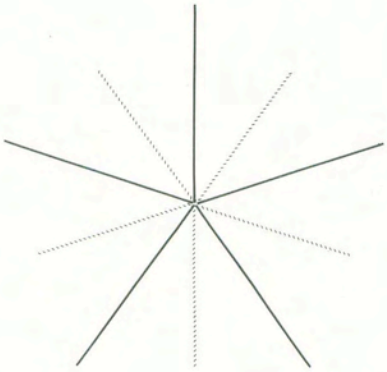
We begin with the first attempts of form analysis:
the lantern in its overall form can be viewed as a right-angle pyramid with a pentagonal base (with the apex pointing down);

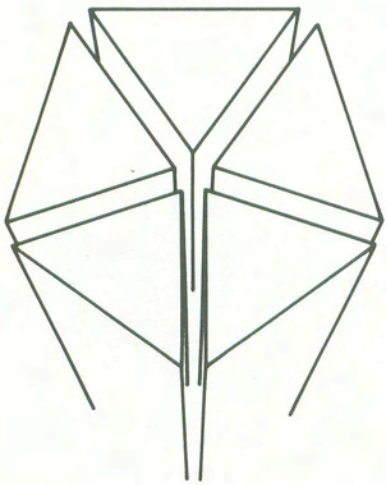


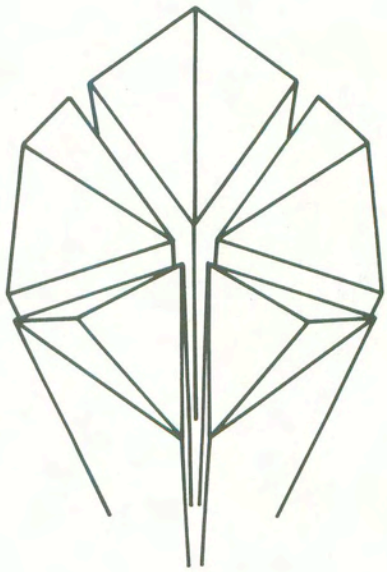
each part composing the lantern can be described and defined by analogy with geometric forms derived from sections of a pentagonal pyramid;
let's immediately note, observing the lantern, its pentamerous symmetry;
a five-side pyramid sectioned along the symmetry axes passing on the vertexes of the pentagon, breaks up into five tethrahedrons, all equal in shape and dimensions;

one of these tethrahedrons can be assimilated to the forms which make up part of one fifth of the lantern's volume;
the analogy with the forms which are visible in the lantern is still very approximate;
the volume of the lantern appears to be better defined if we overlay five tethrahedrons to the five ones of the preceding drawings and then section these forms along their symmetry axes passing on the pentagon's median points.

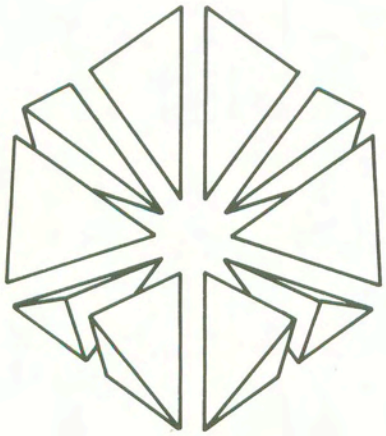


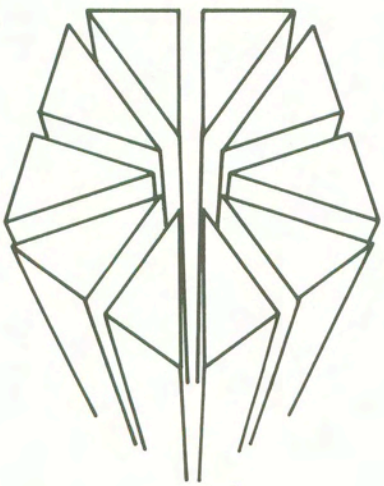


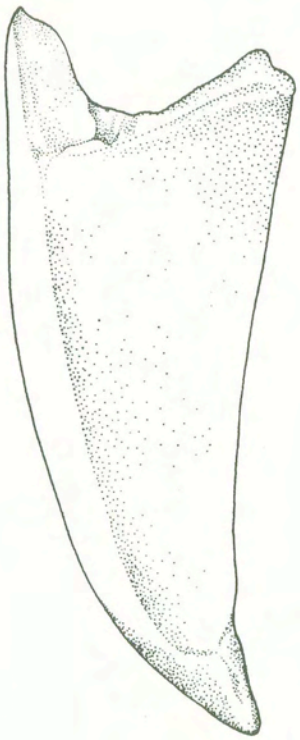


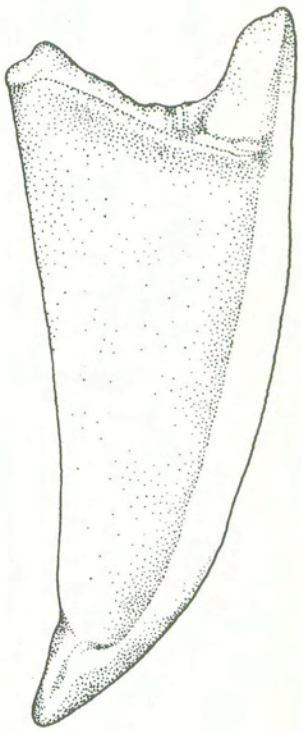


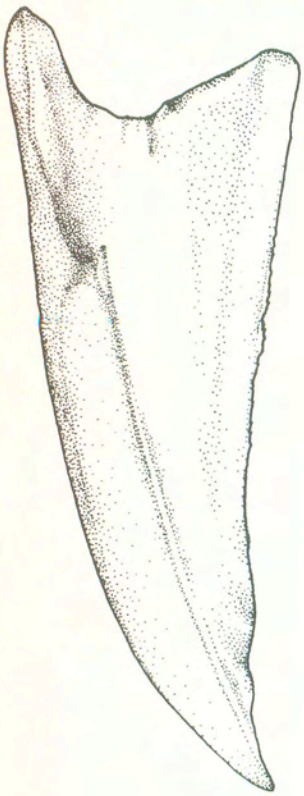
In order to understand the forms in the lantern which seem to have a direct relationship to the articulating structure and to the movements of the whole, let's make some analytical drawings of each piece. With these, it will be possible to better visualize the symmetry of the lantern.

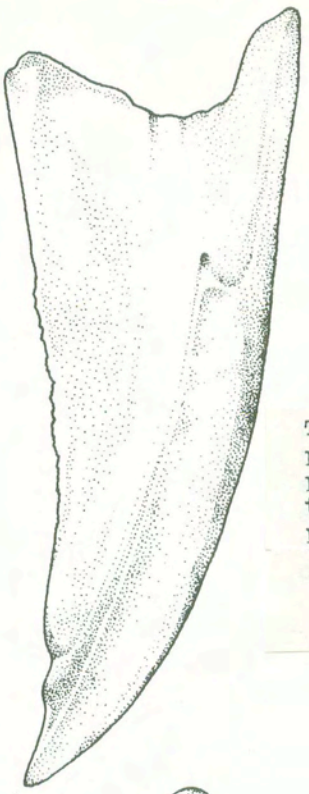




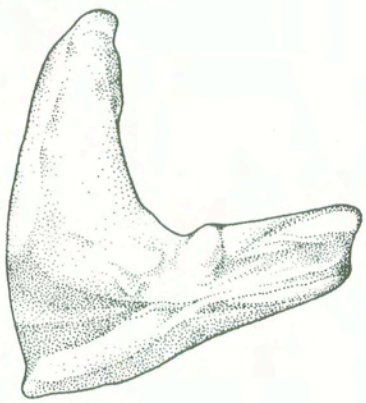


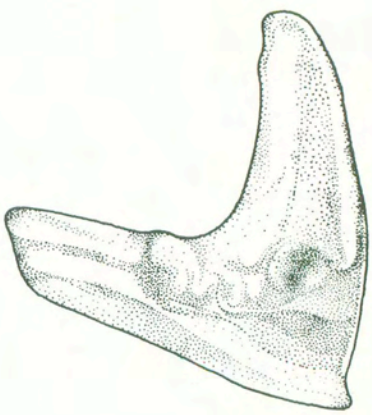






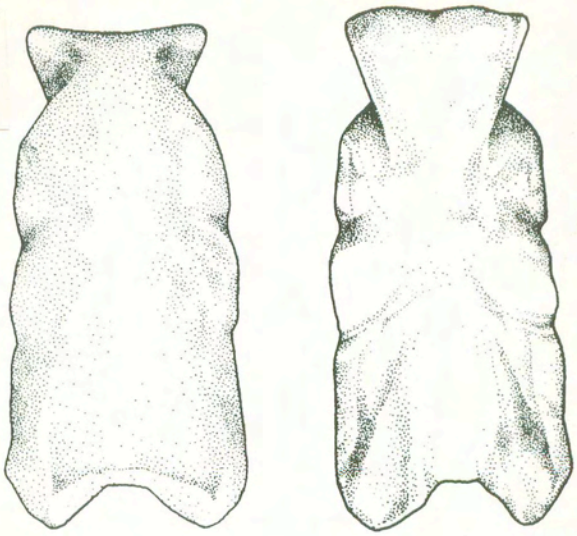
The lantern is composed by thirtyfive pieces: five jaws which break up into ten parts having bylateral symmetry in respect to five symmetry axes passing on the median points of the sides of a pentagon;

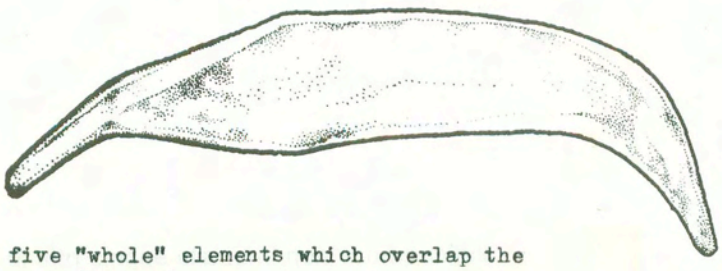




five elements which detach from the top area of the jaws, each being decomposable into two parts, also having a bylateral symmetry which is determined by the same symmetry axes of the jaws;

five "whole" elements which are placed between a jaw and the other, and laying on the symmetry axes passing on the vertexes of a pentagon;

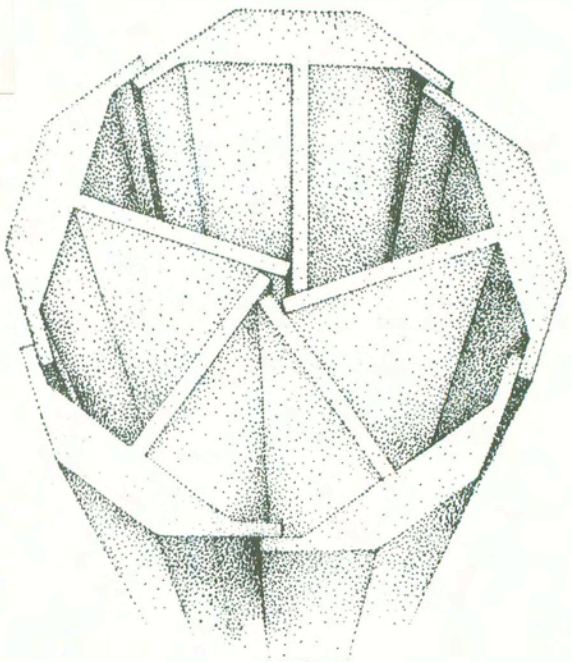


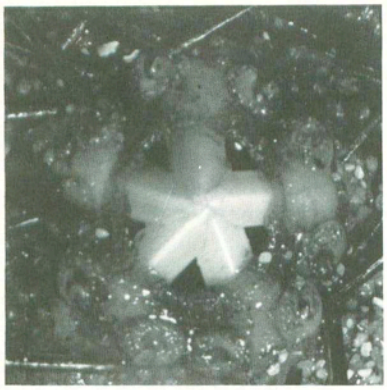


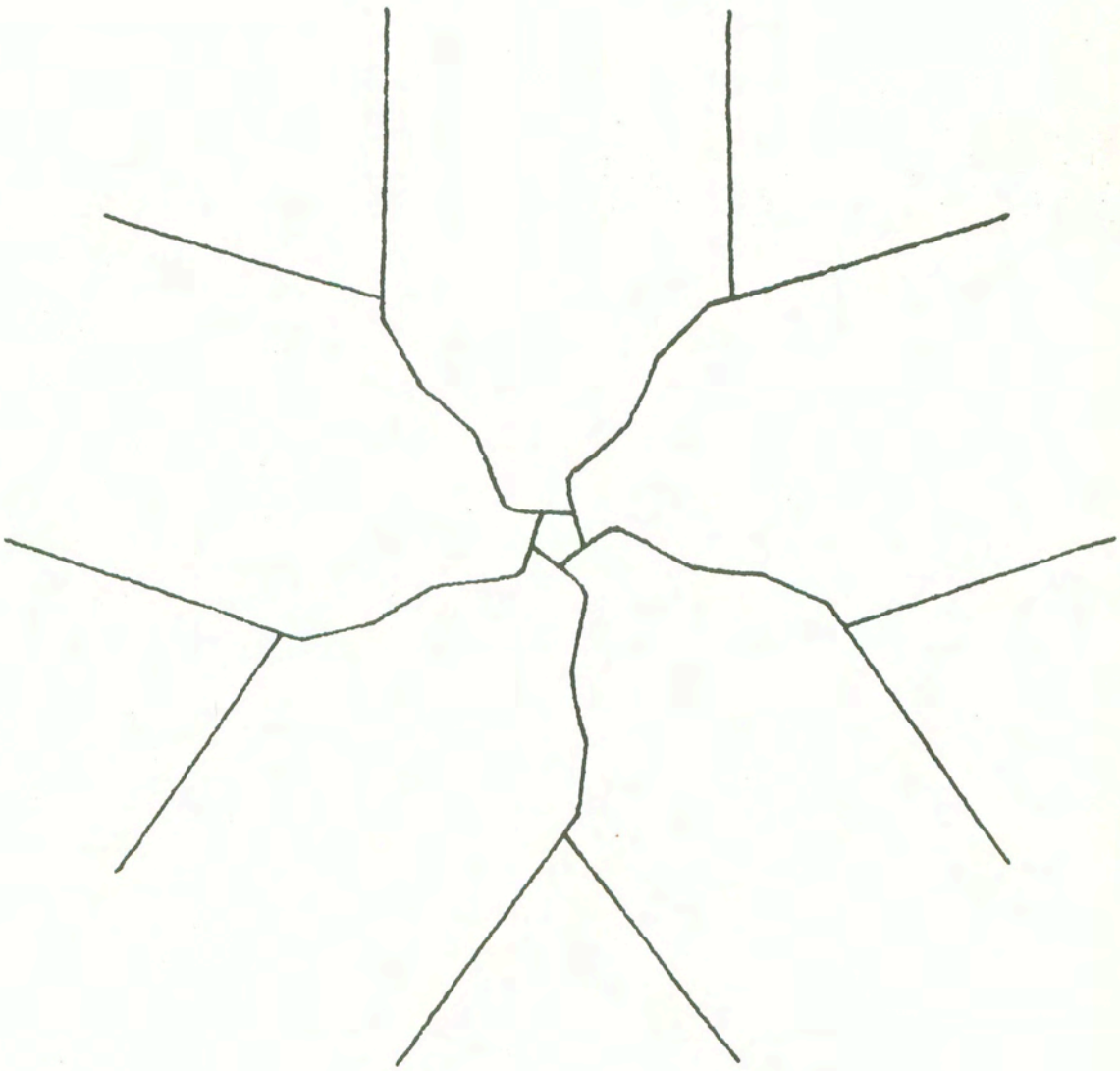
five "whole" elements which overlap the preceding ones;

five "whole" teeth located on the symmetry axez passing on the middle points of a pentagon's sides.

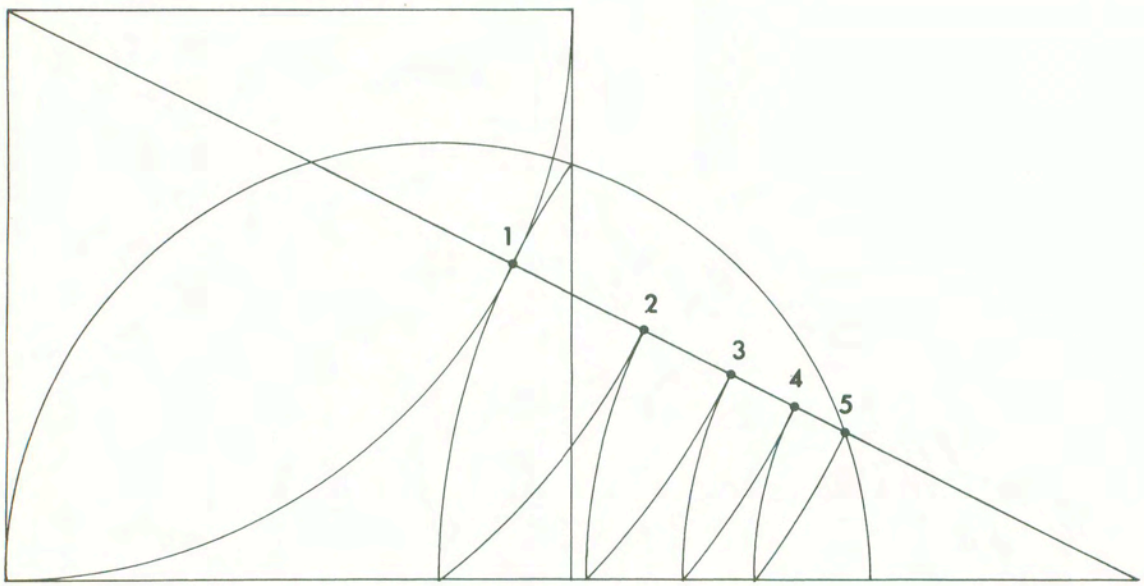
five elements to which the muscles are attached. These elements are actually an integral part of the shell and they must be studied both in relation to the shell and to the lantern.
We will later more closely observe how the specific configuration of each of these five ridges depends upon the symmetry that regulates the division of the shell into sectors.
If we add these last five pieces we get fourty pieces in all.
The teeth of the sea urchin are mobile. From the inside of the jaws, the animal can push them outwards into the external environment, and then pull them back inside the jaws.
If we imagined to observe the teeth from the inside, we could see that their closing system is similar to a diaphragm, the mechanism which regulates the amount of light passing through a lens in a camera.
The drawings visualize a schematic re-construction of the mechanism.

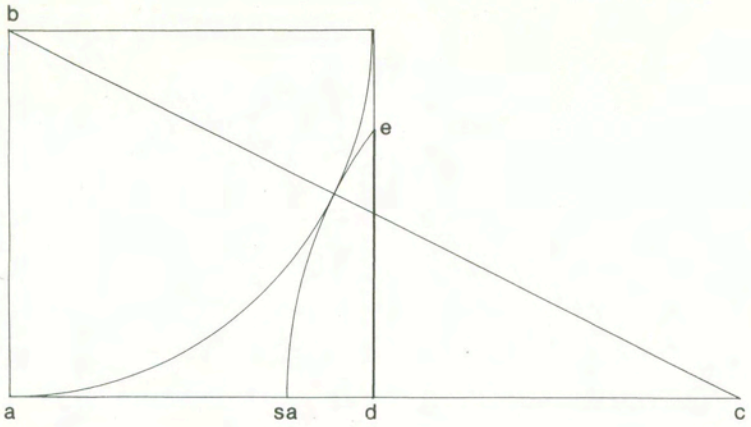






If we section a square along the line A-E we obtain the forms A and B.
Form A and its specular image with which it forms a pair, combined together, originate a polygon shaped like a pentagonal doughnut.
This form reminds us of the configuration of the ten parts (five pairs of parts) into which the jaws of the lantern separate, laying themselves out in radial symmetry around the longitudinal axis of the sea urchin.
Instead, a pentagon with no internal voids is the result of the combination of figure B with its specular image.
By moving the piece A ten times we obtain a decagon (see page 30).
The configuration of the muscle-attachment structure of the lantern seems to have a decagonal symmetry.




b
e
a
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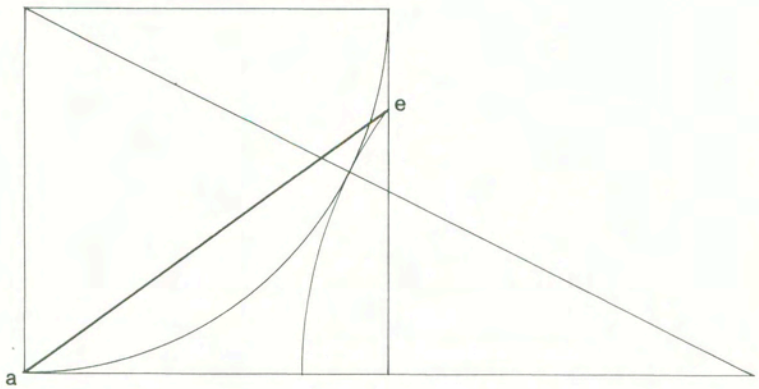
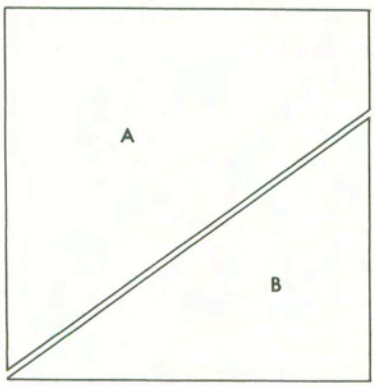
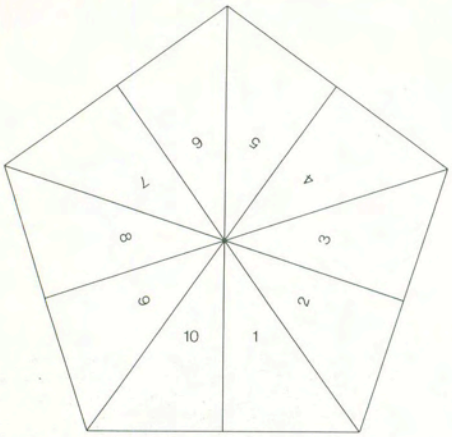
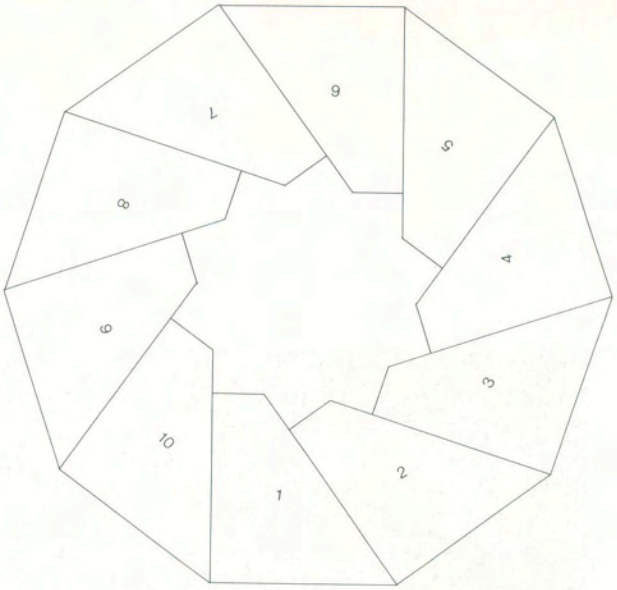
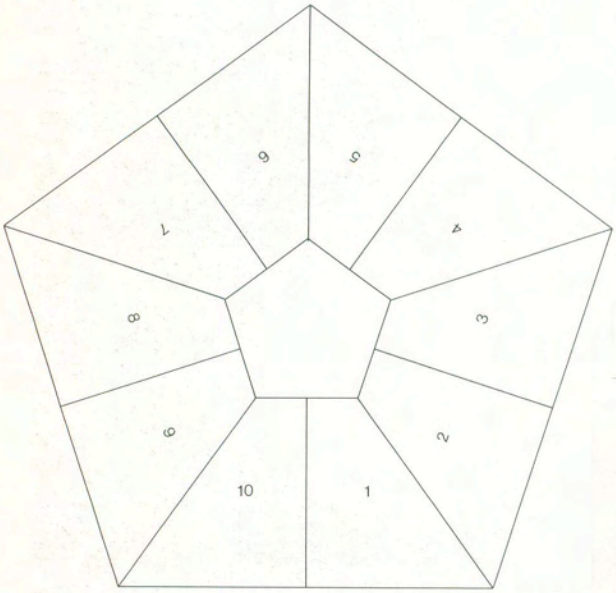

e
a


A
B

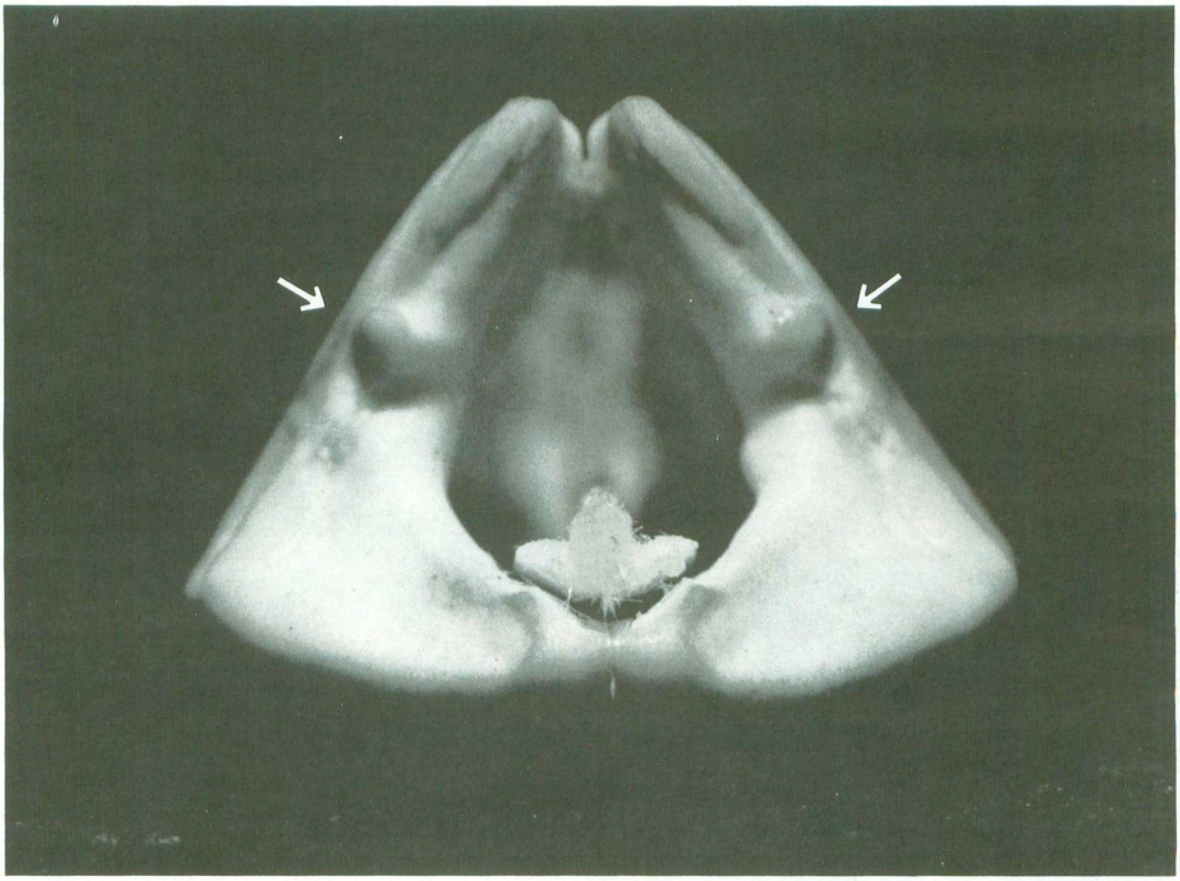




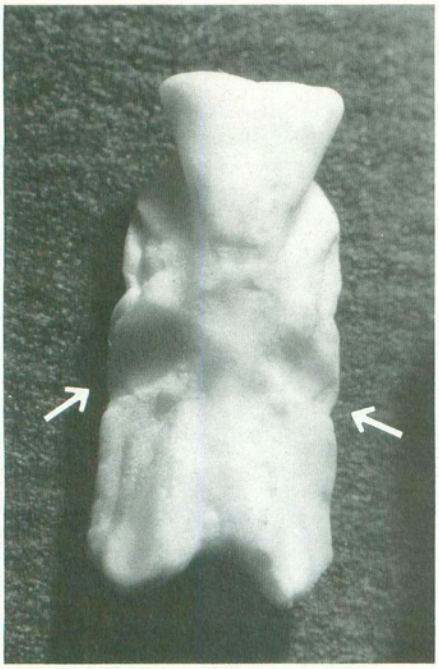


WHAT "NOT TO DO"

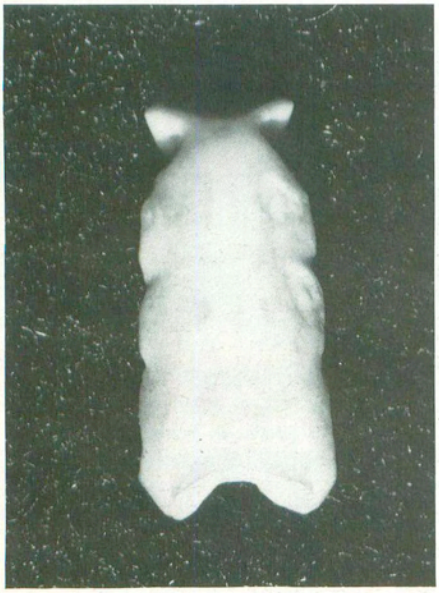
In exploring whst is known and what is unknown of the situation we are going to face, one soon realizes that "copying" would be a very difficult endeavor, and a rather senseless one.
One must not make an external imitation of the chosen natural object.
The analysis we will make of it will help us to understand how nature makes things happen. One should not oversimplify the representation, while concretely describing what one has perceived of the natural object. One should not work too much in detail while designing and building models which simulate the parts of the natural object.
In this way one would not get a good understanding of what is really fundamental in the object's functioning.
One must not be afraid to make mistakes. Sometimes the very consequences of a mistake can become highly stimulating in lieu of the unforeseen aspects which they tend to reveal.

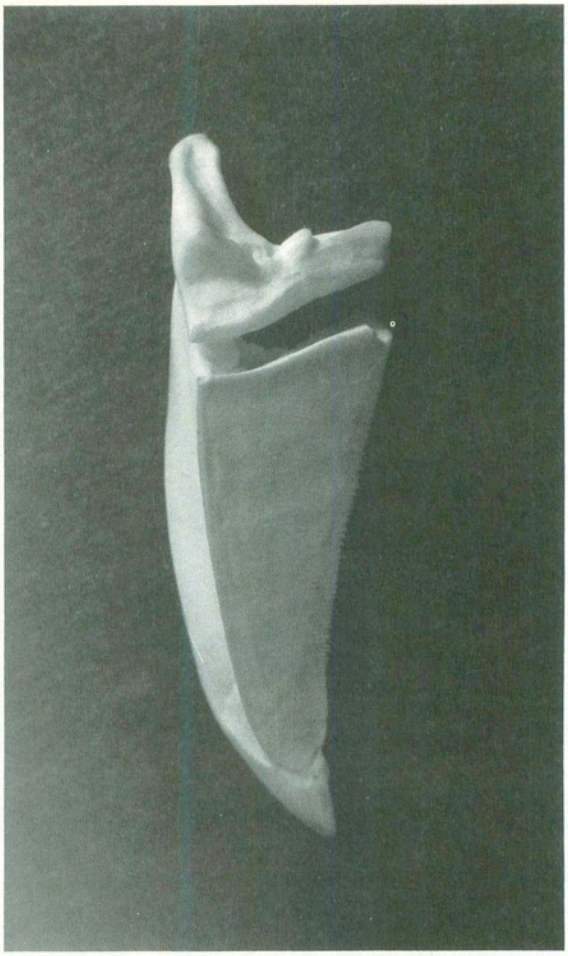


The "break-up" of the lantern into parts helps in the survey of bumps, depressions, cavities; it makes us notice how each part adapts itself to the other, what are the points and surfaces of connection, the knots and the joints.
Jaw seen from the top.
In this picture we see two bumps which correspond to two depressions - indicated by the arrows - in the picture on the next page. They belong to the element which functions as a bridge between a jaw and the other.



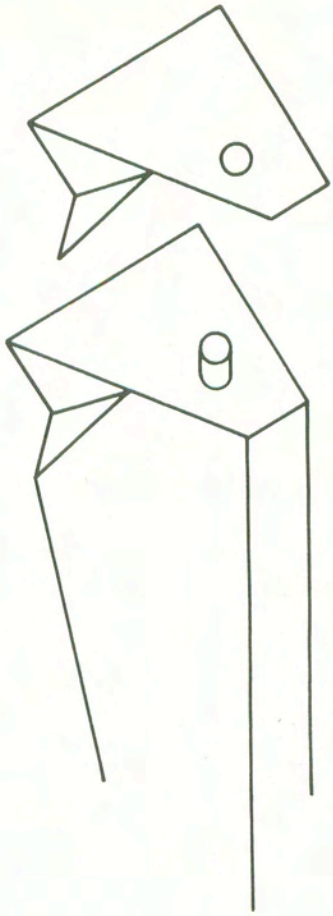
In the upper part we notice a trapezoidal volume with two other lateral depressions. These become more evident if we turn the same piece upside down.





The depression in the upper part of the jaw seen in this picture will accomodate the trapezoidal ridge of the "bridge" plate; ridges and depressions of this plate adapt to complementary forms of the jaw, making for a very peculiar joint.

The drawing whows a partial and schematic interpretation of what seems to be more than just a joint between two complementary forms. These forms will have to be studied in detail, in pairs, and in relation to the whole jaw.

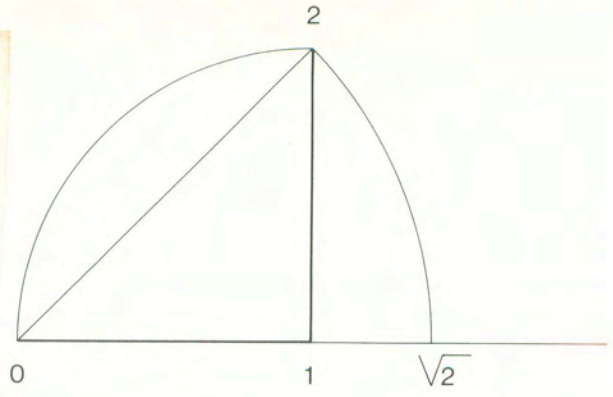


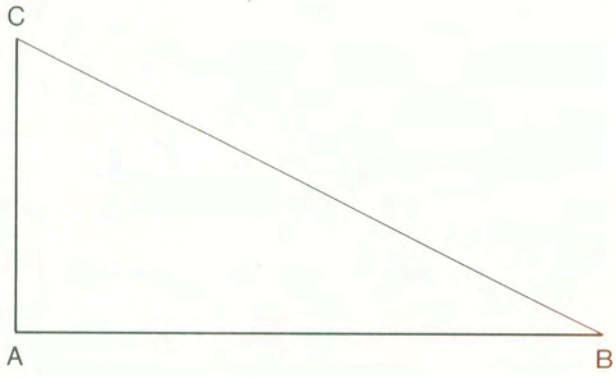
PROPORTION RELATIONSHIPS

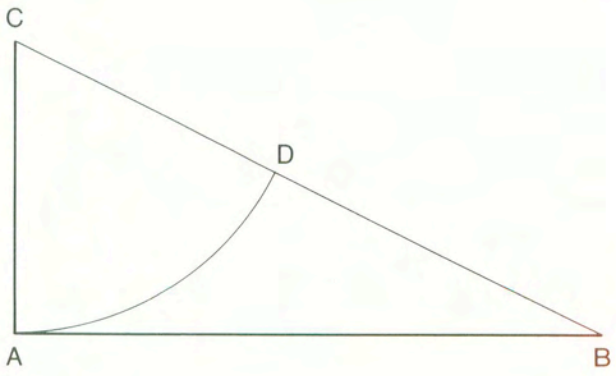
For the sake of simplicity, we can break down the external surface of the jaw into four sides. Two of them are similar to two equal right-angle triangles, the other two are similar to two different isosceles triangles. These geometric forms are relatively similar to the sides of a jaw.
Yet, a better analogy between the natural model and the geometric model is still needed.

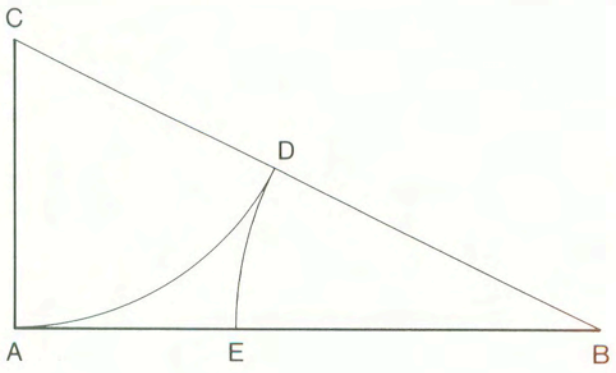
One of the first concrete operations we can attempt will be the designing of a more complex form, as derived from a modified version of the tethrahedron.
We will begin by studying the dimensional/ proportional relationship which we must establish between the two sides of the right-angle triangle. This relationship must be as close as possible to that obtained from the controlled measurements made on the actual jaw.
In order to define this and other proportional relationships between given linear dimensions, or dimensions to be found in the course of this study, we will use two historical examples of a precision tool. This tool will be used in determining certain measurements.

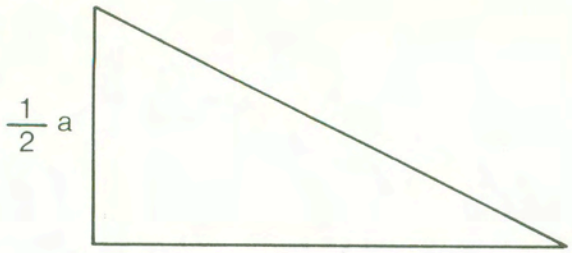
Two thousand years ago the Greeks discovered that the diagonal and the side of a square are incommensurable; in fact the length of the diagonal of a square with side I, which in the Pythagorean theorem is indicated as $\sqrt{2}$, is an example of a length which is impossible to measure by using whole numbers.
Given the segment I-O, center in I, project O-I in a vertical position; center in O, project O-2 on the extension of O-I.
I is the section point which divides the segment O-2 in two uneven parts.
Of course a segment can be divided in two uneven parts in many other ways. A particular case of division of a segment in two uneven parts is known as "Golden Section".
Luca Pacioli, in its treatise "De Divina Proportione", published in Venice in 1509, says that the "Divine Proportion" is the golden section: given a segment the entire segment is to the longer segment as the longer segment is to the shorter segment, $I:X = X:I-X$; $X = 0.618$.
Given the segment A-B, project the segment $AC = \frac{AB}{2}$ perpendicular on A, center in C with radius C-A, the segment C-B intersects the arch in D, center in B, with radius B-D, intersecting A-B in E and dividing it into two parts.



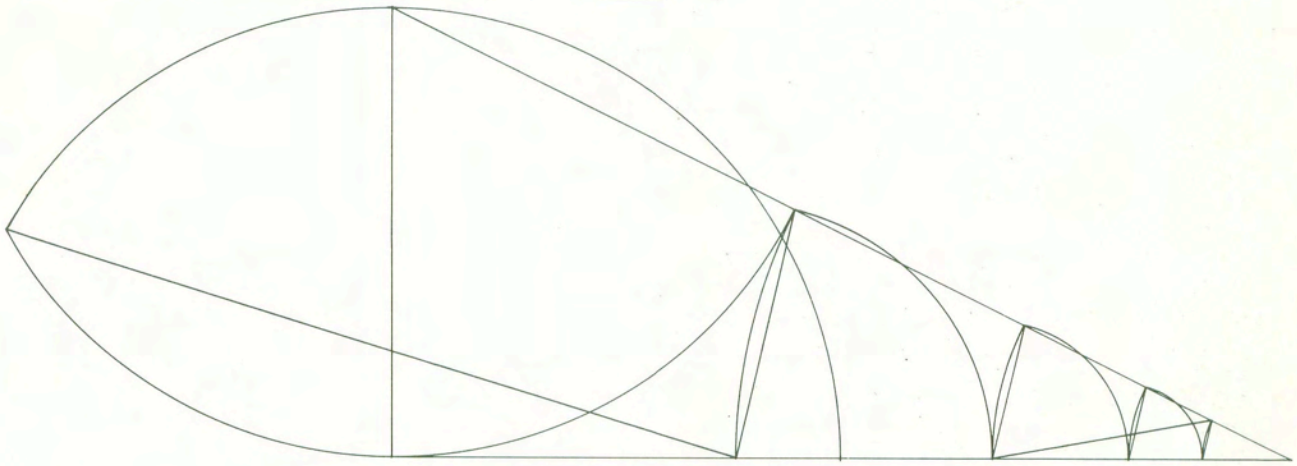


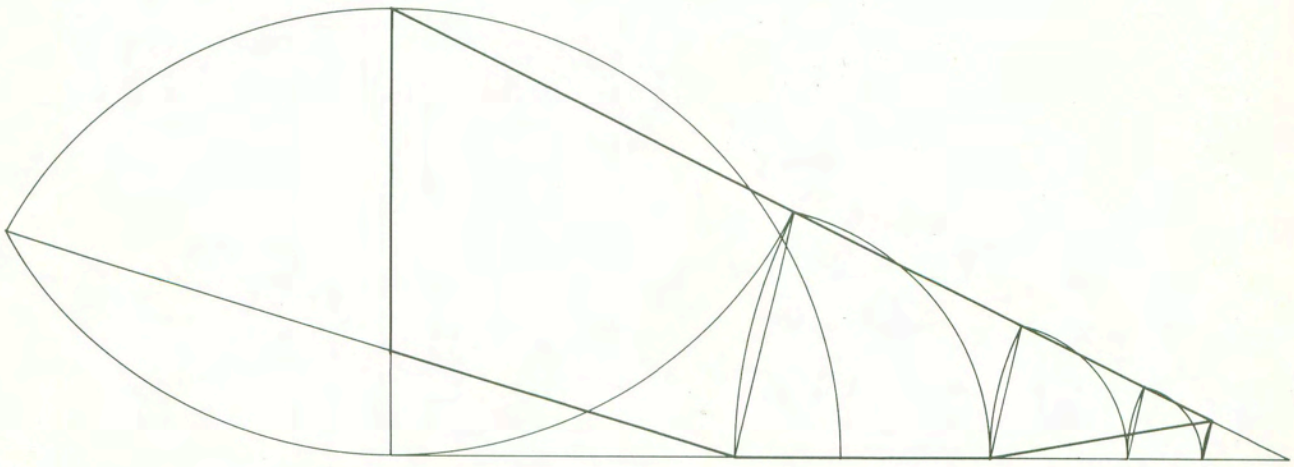


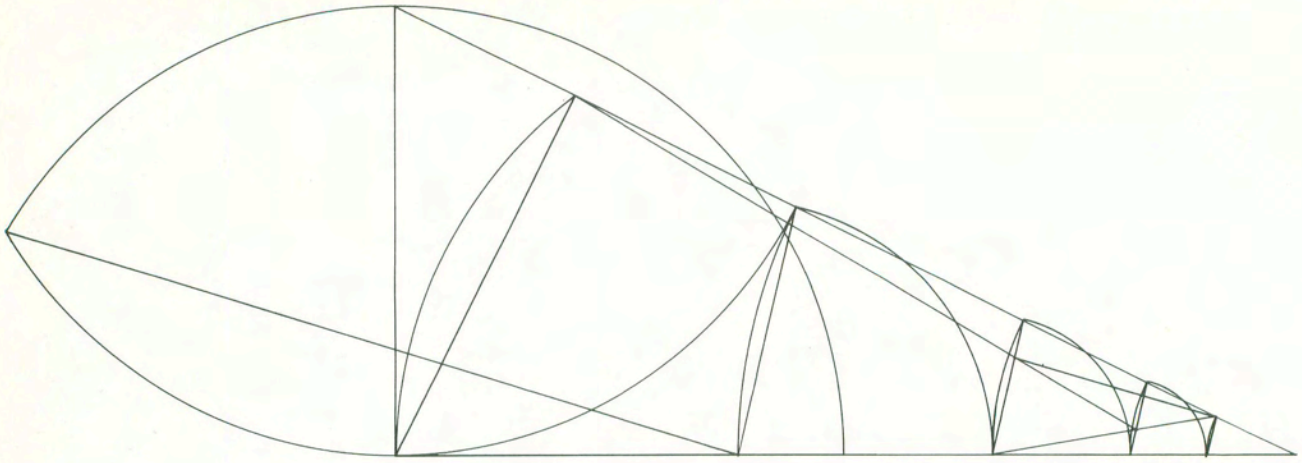


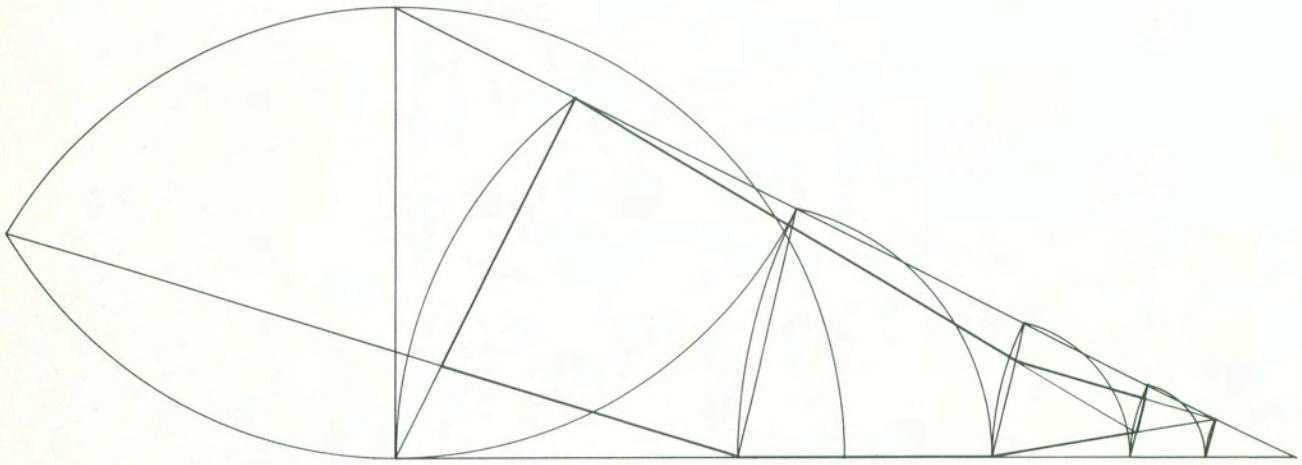


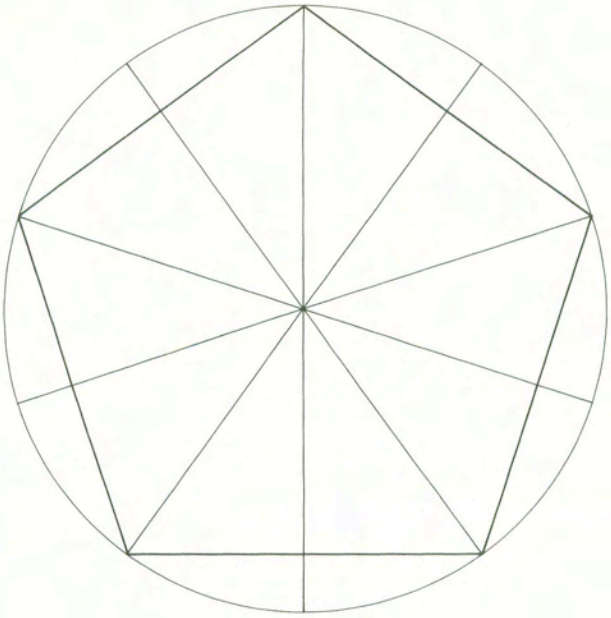
From the measurements taken on the jaws we gather that the longer side of the right-angle triangle is double the size of the shorter side.
Construction drawings of a model of the jaw.

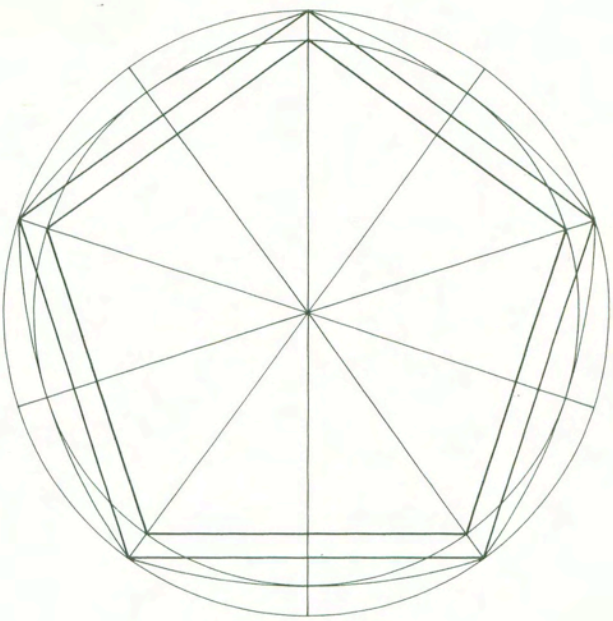


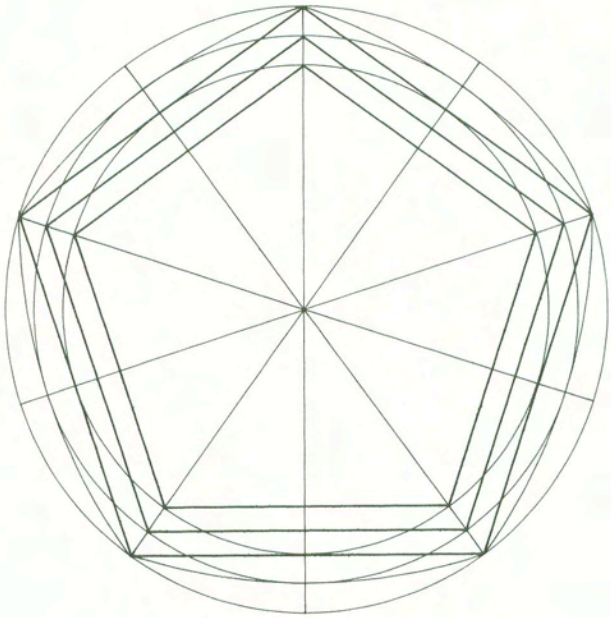


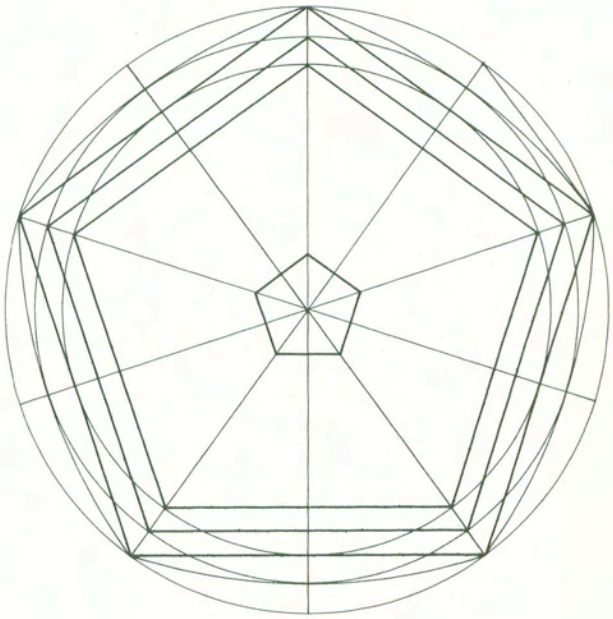


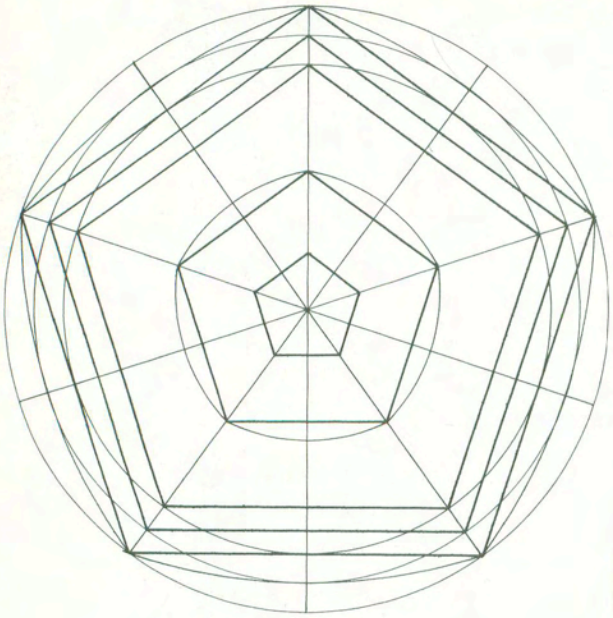




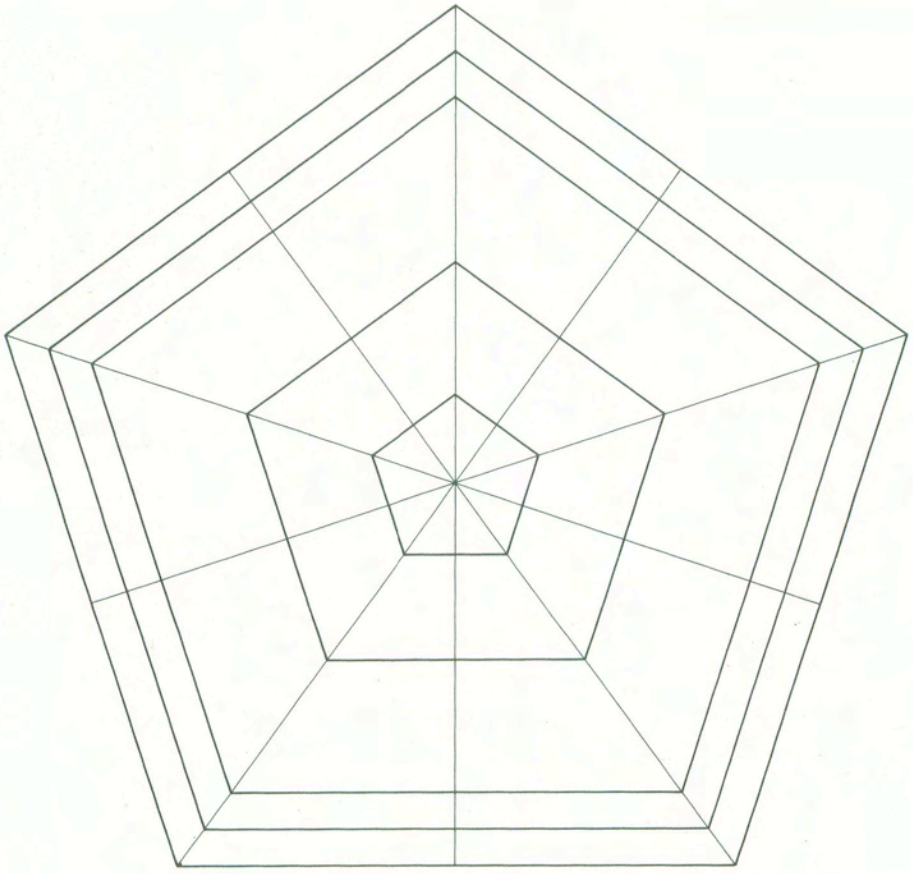


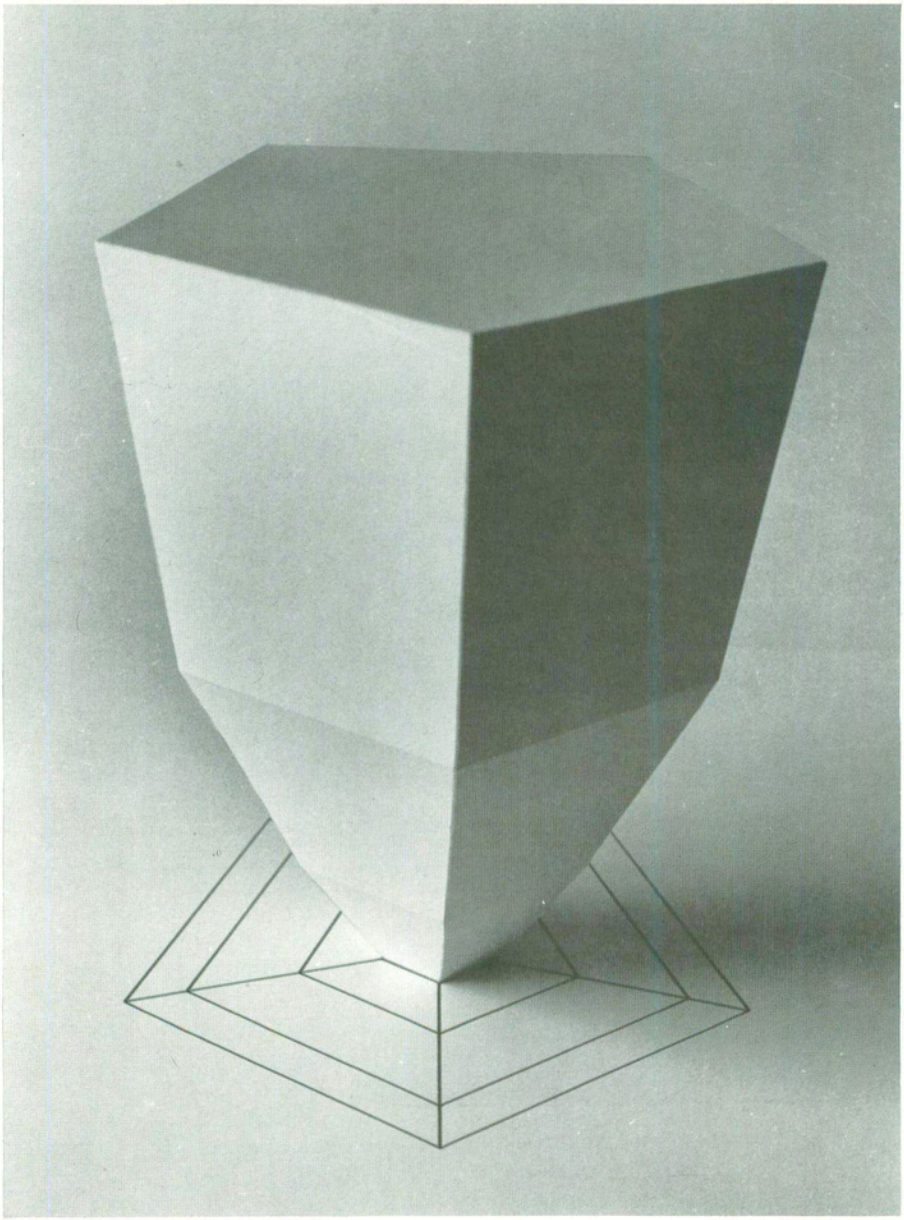






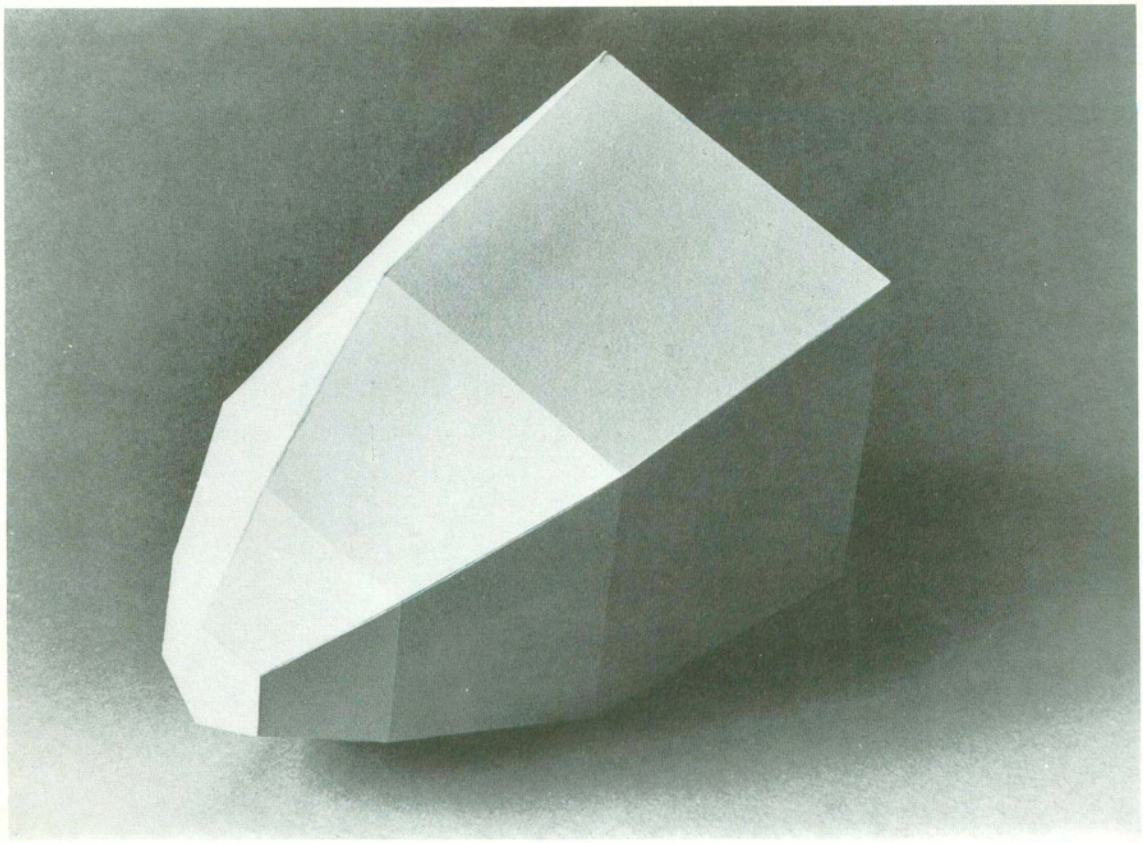
These drawings refer to the horizontal planes of the superior, internal and inferior surfaces of the model to be constructed.



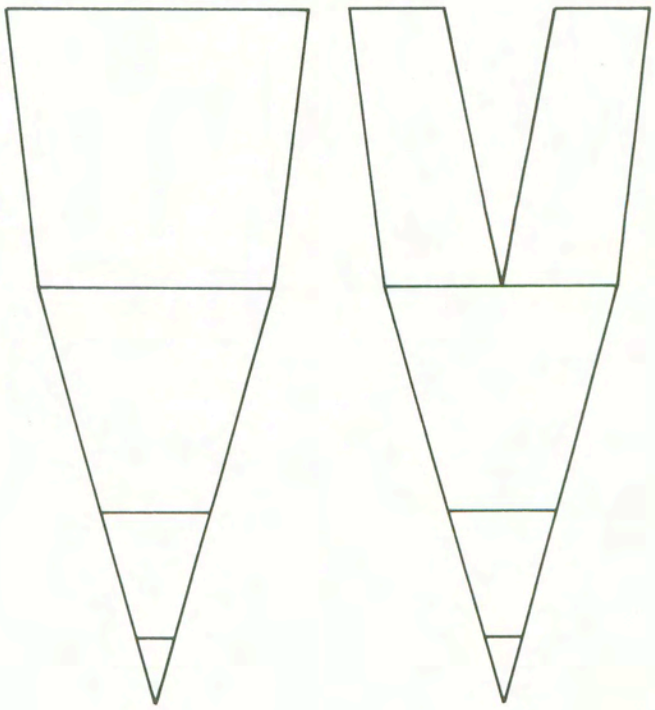


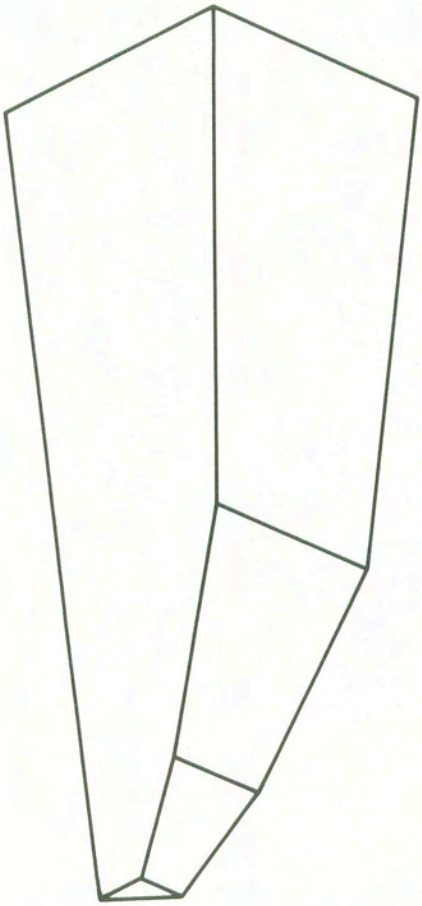
Modified pentagonal pyramid.
This model, analogically more defined and constructed, offers a helpful reference for the realization of jaw models.
After carefully choosing the materials to be used, having evaluated their characteristics and limitations in usage, only then can the construction of the models begin. These models will refer to parts or sets of parts of the natural model.

The validity of the formulated hypotheses must be verified through the construction work of the models themselves.
Sometimes it happens that the first model is also the definitive one.
The model will perform, to an acceptable degree, a behavior which is analogous to that observed in the natural model.
If the results are not satisfying, we will try new experiments and build new models.

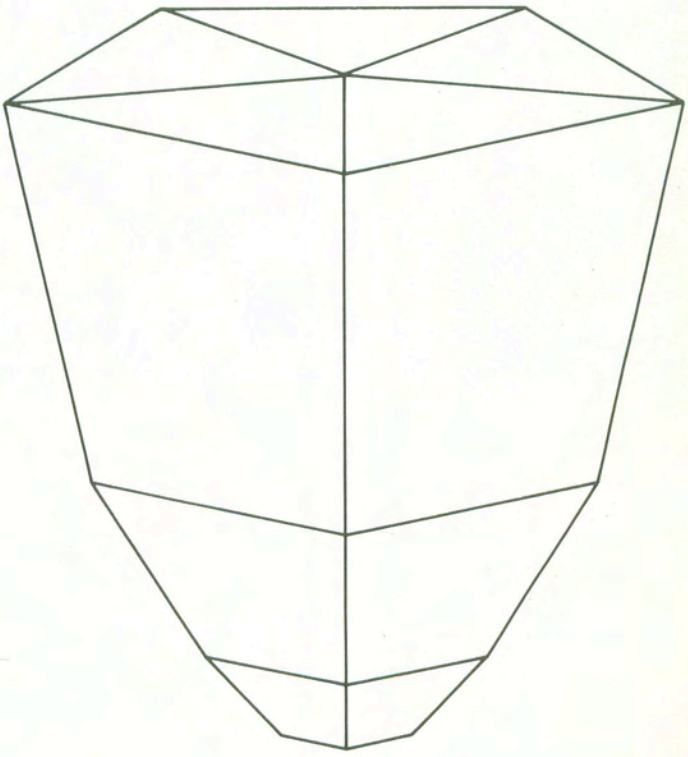


The same model seen from the side.
These drawings refer to the external surface of the model.

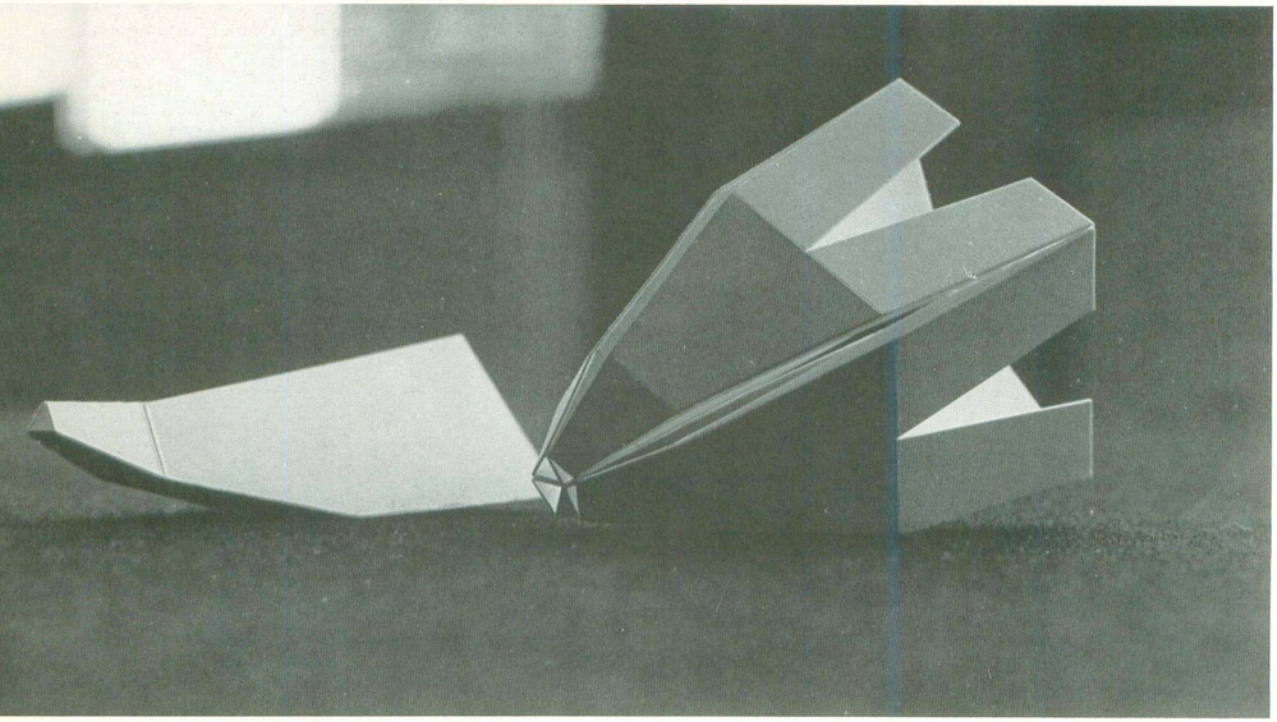




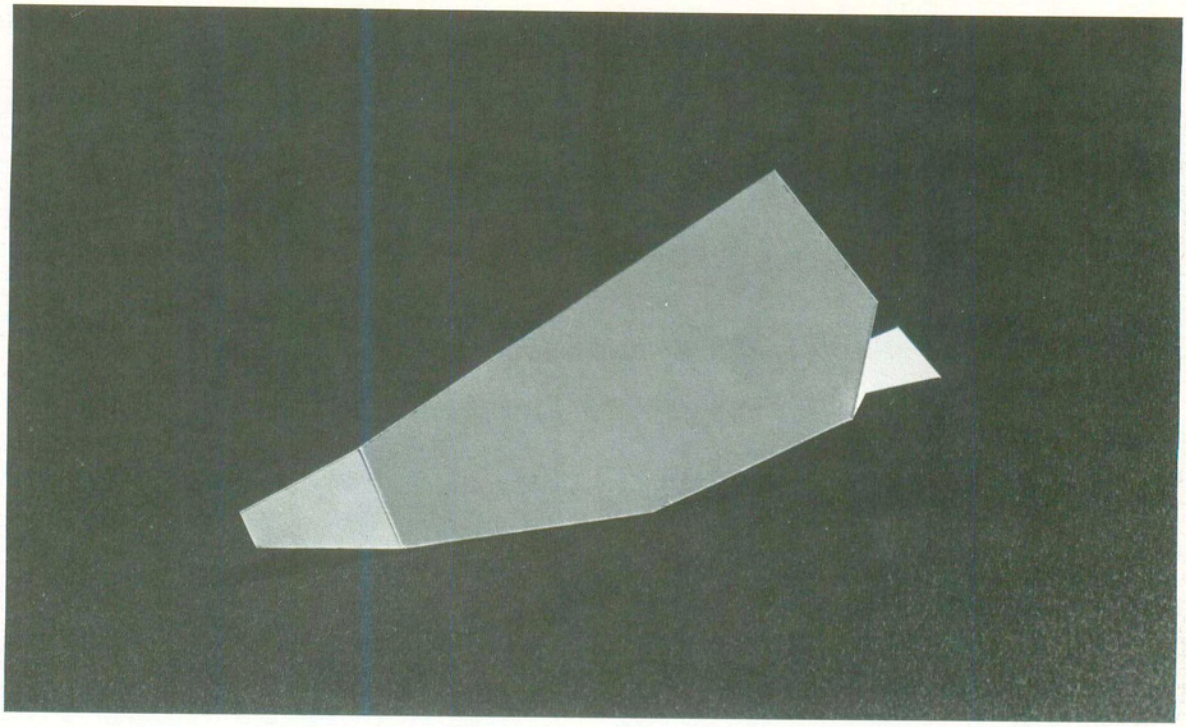
Drawing of a model of jaw.

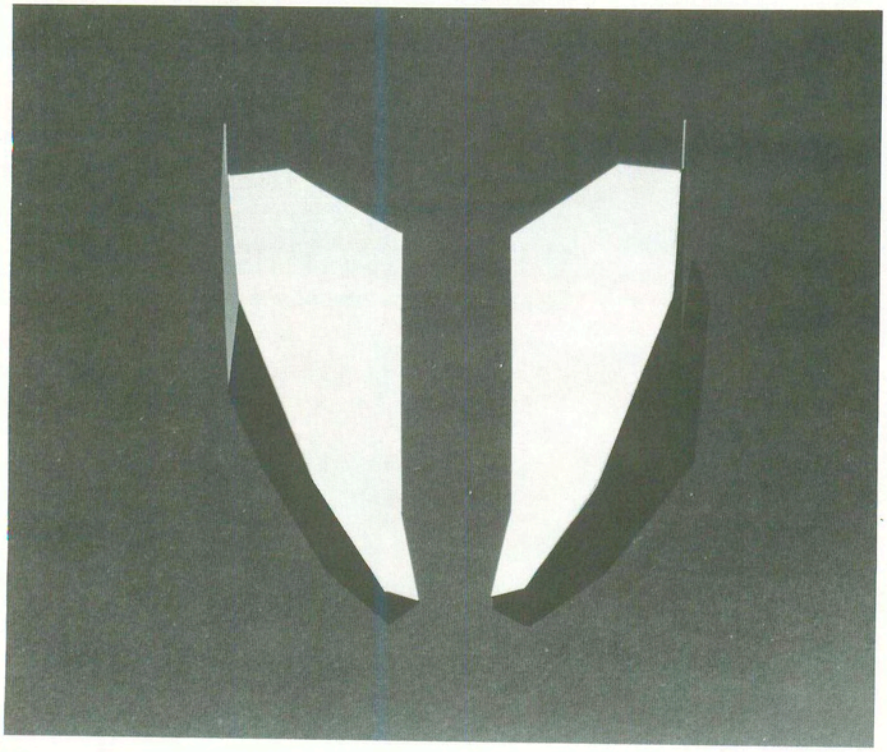


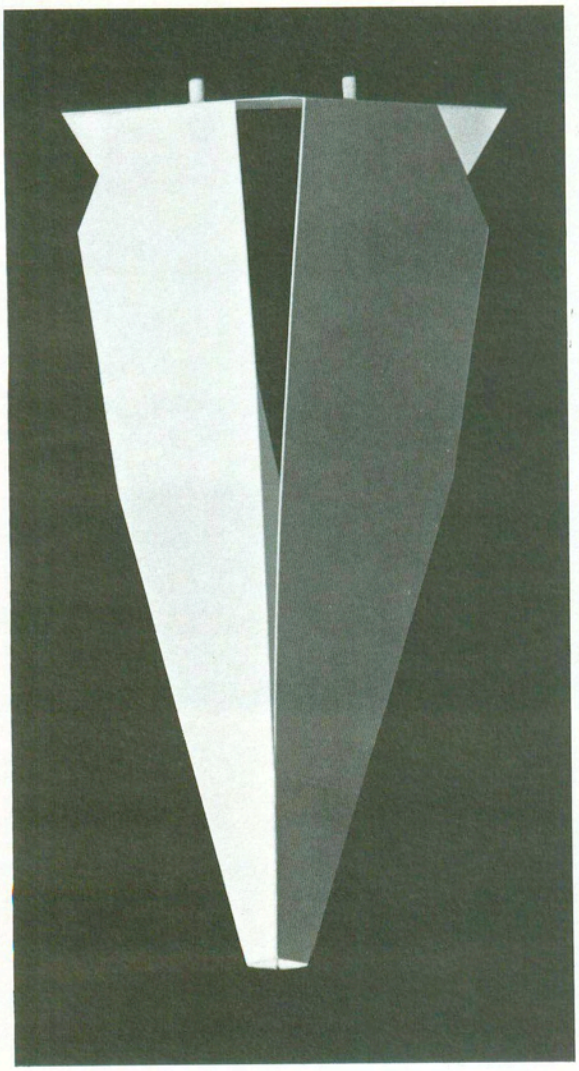
Five models combined together.



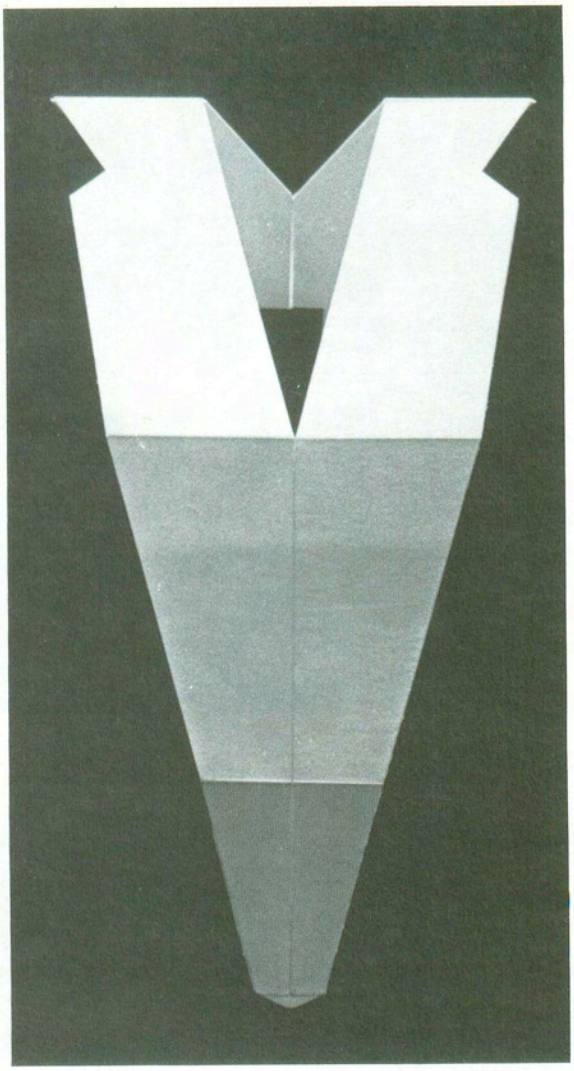
In comparison to the previous model, this one is more elaborate and detailed. The next most important operation is to divide each model of the jaw into two parts. The second is to design a part which will function as a "bridge", as a connecting element, holding together the five models of the jaw.



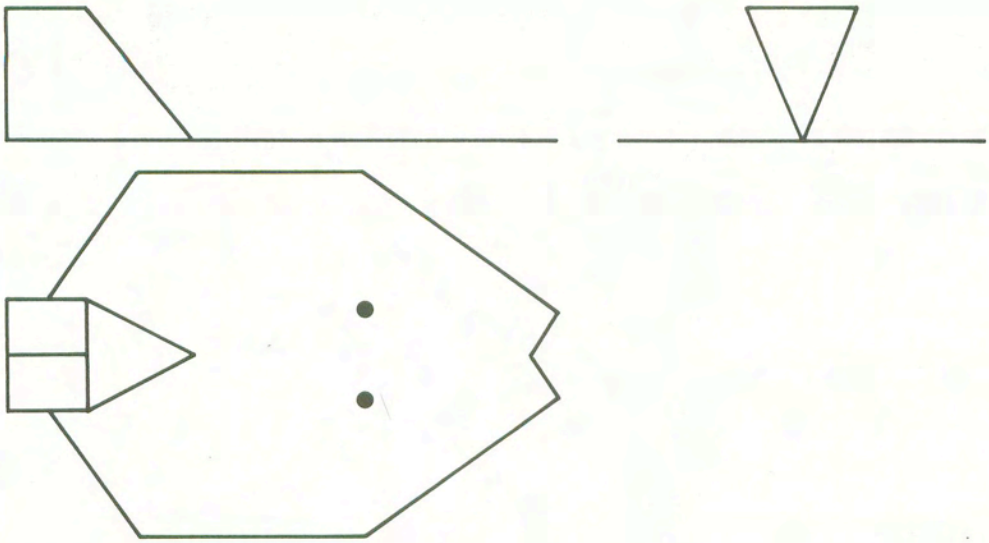




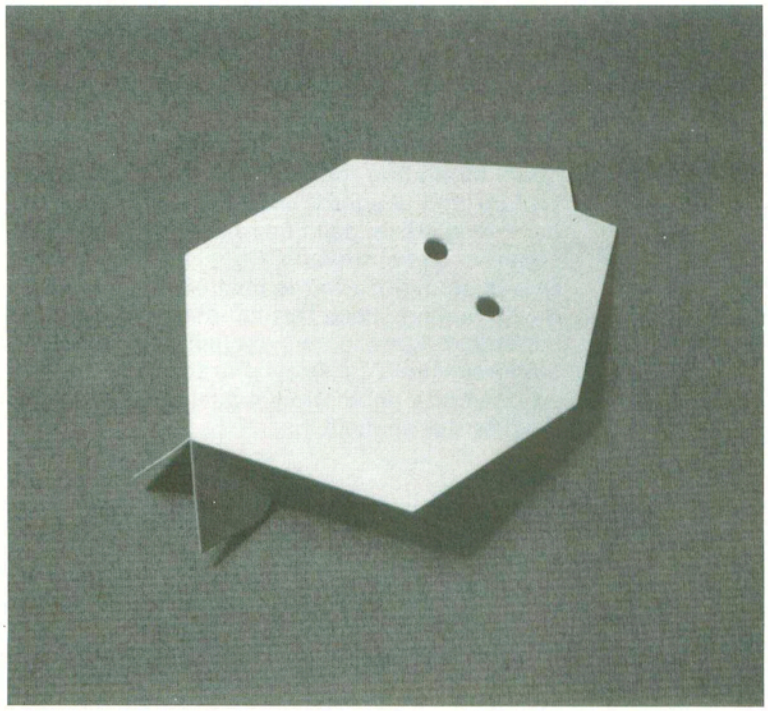
Front view of the model.

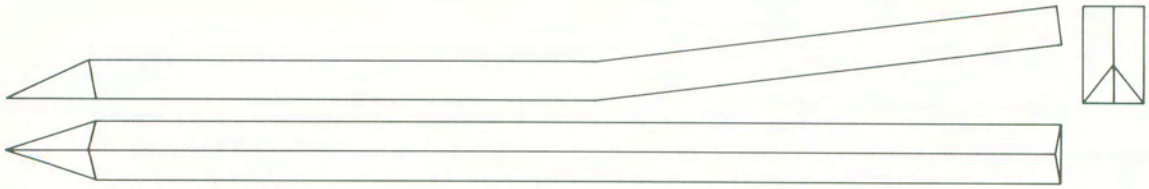


The same form, only reversed.

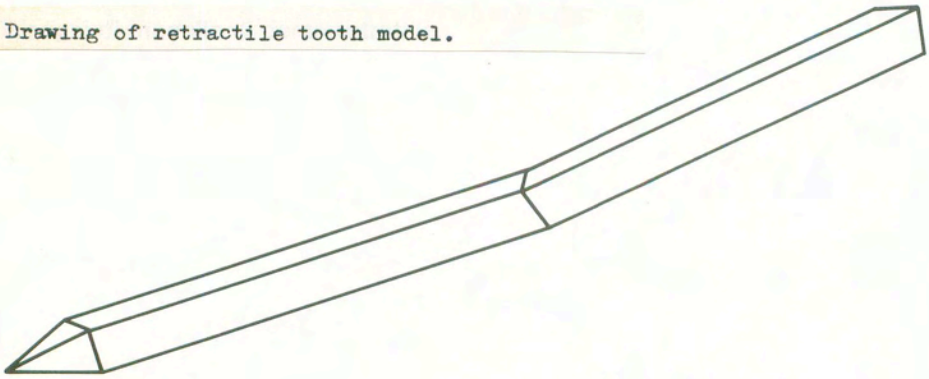


Drawing of the connecting element, seen in top, front and side view.

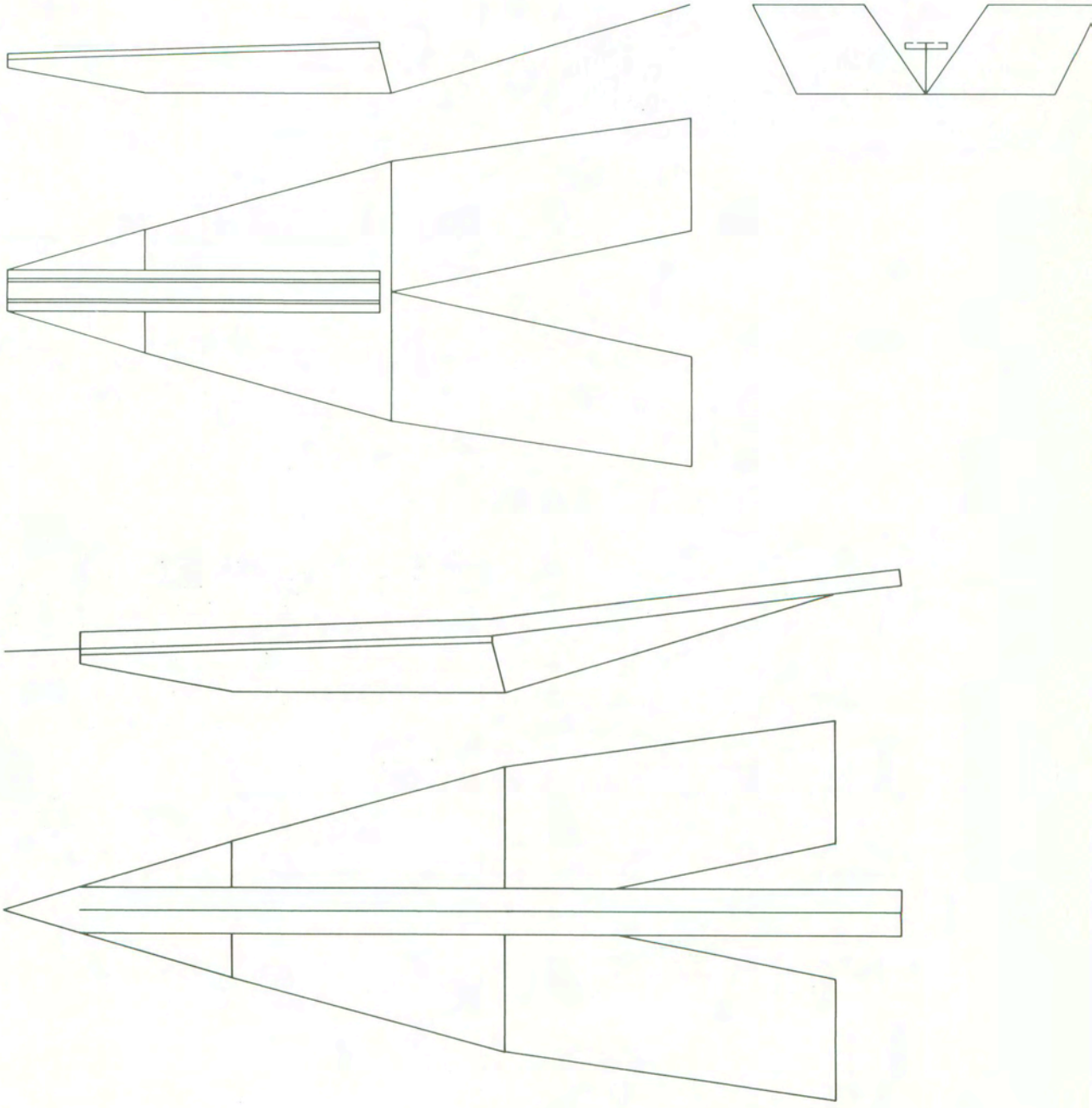


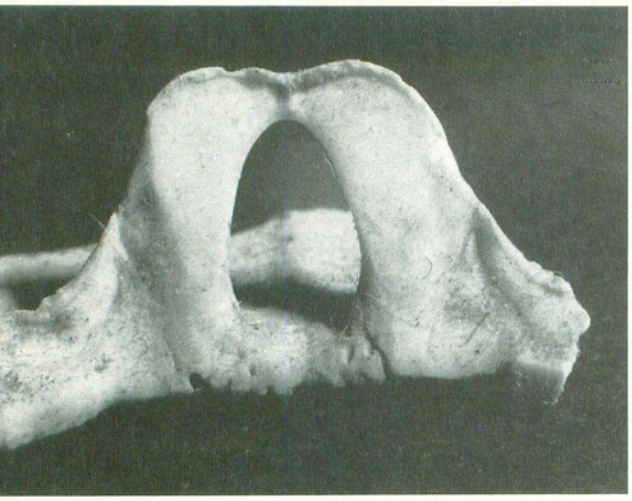


Drawing of retractile tooth model.

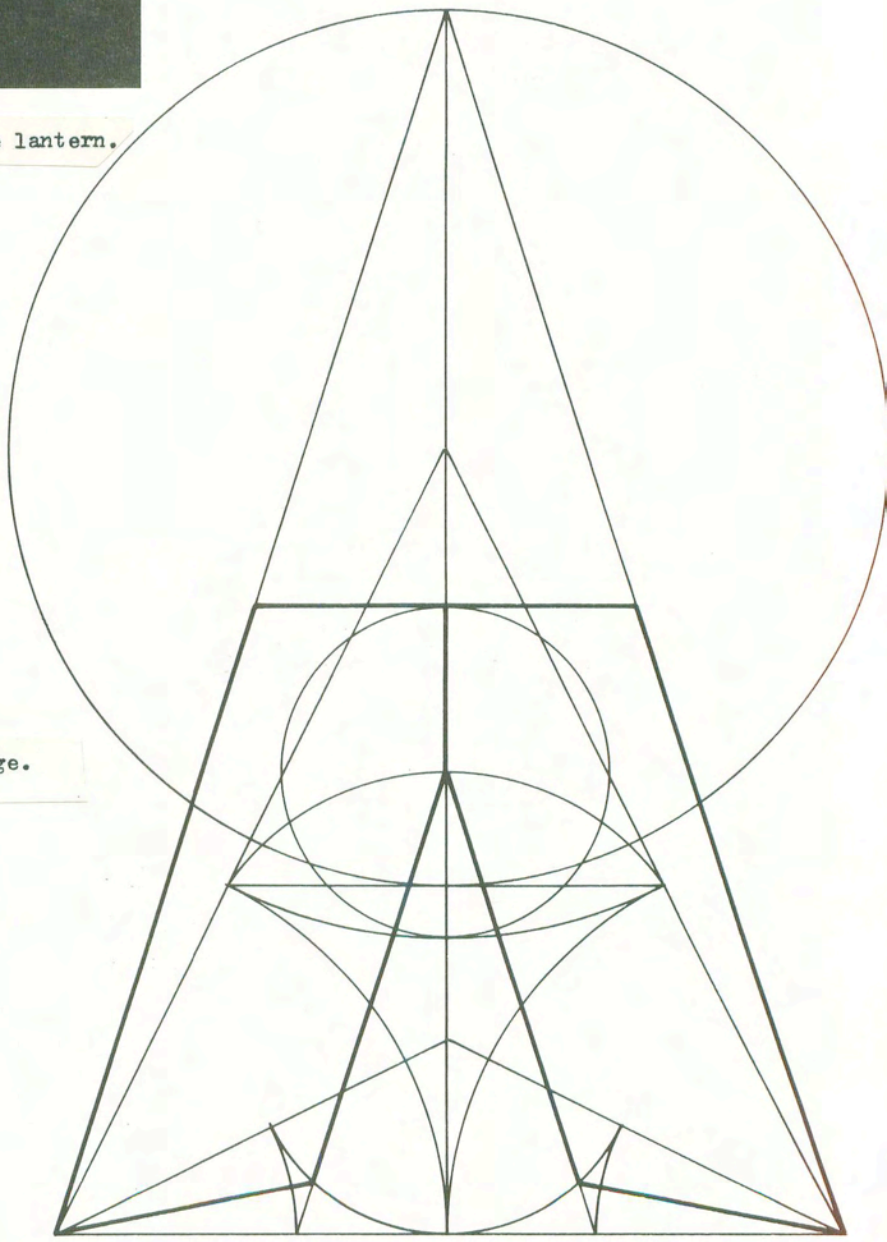


The drawings refer to the study of the shape of the tooth and its position inside the jaw.
The problem consists in understanding how one form slides inside the other.
The sliding movement of the tooth depends, in part at least, on the composition of the surfaces which are in contact with each other. Two of the four specular forms in which the jaw is divided up, have an inner "grooved" surface. There are many grooves running in a longitudinal sense, which make it feasible to think of a track-like guide where the tooth of the animal can slide.

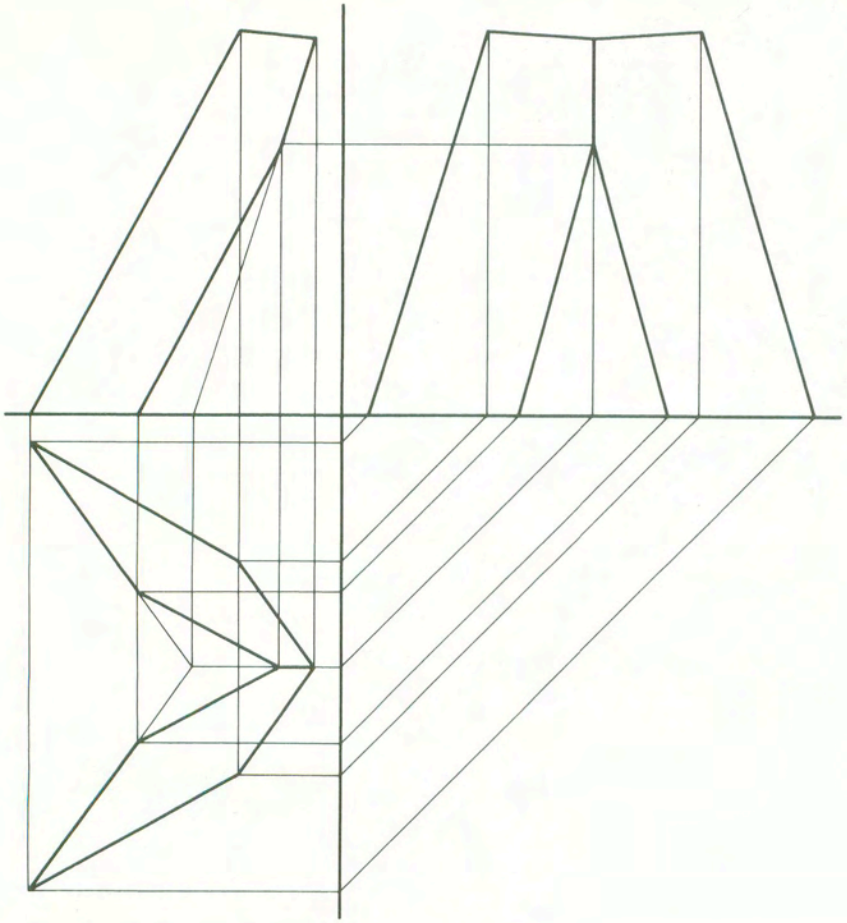




Ridge connecting the shell to the lantern.

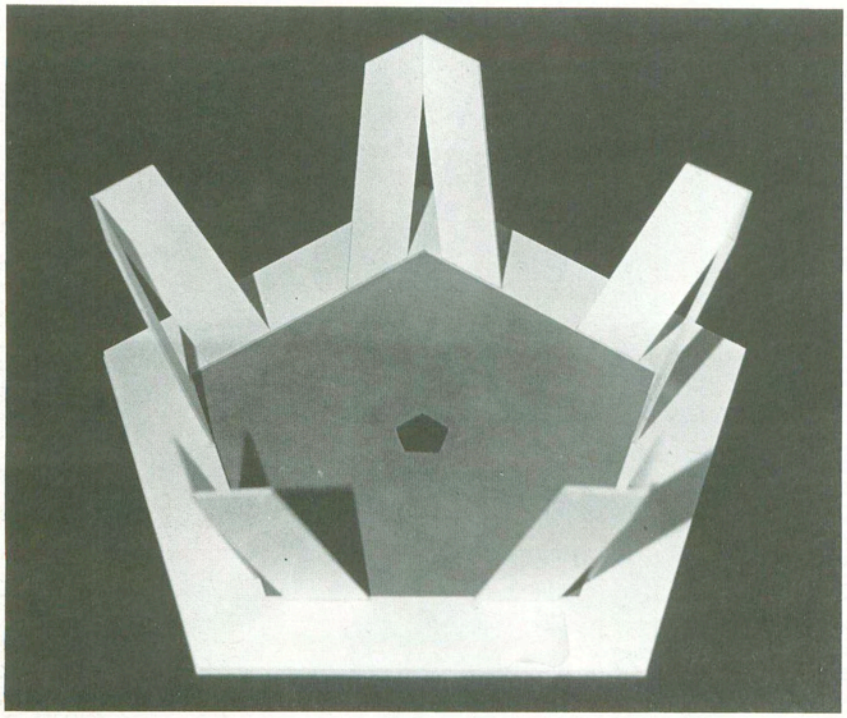


Construction drawing of a ridge.

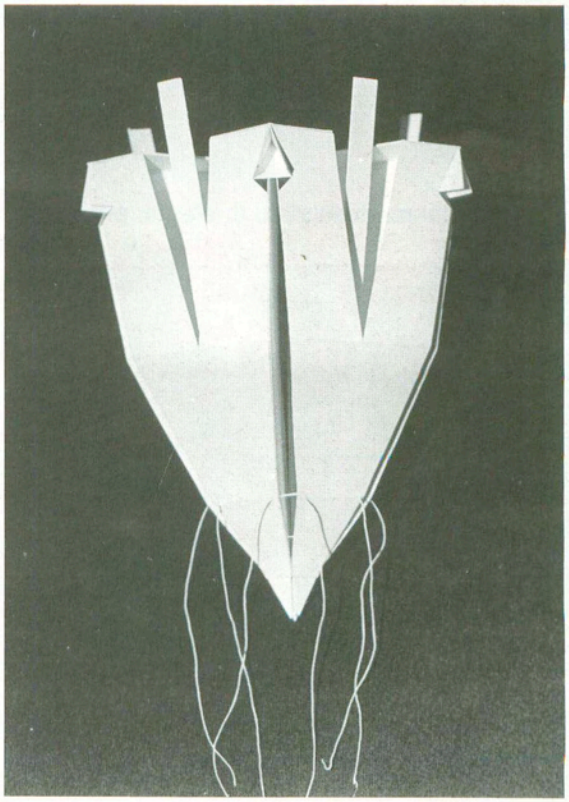


Drawing of the model, in top, front and side view.

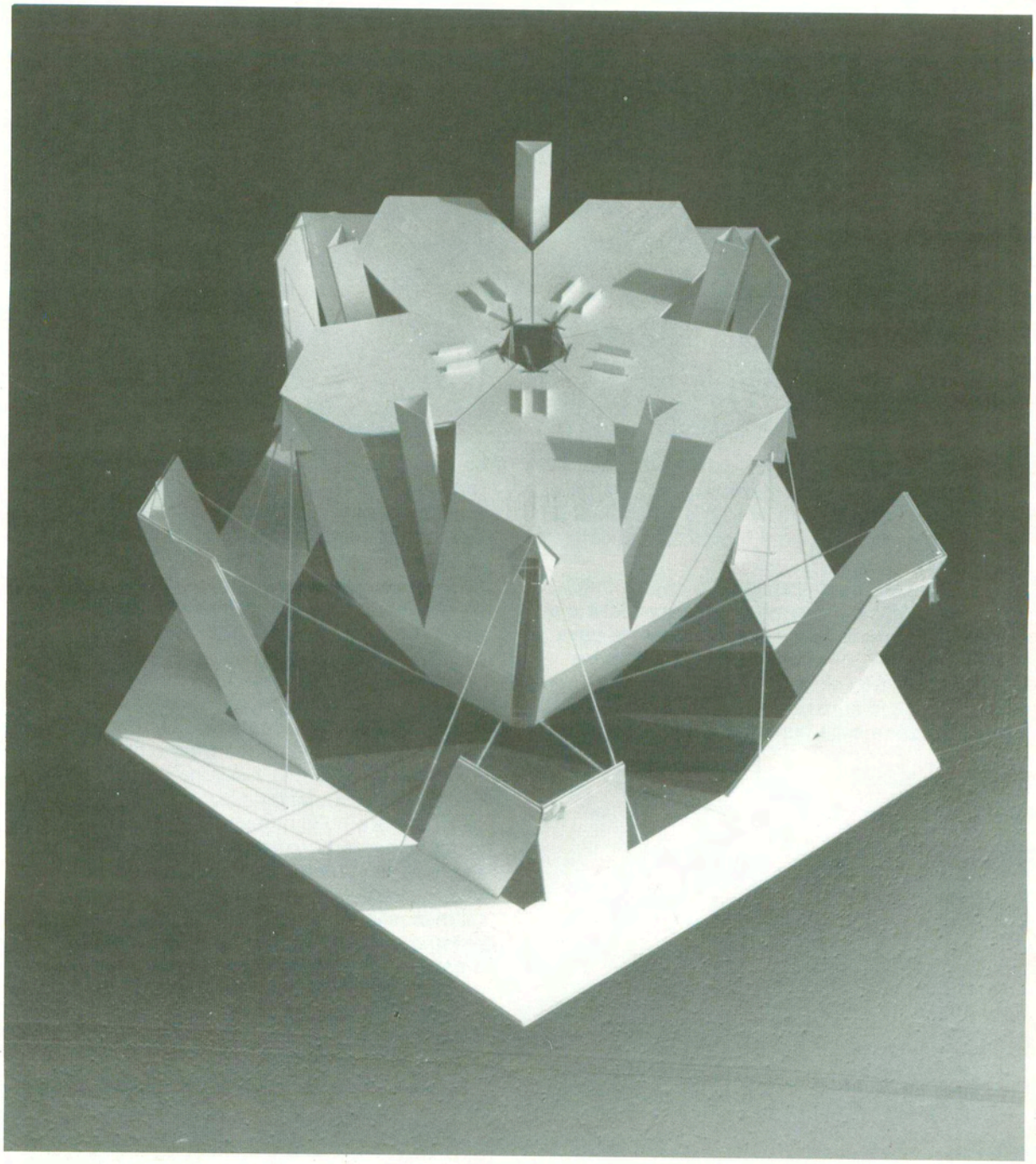
We will build a pentagonal crown made up of five of these ridges and of a pentagonal rubber foil with a pentagonal hole in the center.
The models of the jaw, of the bridge elements and of the teeth are then combined together into an organized whole.
The parts will be connected together with rubber bands (muscles) after the attachment points have been determined, on the internal and external surfaces of the various pieces. This will also determine the overall design, which in turn will influence the functional equilibrium of the whole.
In this first global model, the shape, the configuration of the parts and the overall mobility, only partially satisfy the analogy with the architecture of forms, the structure and the movements of the mouth of the sea urchin.



Model of pentagonal crown on which the model of the lantern will be inserted.



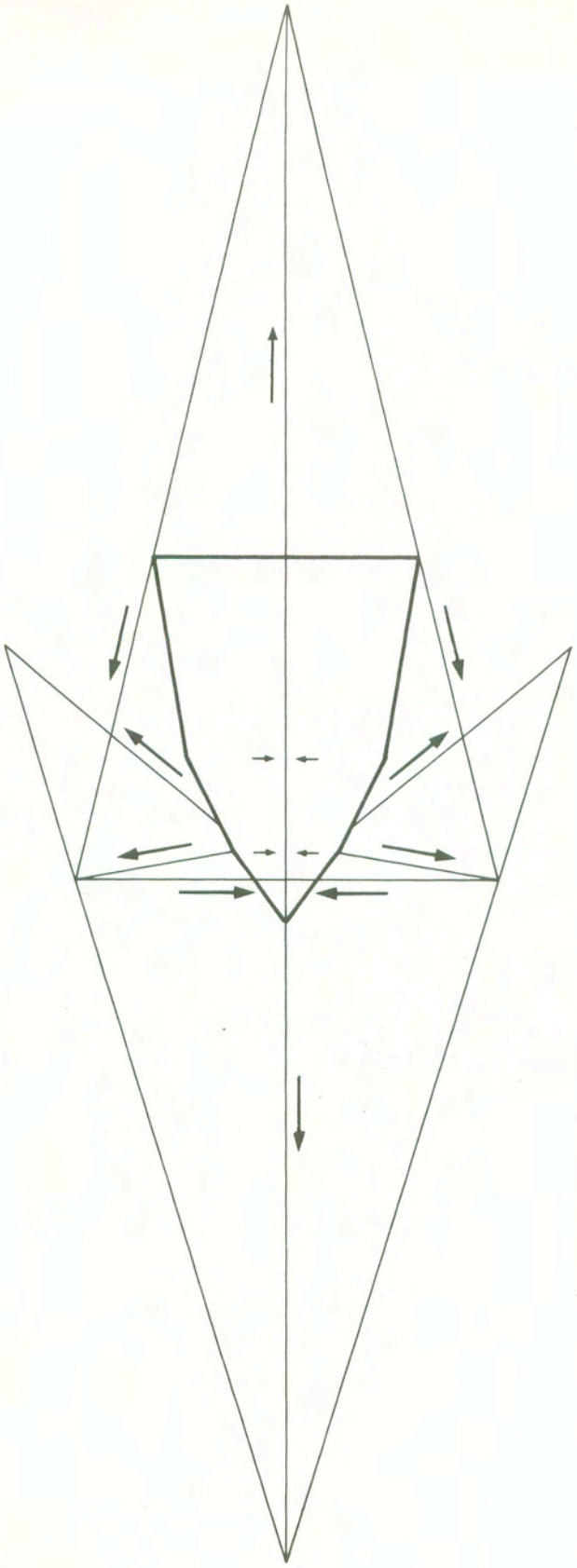
Model of lantern.



Overall model, complete with all the parts.

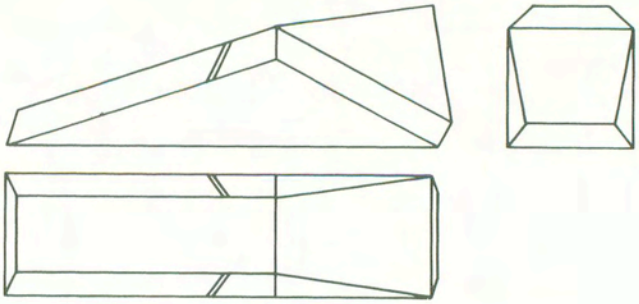
In the opening movement of the mouth of the sea urchin, the jaws are an active part, together with all the calcareous components, of a complex and integrated give-and-take game of opposite tensions.
When the mouth of the animal is closed, a specific form protuding from the jaw is in contact with a complementary hollow shape in the "bridge-plate" which works as a joint between one jaw and the other.
If the mouth opens, the jaws push - in a semi-rotation - on the plate. The plate itself simultaneously works as a joint and as a hinge.

The movement of rotation of the jaw is regulated by a "stopper" which consist of the end part of the plate itself.
This mechanism plays a role in determining the maximum opening limit of the mouth.
Another calcareous shape, superimposed on the plate, releases the pressure applied by the jaw on the plate, within a muscular circuit which connects the lower part of the jaw (mouth) with the shell.
In a complex game, which tends to balance forces and counterforces, we discover that each part of this organized whole embodies more than just one function.
For example, the bridge-plate acts as a spacer between two jaws and probably allows a wider opening movement of the mouth; moreover, it works as a holding device and as a joining hinge.
The jaw, hollow in the inside, has its external surface ending in a very fine comb-like shape: the "envelope" within which the tooth slides is also a container/filter which regulates the flow of substances that enter the mouth of the sea urchin.

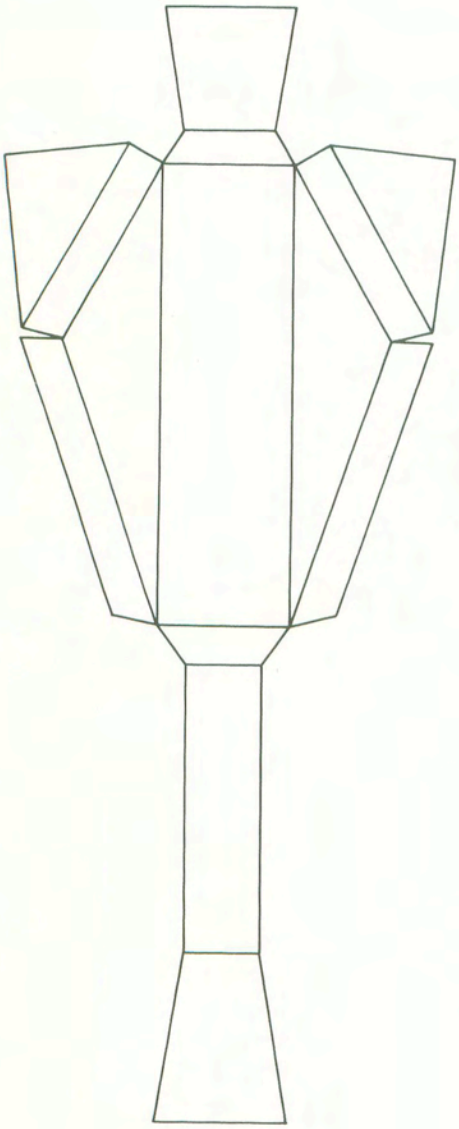


Schematic drawing of the forces acting as a result of the muscular tensions.
The components forming the enveloping of the movements counteract each other within a module and this module is basically shaped like a double pyramid.
Its vertexes coincide with the ends of the same straight line.
The straight line represents the equilibrium axis of all the dinamic tensions to which the whole structure can be variably subjected to.

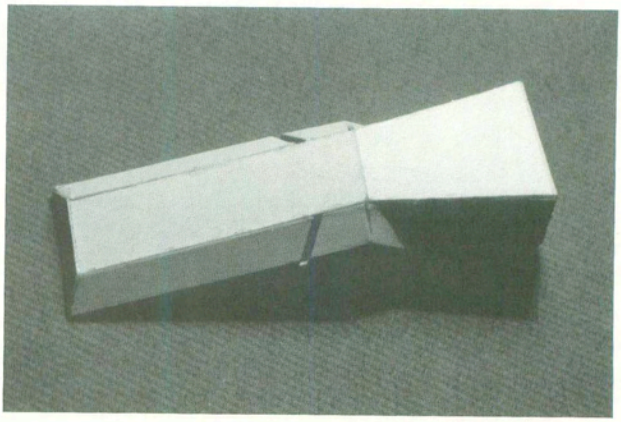
In the light of these new observations, the construction of a new model of the bridge-plate will have to be based on a clearer definition of its functions. In fact, compared to the first model, the new one will be supplied with appropriate slots where the complementary forms - belonging to the jaw models - will be able to rotate.



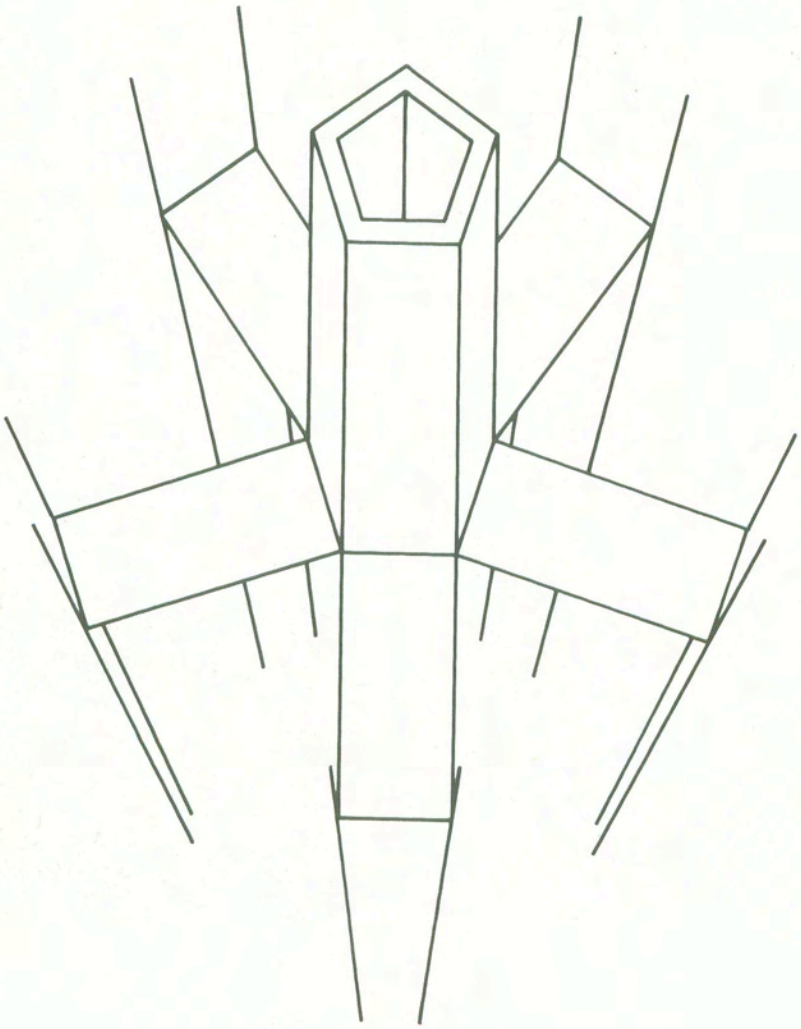
Top, front, and side view drawing of the new model.



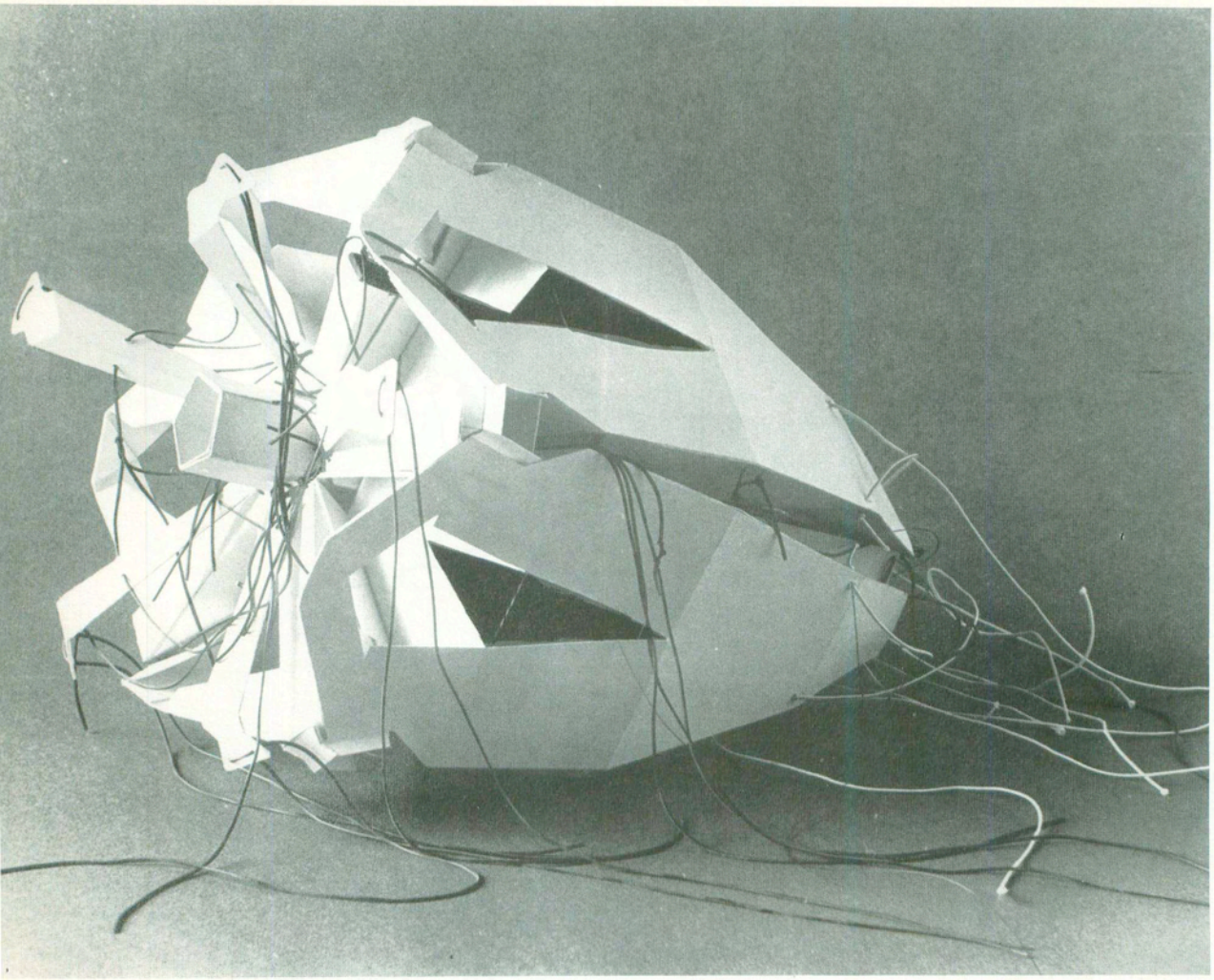
Fold-out



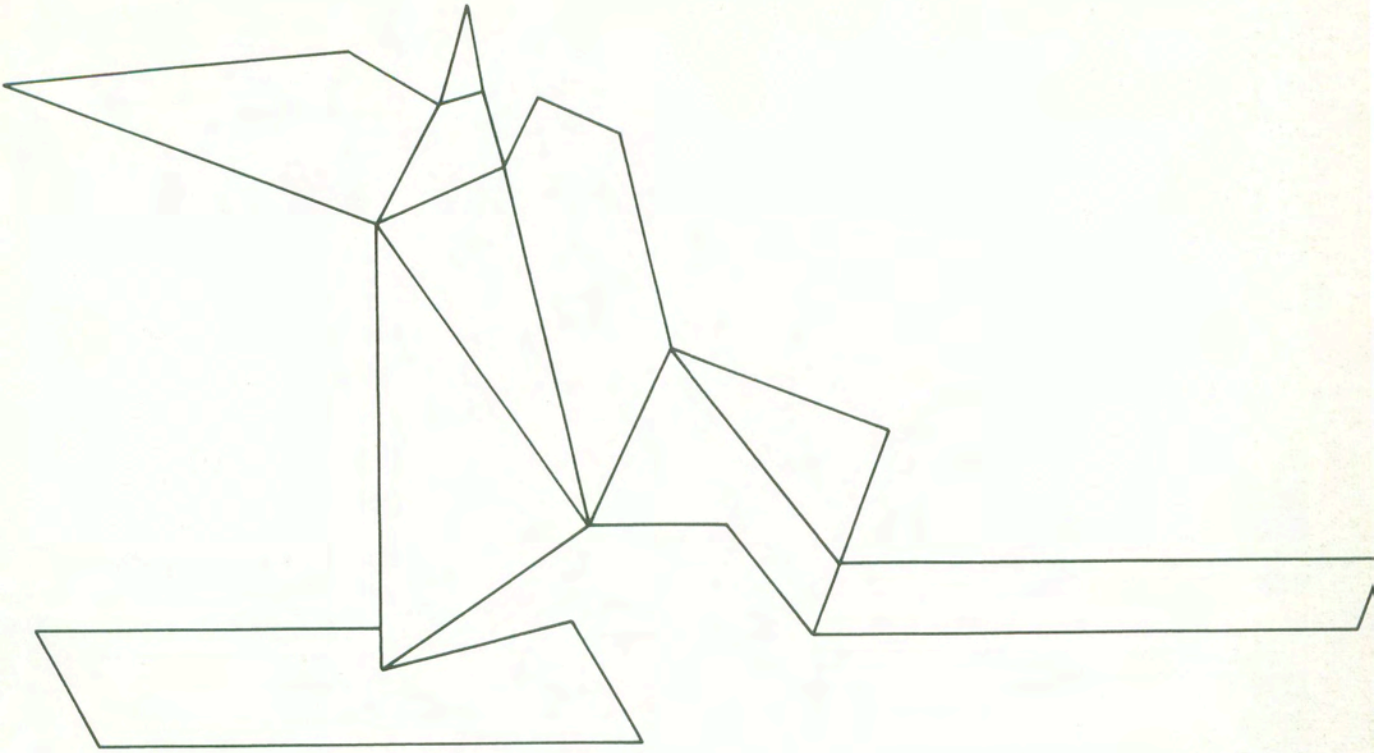
Model.



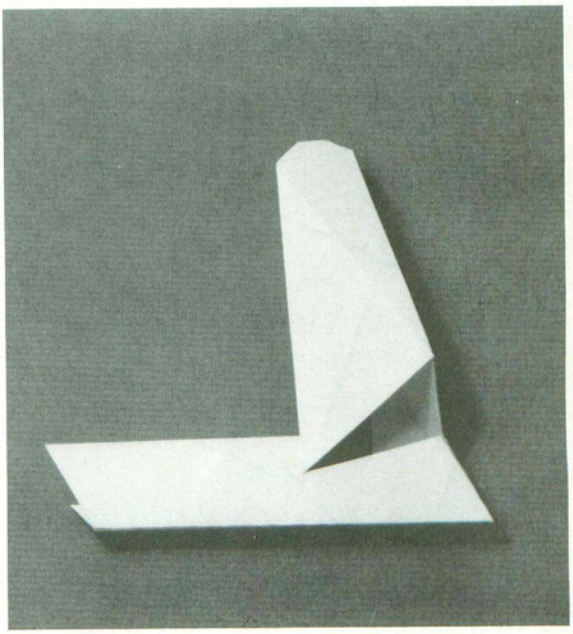
The five jaws will also be supplied with a movement which should not contrast the architecture of forms and the overall symmetry.
Instead, it should tend to strengthen the basic constructive module.
The jaws are then joined by movable bridges hinged to a hollow pentagonal prism.
This prism works as a transmission device of the movement along the longitudinal axis.
It also works as a symmetry axis to which all the various parts of the model will refer to.

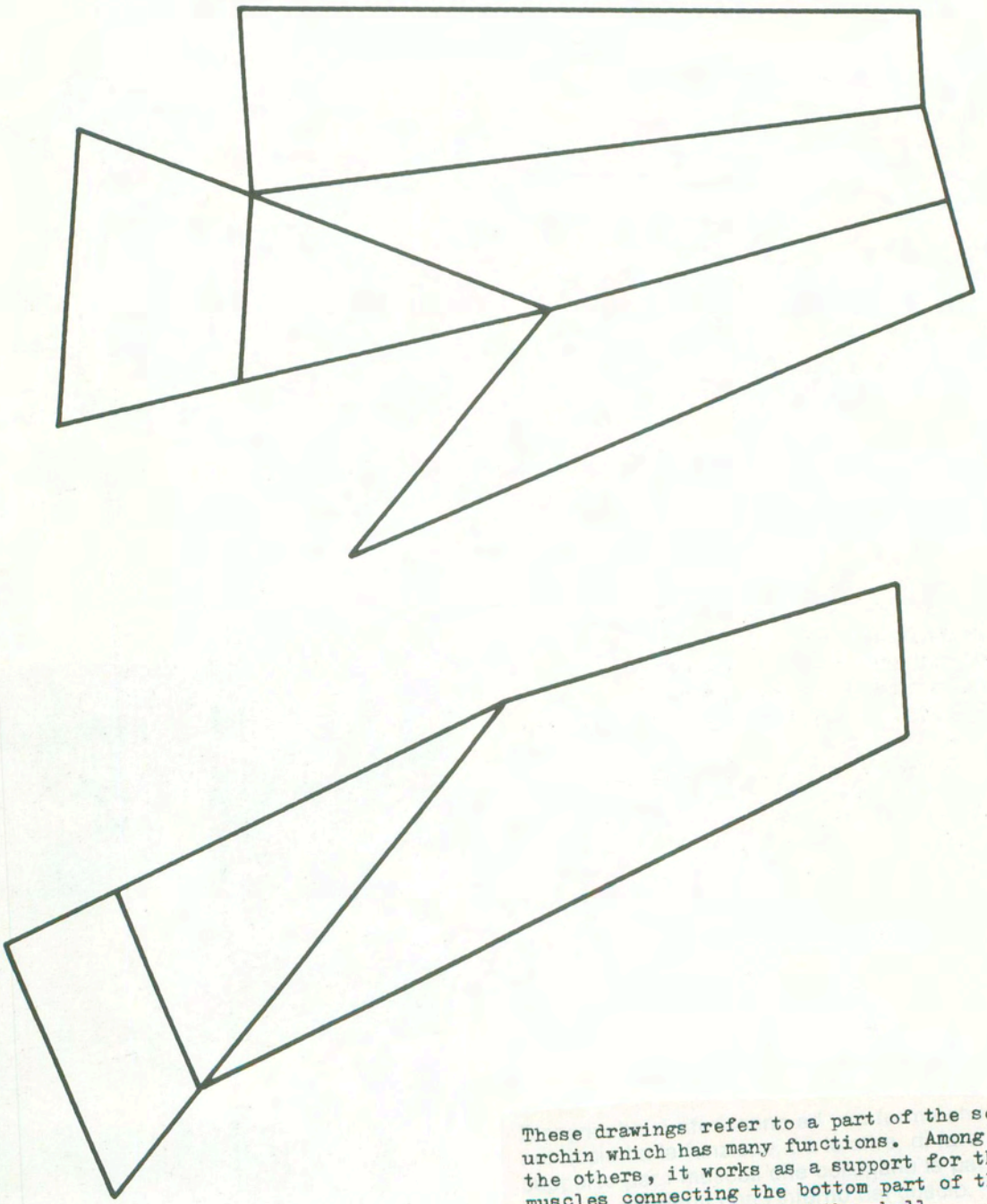


A new model, built in an approximate way, will enable us to check the validity of this mechanism, and to immediately see if the joining points of the rubber bands are correct. To see if the height on which the hinges on the prism planes have been located is correct and make the necessary improvements.



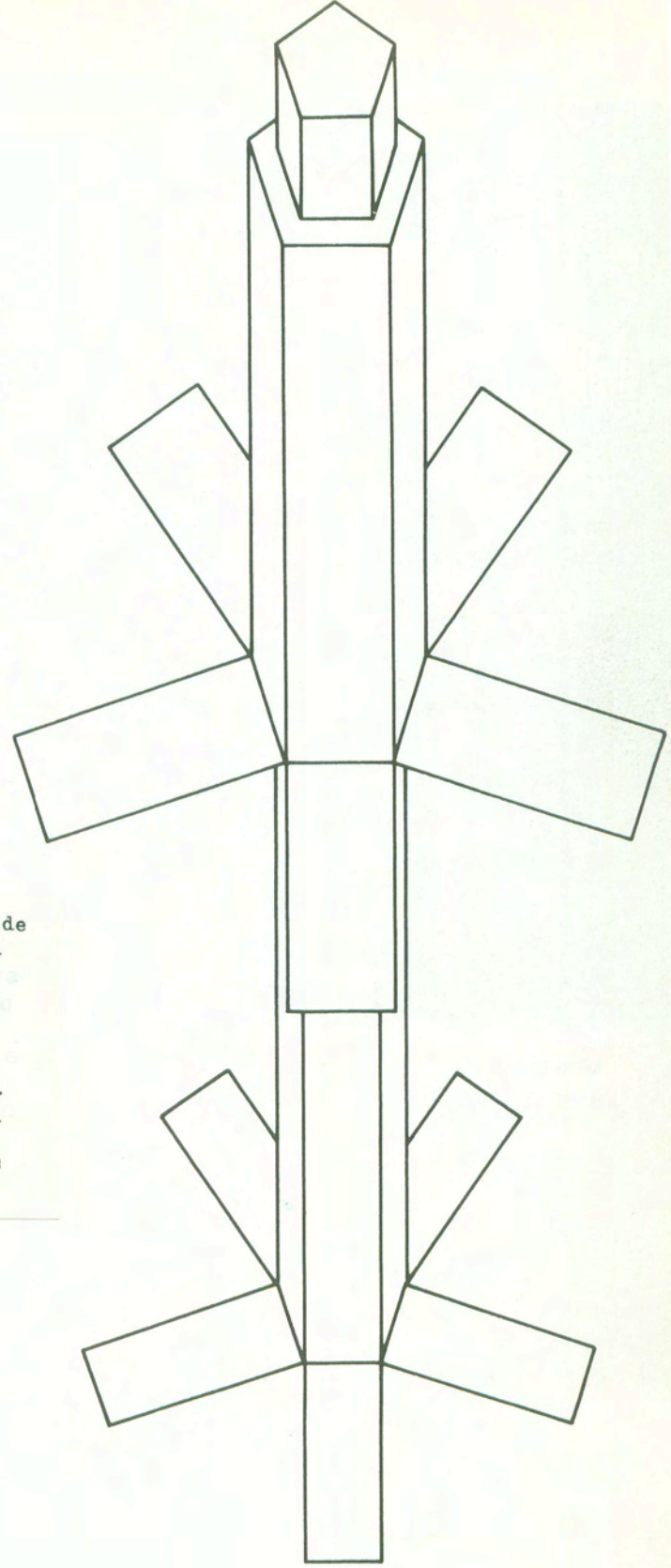
Study of the form which works as a support and attachment-point for the muscles holding the teeth in the upper part of the jaw. Three-dimensional form and fold-out drawing of the model.

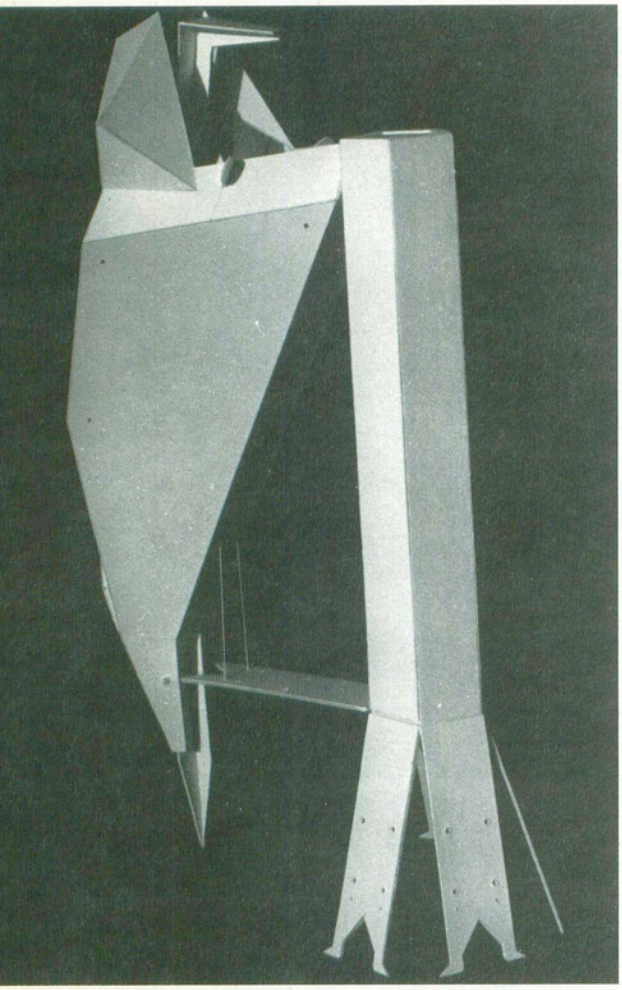


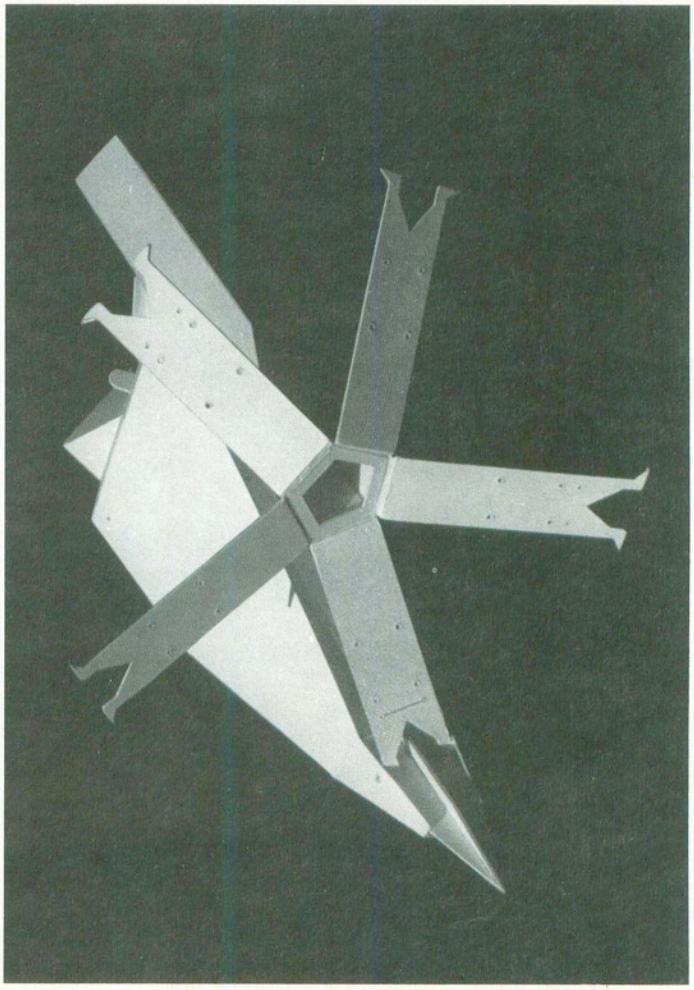


These drawings refer to a part of the sea urchin which has many functions. Among the others, it works as a support for the muscles connecting the bottom part of the teeth with the inside of the shell.

Since the teeth must be able to move inside the jaws and the movement be in sync with the opening and closing of the mouth, we must establish a connection between the upper and the lower parts of the jaw and the inner pentagonal prism which is capable of determining these movements. This problem can be solved by inserting - like in a telescope - a second pentagonal prism inside the hollow one.
The second prism will have hinged bridges which will be connected to the teeth.

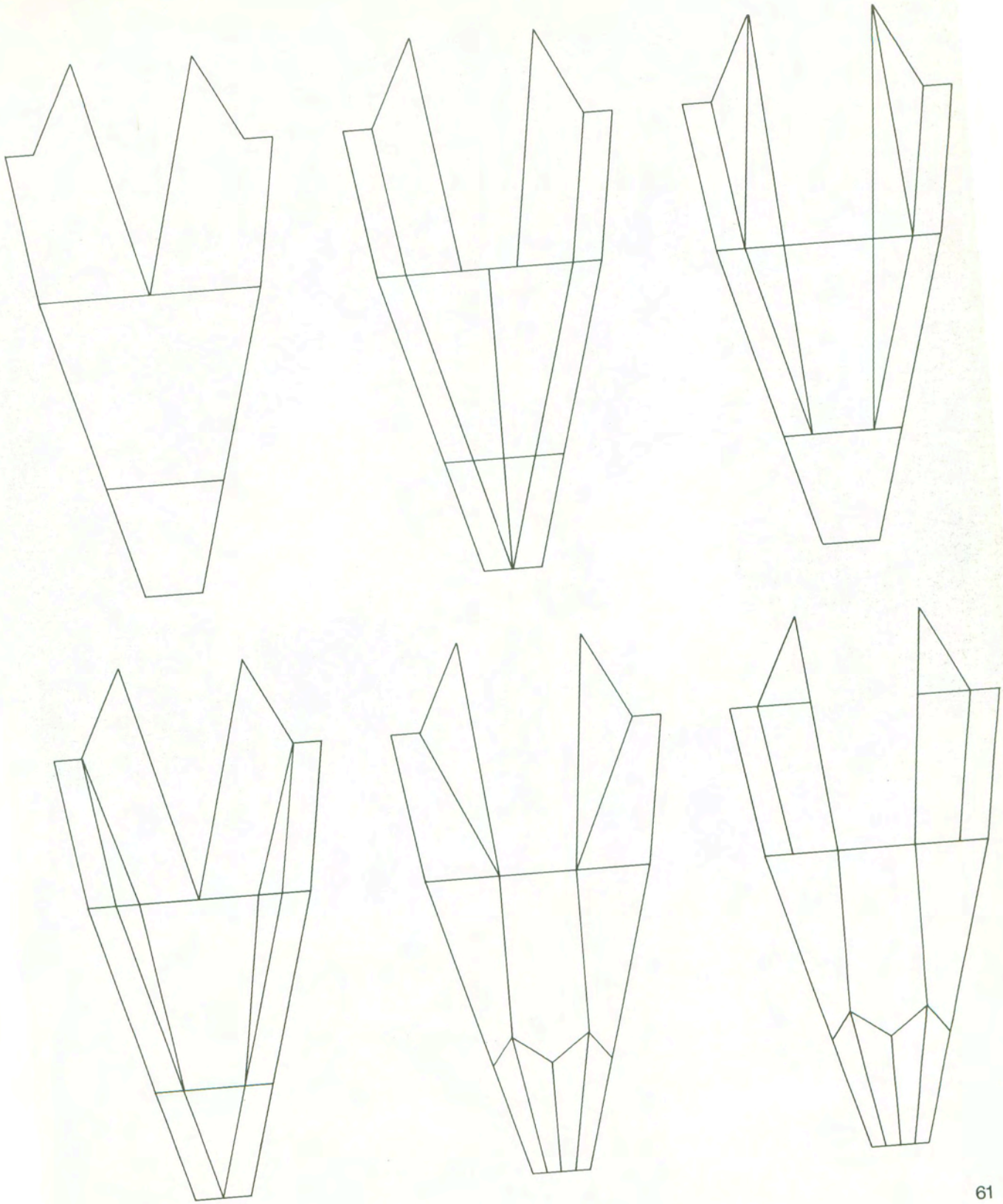


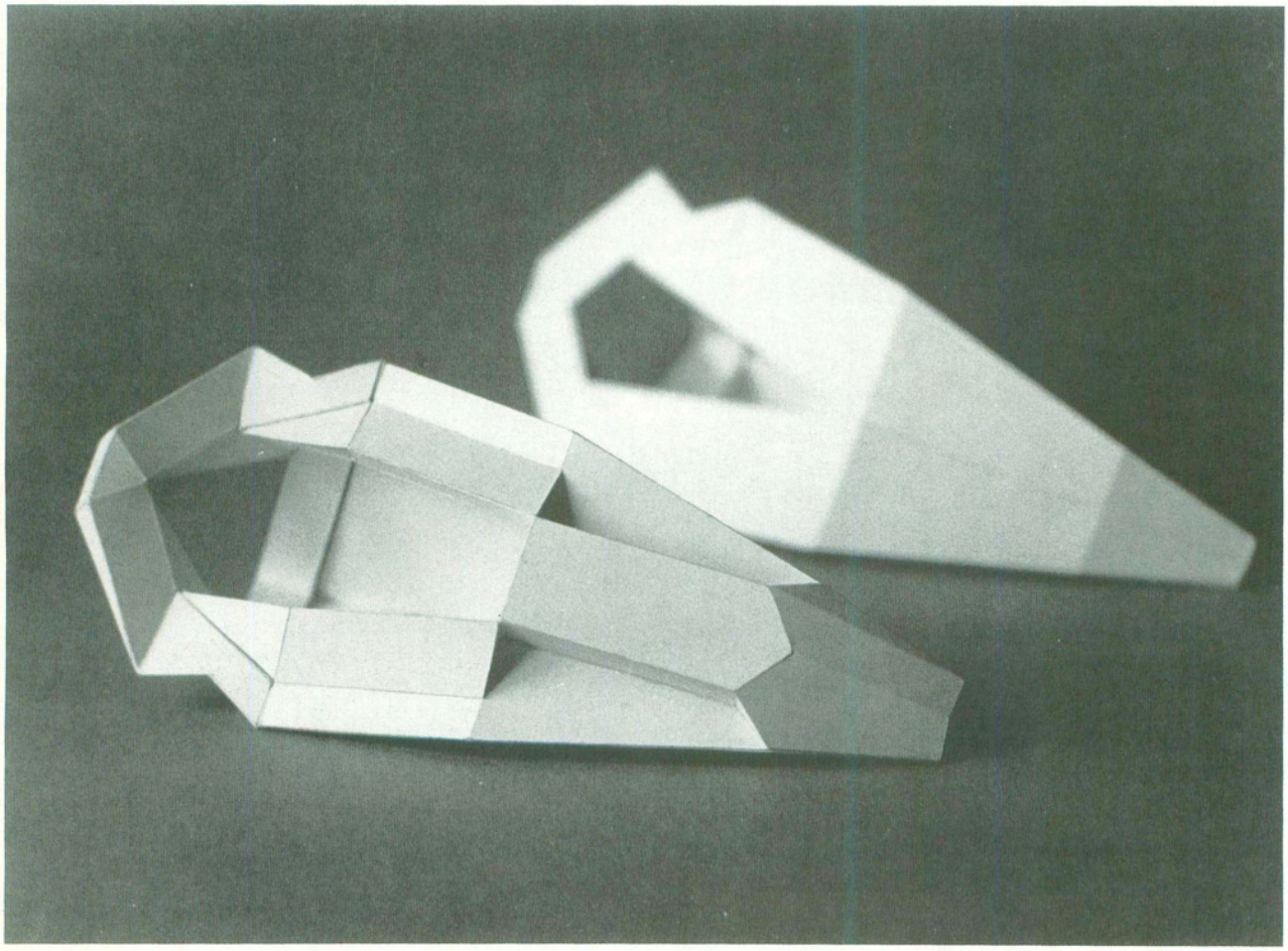




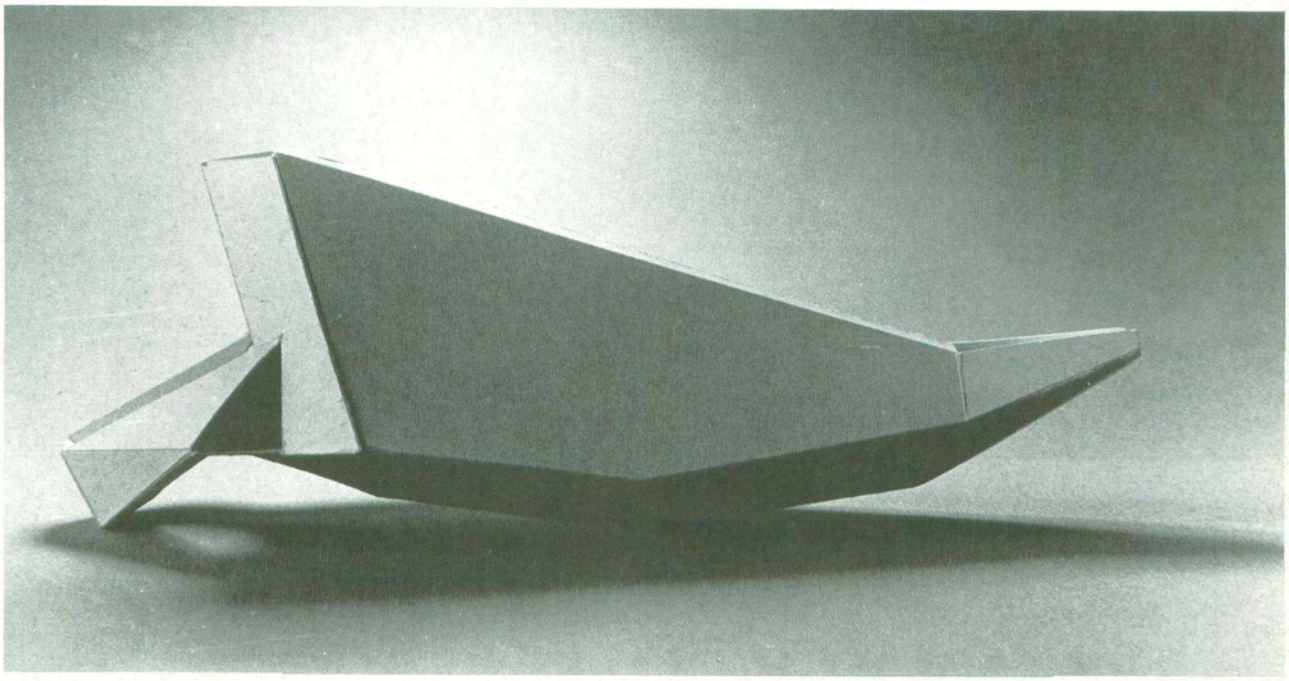
Models of the pentagonal prism and the jaw, connected together.

Of course, in some cases, the inserting of these new forms will require changes in the previously designed forms.
An accurate check-up is made, in order to improve the coordination of the various pieces, towards an improvement in their functionality.
After these changes are made, we move on to the final assembling of the model.

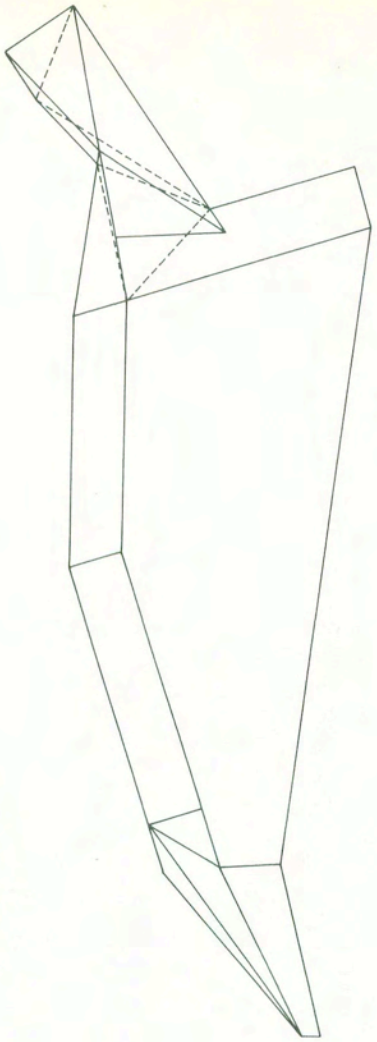




Example of modified piece.

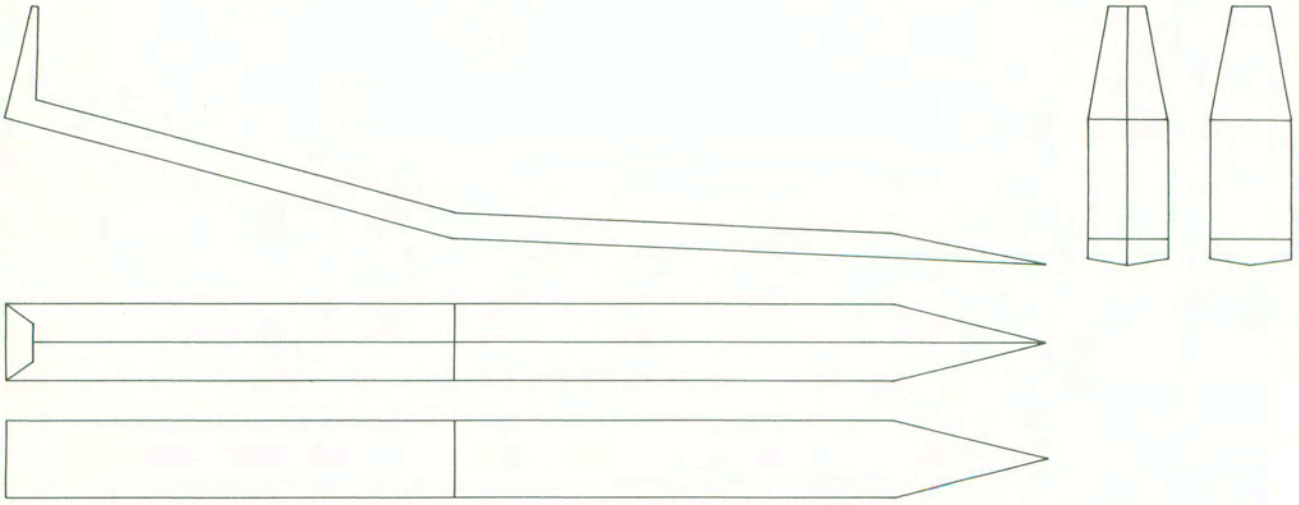


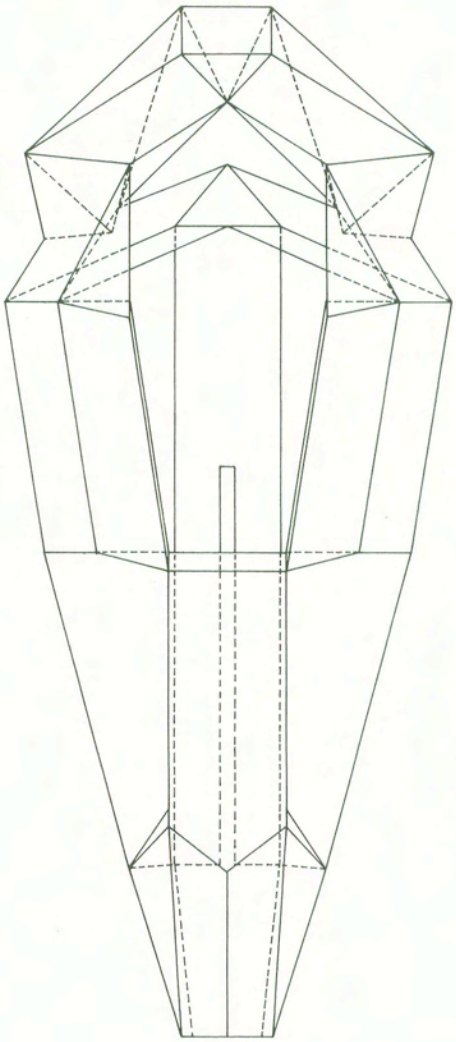
The same piece, seen in side view.

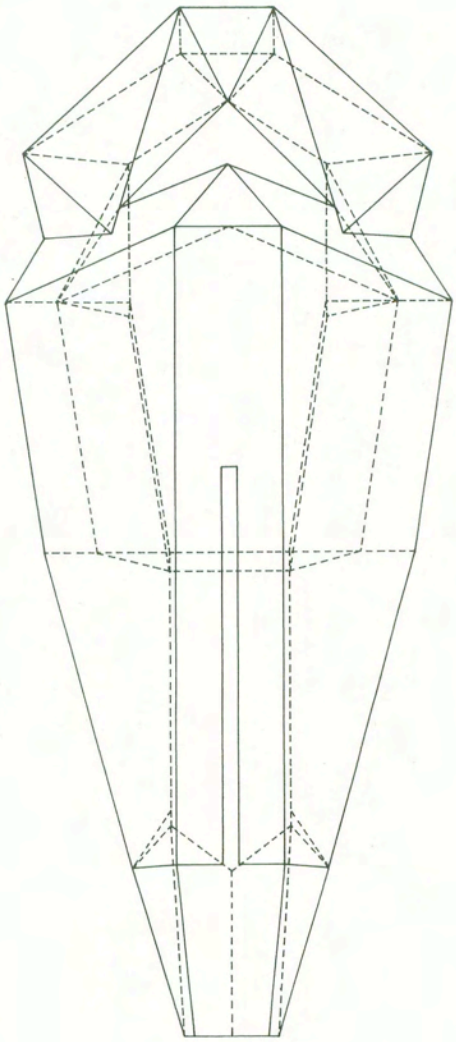


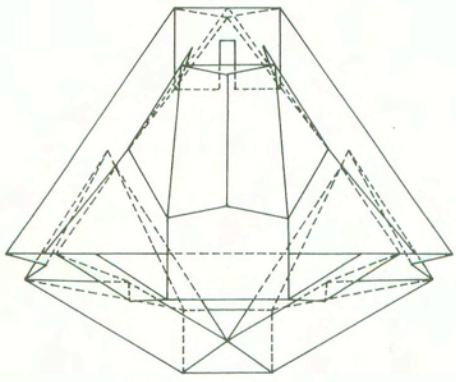
Construnction drawings of the improved jaw model.

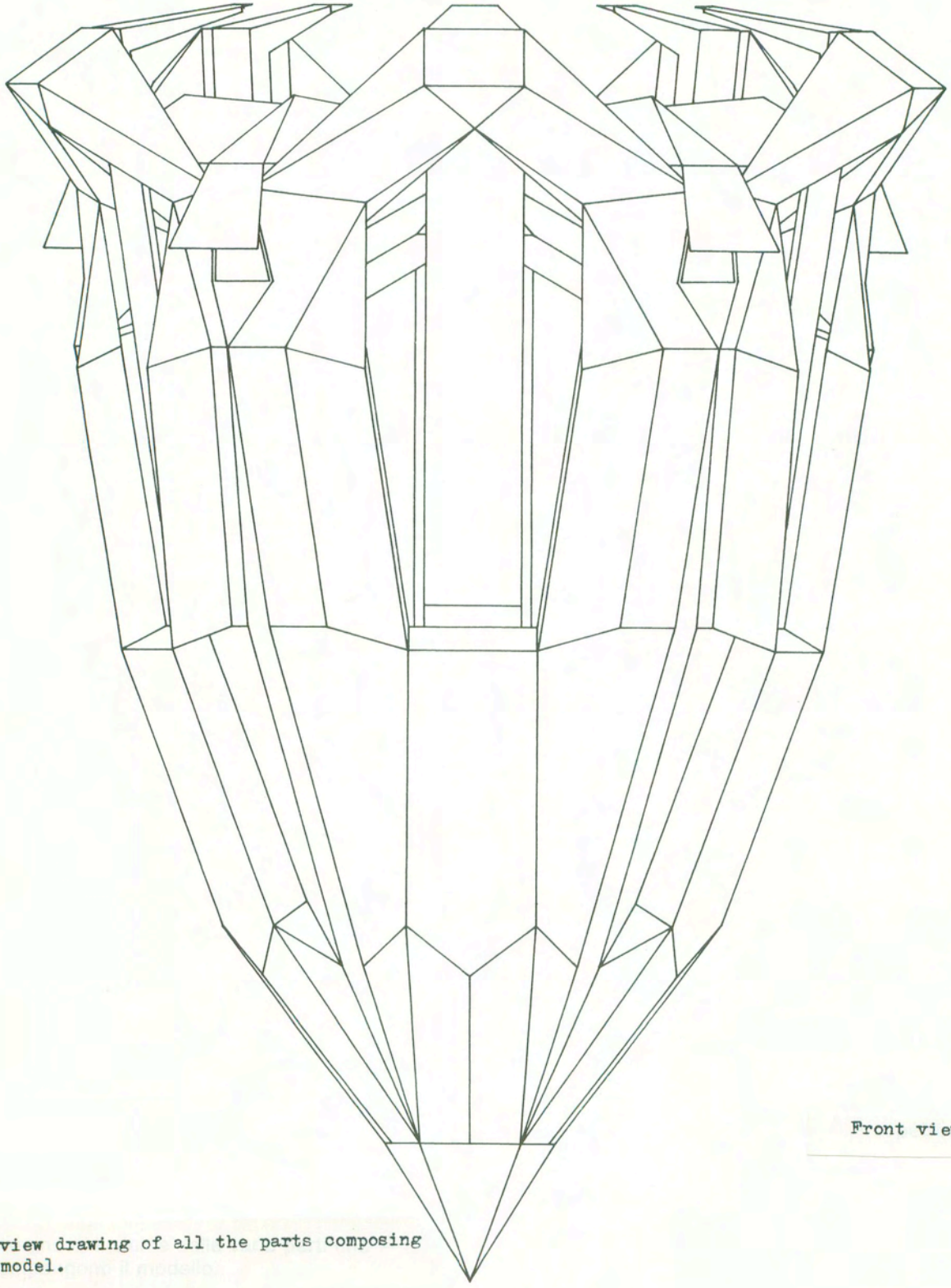
Drawings in top, front, and side view of improved retractile tooth.





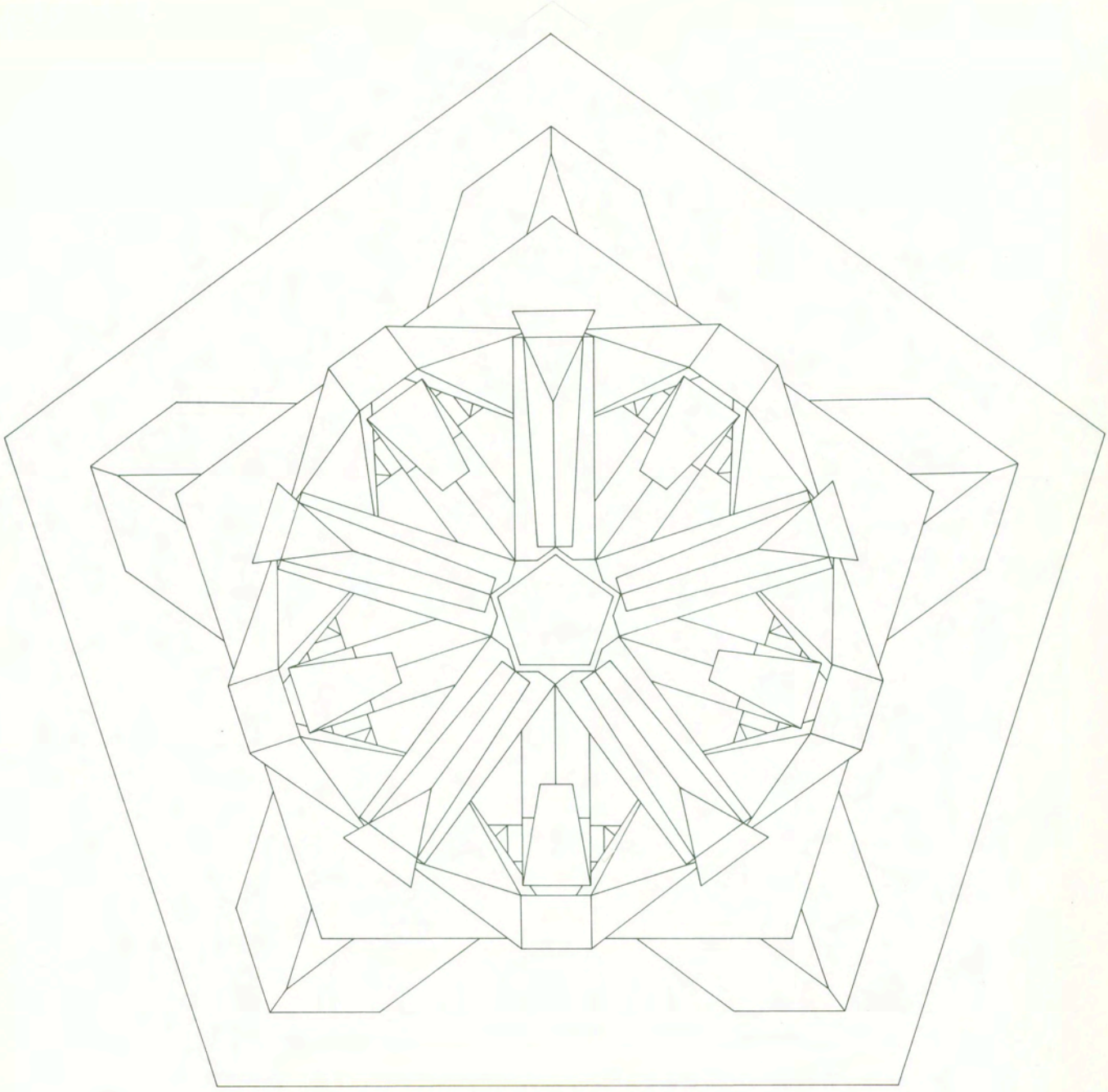




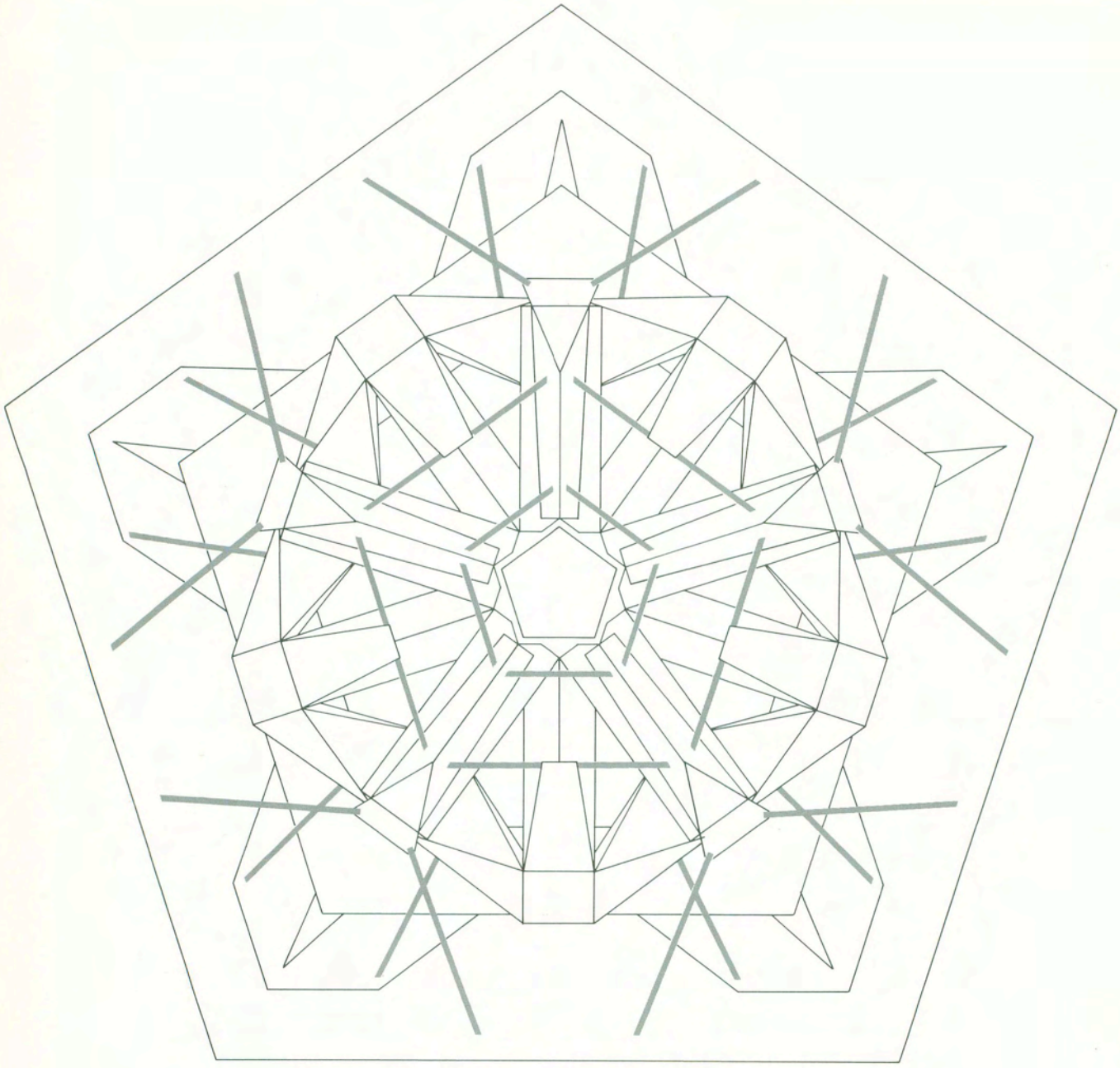


Front view.

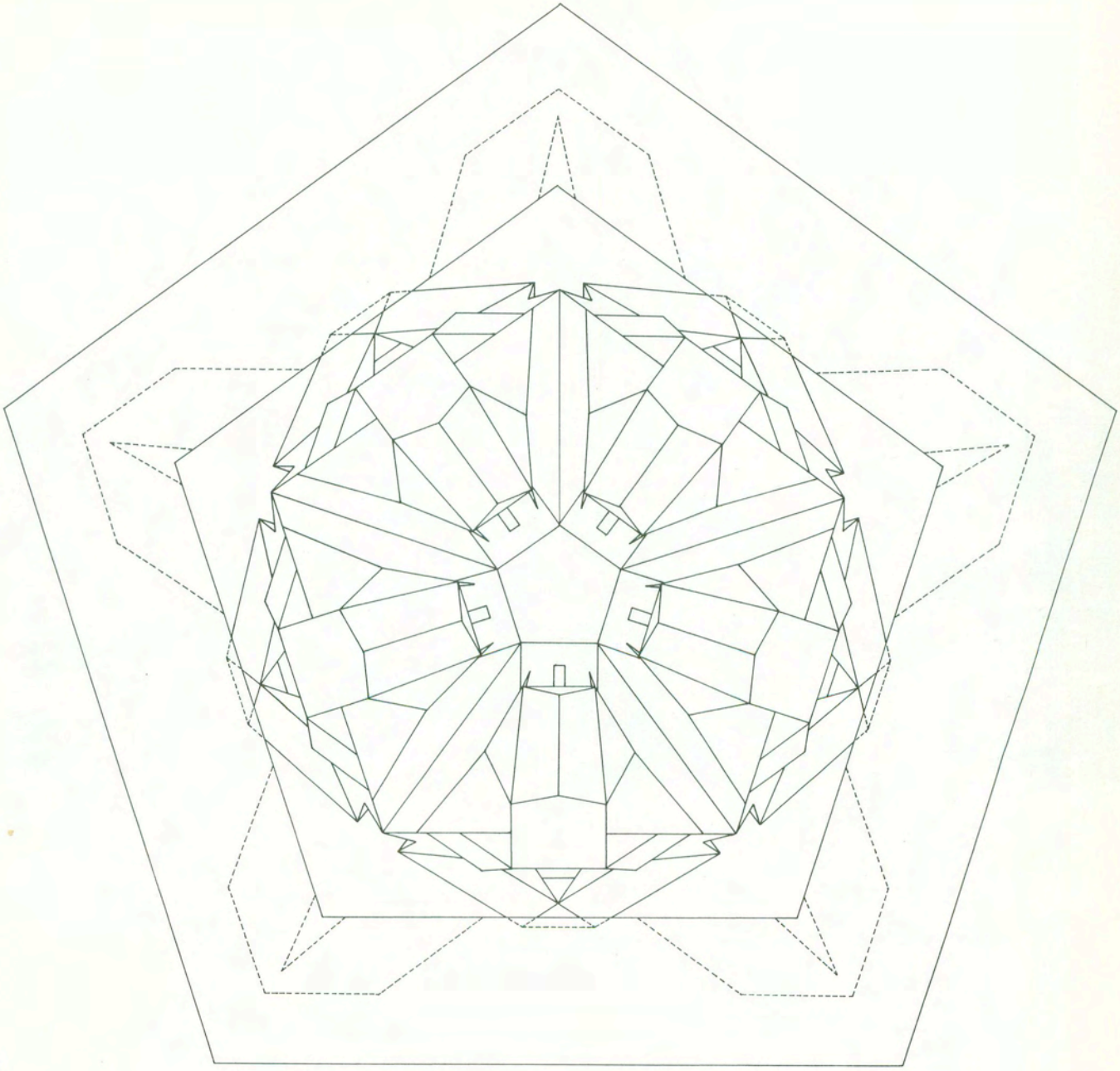
Overview drawing of all the parts composing the model.



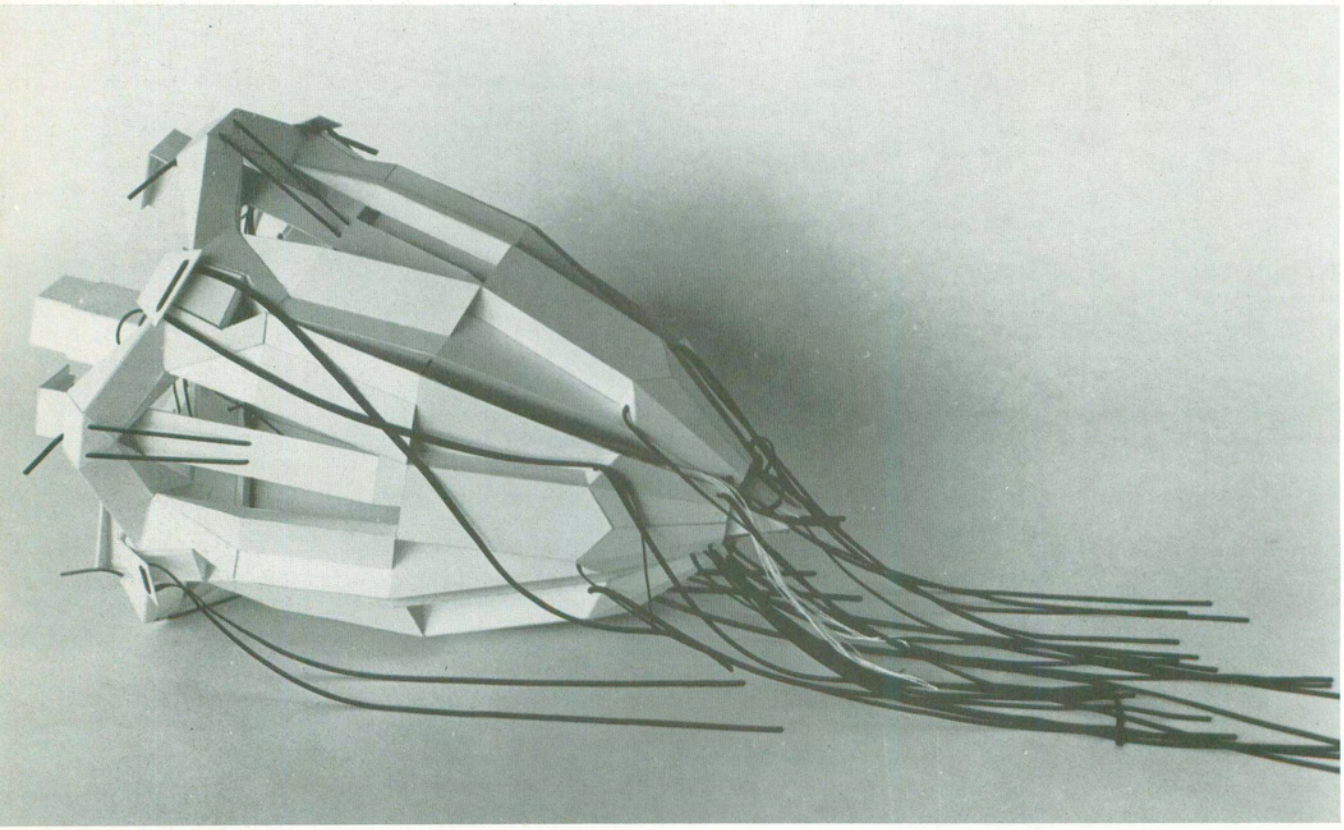
Top view.



Drawing showing the lay-out of the rubber bands which set the model in a state of balanced tension.



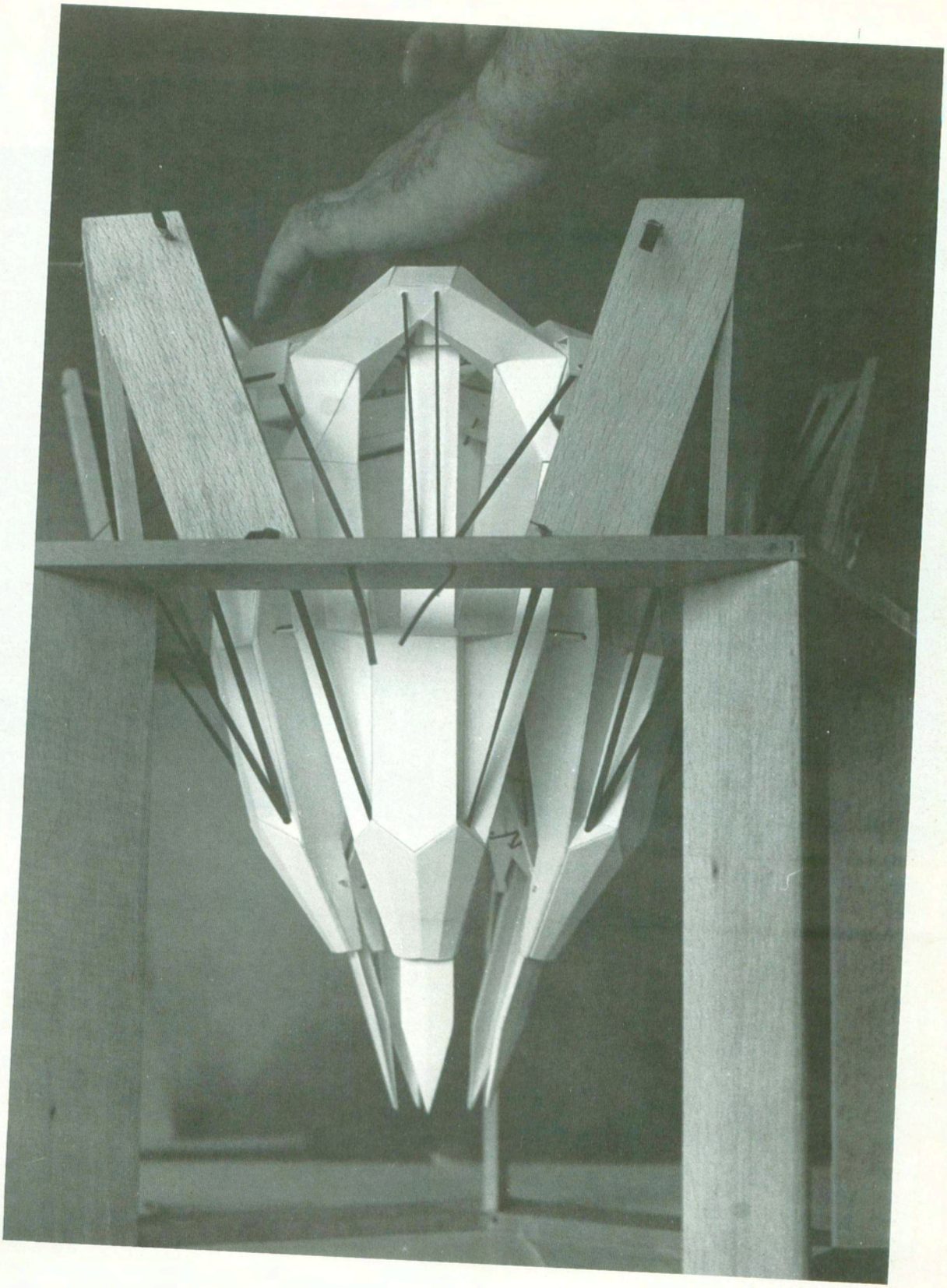
Drawing showing the same model, seen from a different position.

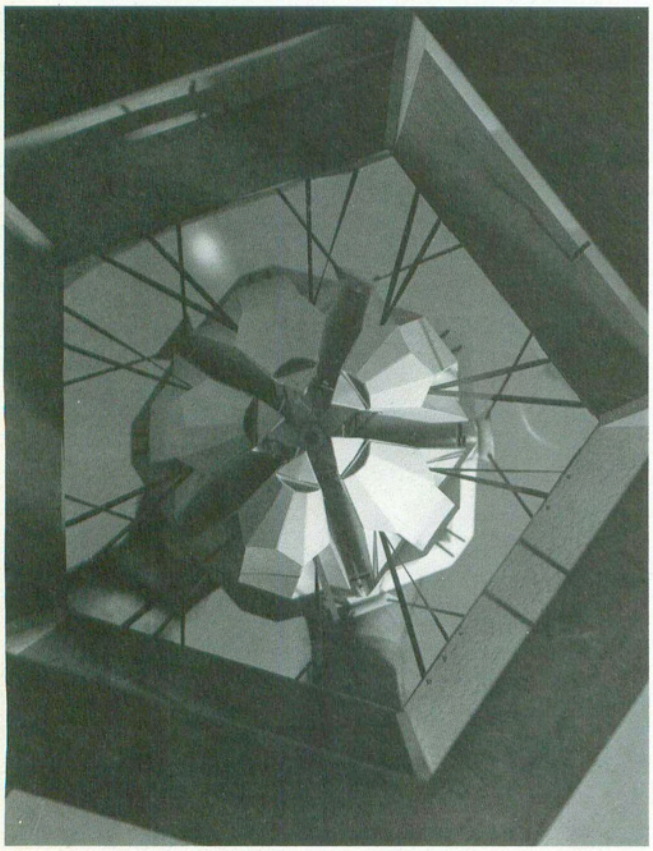


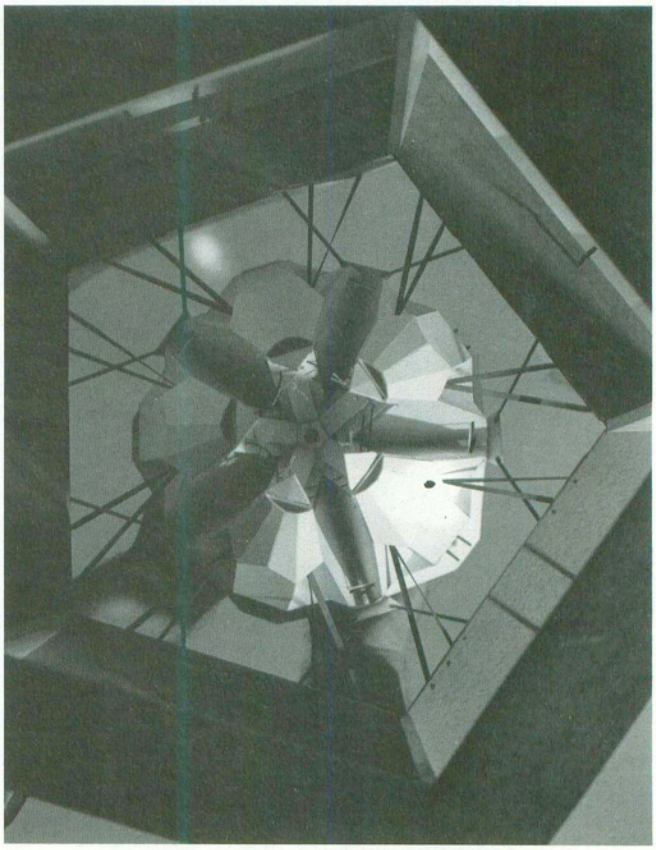
Model in the assembling phase.

When all the parts are assembled to form the complete body of the model, the precision problem of their pairing up and coupling must have been already solved.
The parts must be in an organic dimensional relationship which represents the constructive synthesis, the module of all the structural relationships.
The model has to visually convey the degree of constructive synthesis which we have reached.
This holds true for the parts which are in direct contact, but also for the parts in the structure which do not directly touch each other.
Measurements, dimensions and forms must obide to this principle.

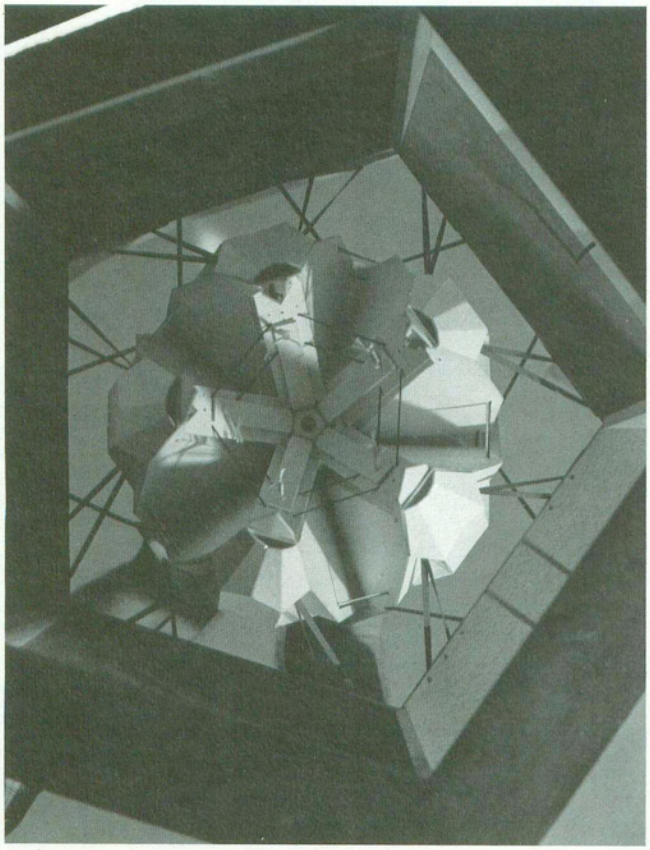
Final phase of the assemblage which shows the model inserted on a supporting structure, the opening of the end part, and the downward movement of the teeth.

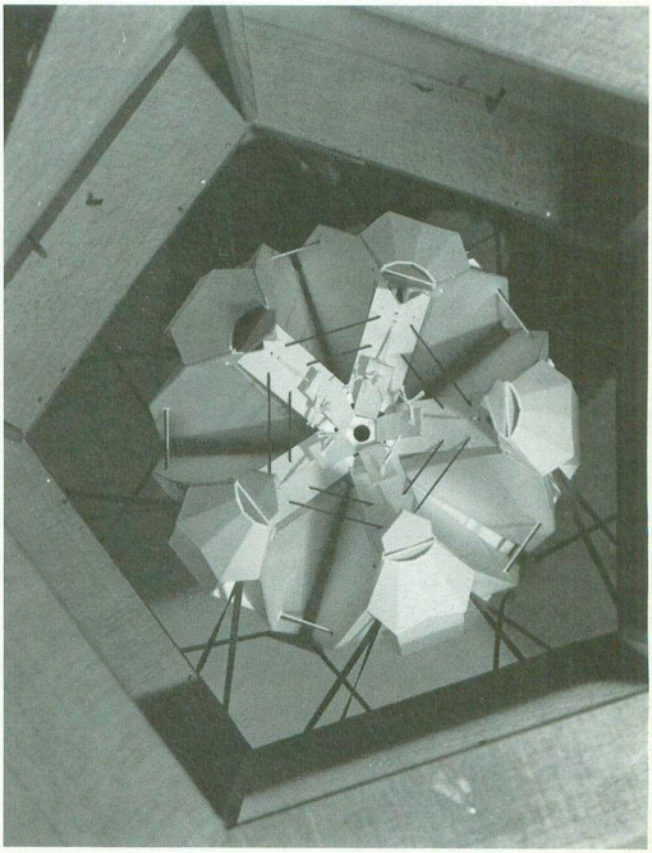


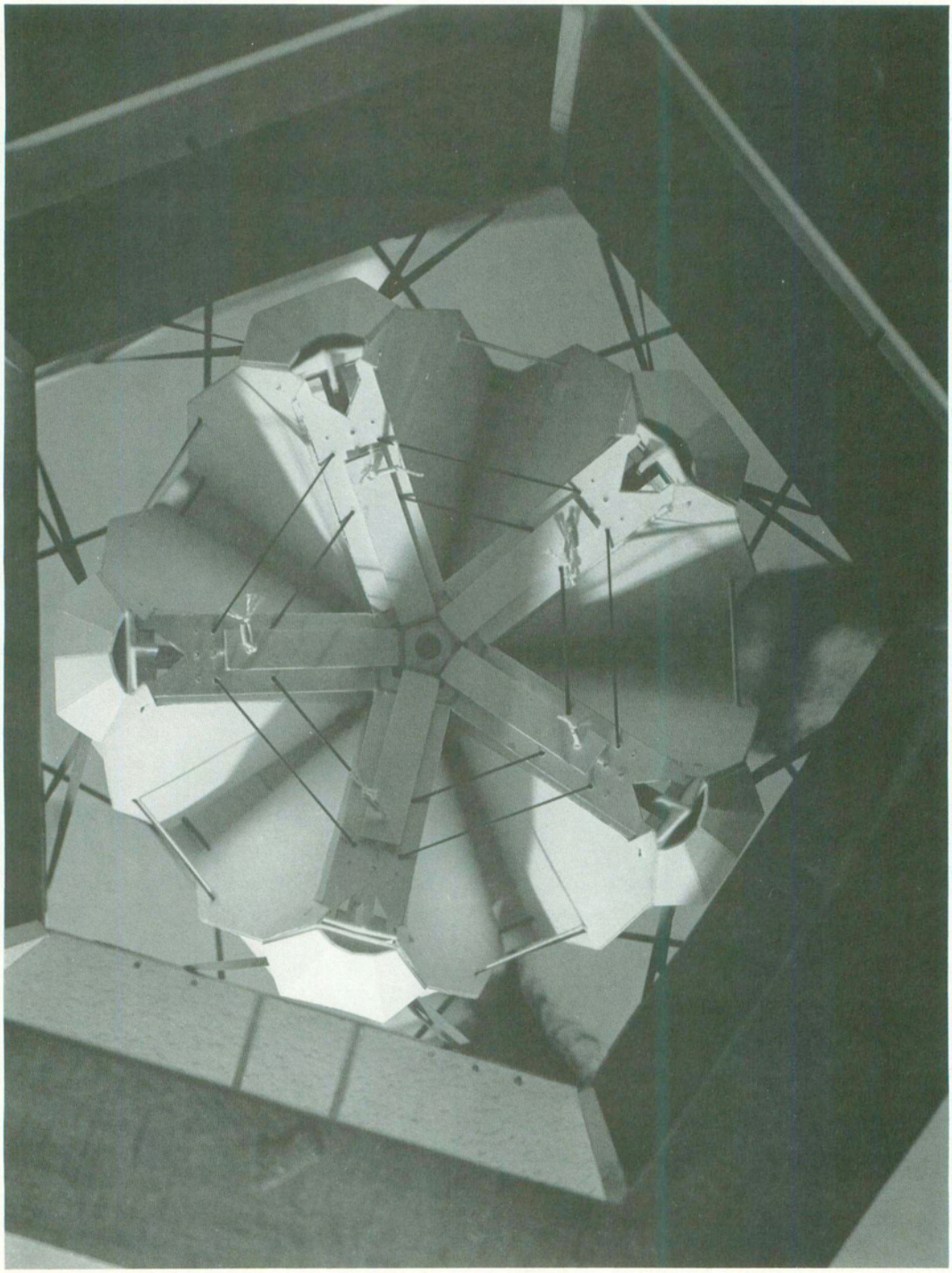




Mouth opening sequence, from a minimum to a maximum.

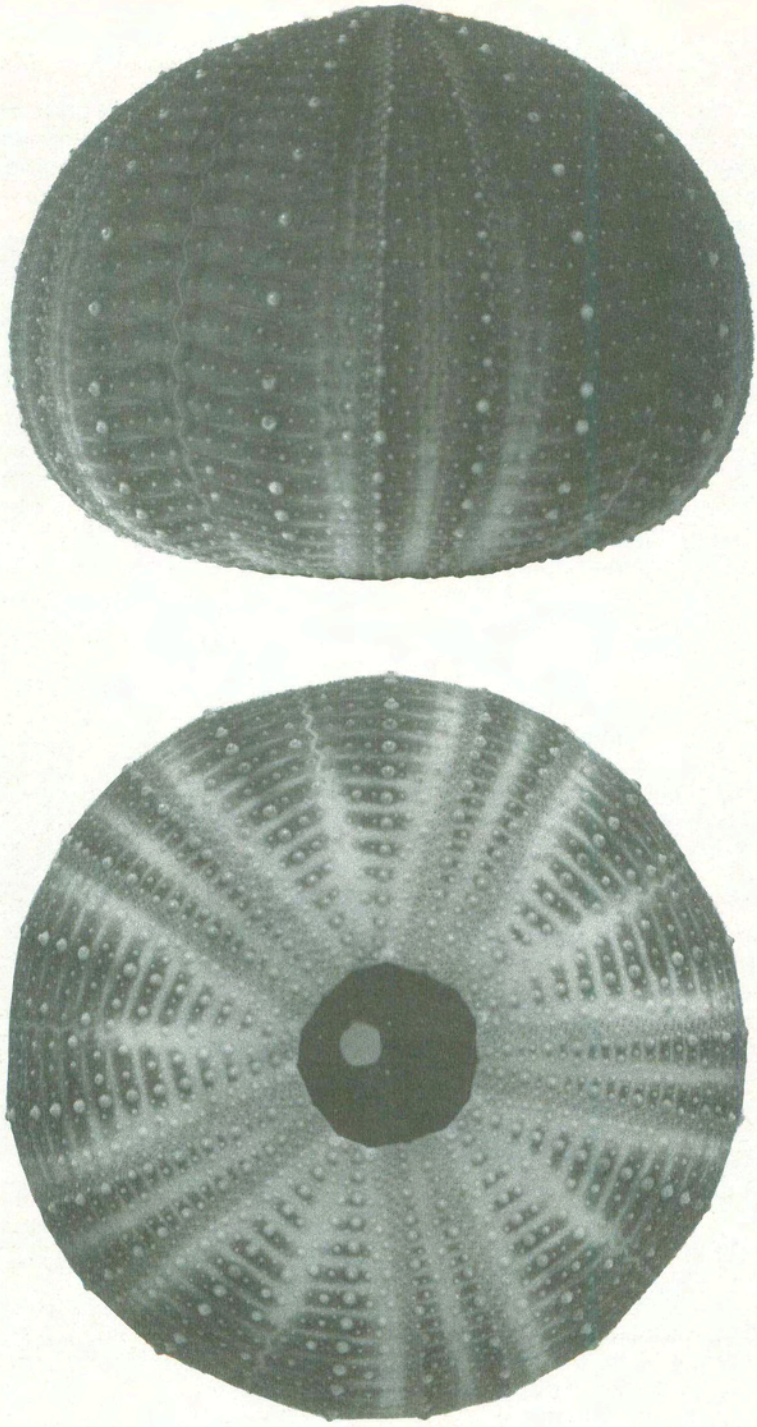




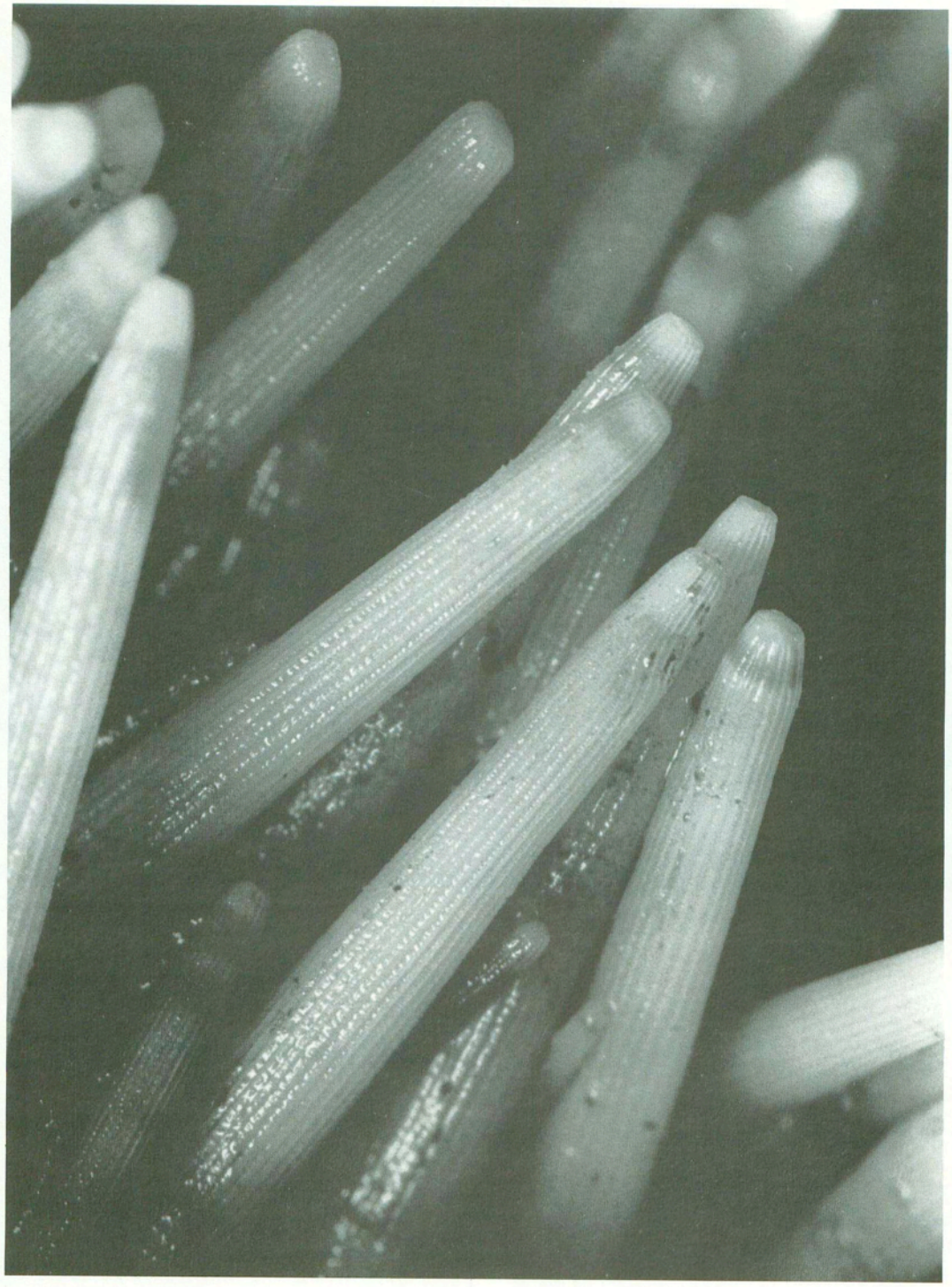


THE SHELL

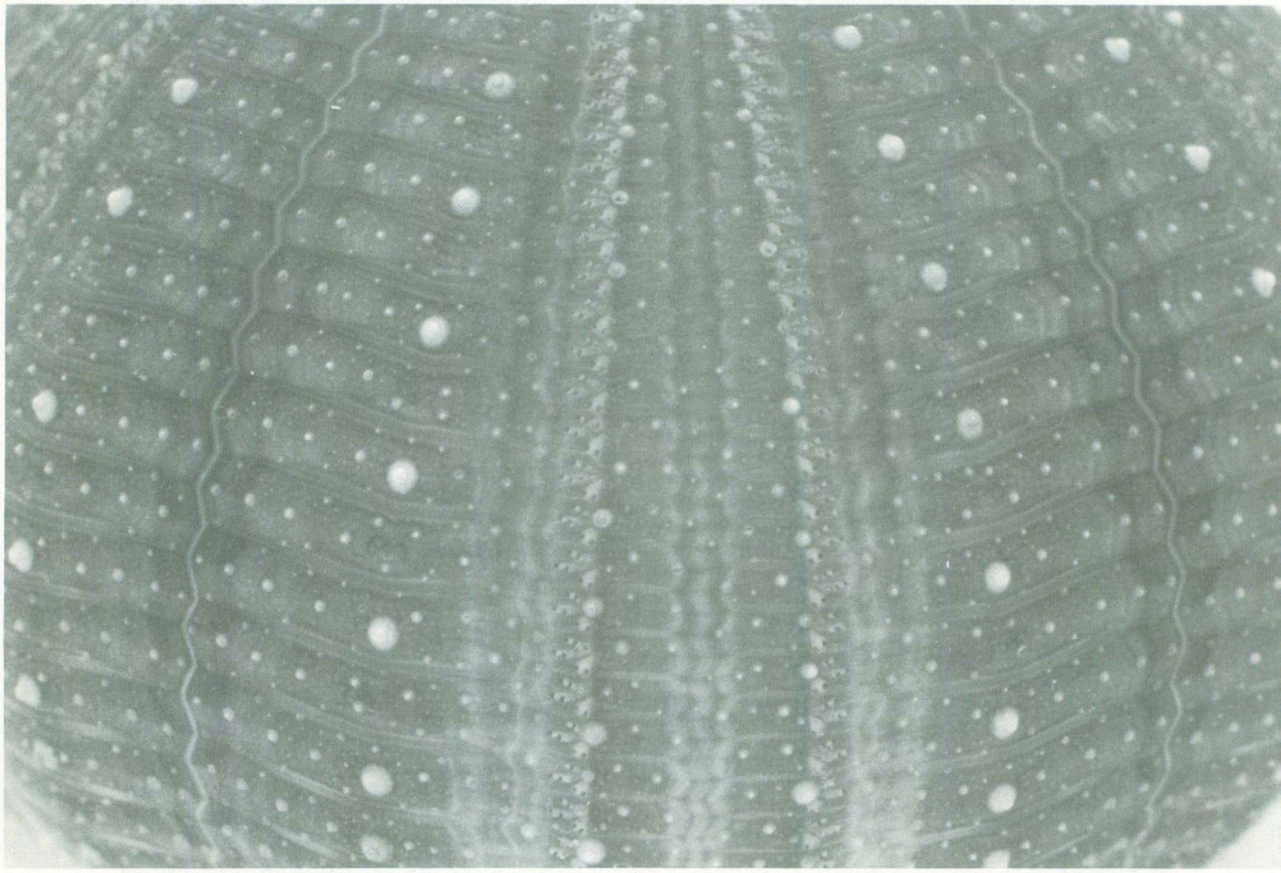
We observe now the appearance of the shell, how it looks from the front, what shape can it take on if we observe it from the top or from the bottom. We move it around slowly in our hand to understand if its overall shape mantains a constant curve. Or, if, from some barely perceivable indication, it is possible to reconstruct the shape of some unknown polyhedron.
For the moment, the contact of the fingers with the surface of the shell conveys a feeling of roughness, as if the fingers were touching sand paper with, in addition, something smoother.
If we observe the shell more closely, or better if we observe it slowly through a hand lens, we will notice many small spheres of various dimension, each one being partially inserted inside a truncated cone. Each cone holds up a sphere and is larger at the base, growing out from the surface of the shell.
These small spheres do not appear to be randomly arranged, but rather orderly distributed on the surface of the shell. They seem to be located on the lines of maximum curvature and be arranged in rows running longitudinally from one pole of the shell to the other.
If we look inside the shell through the large opening, we see the small opening located on the opposite pole, surrounded by five very tiny holes.
Light also penetrates the shell through rows of small holes, alternating two by two in a zig-zag fashion. These form an overall pattern of five pairs of rows, which have their originating points in a clearly visible pentagon, situated on the upper part of the shell, around the small opening.
Departing from each of the five vertexes of the pentagon, two rows of holes draw two diverging lines which end without meeting again, on the opposite pole of the shell. Here, the large opening begins and, from its edge, an architectural structure in the shape of a pentagonal crown, rises up, slightly bending towards the inside of the shell.
The holes which we observed on the external surface of the shell are now hardly visible, located as they are between a smaller and a larger sector.
In fact, the shell clearly appears to be divided up into complementary pairs of larger sectors, and of complementary pairs of smaller sectors.



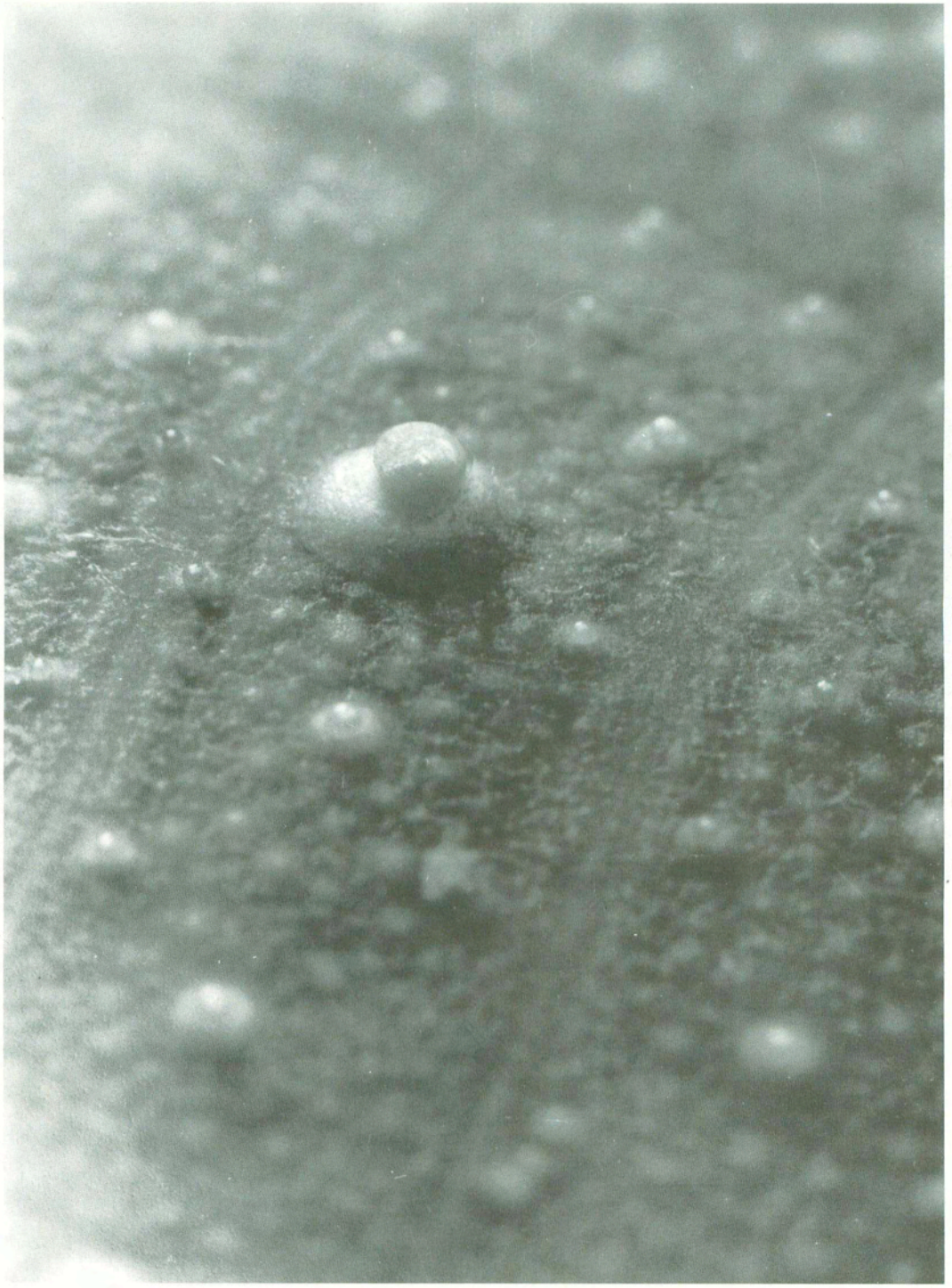
Front and top view of sea urchin.

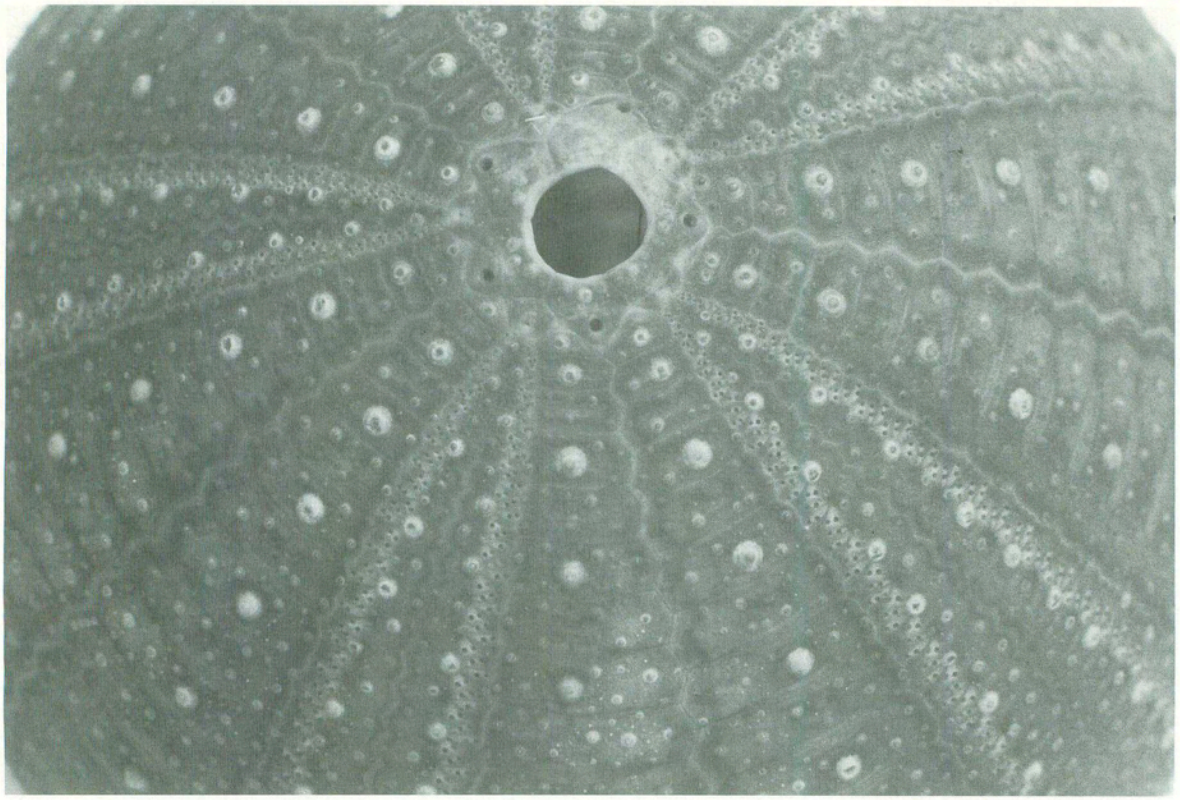


Enlarged view of forms and structures of the shell.



In this photograph, among other forms, you can see the joining lines of the sectors. The picture on page 79 shows the spheroidal element which allows the movement of the spines on the base of the shell. These in turn allow the movement of the sea urchin along the bottom of the sea or on submerged reefs.



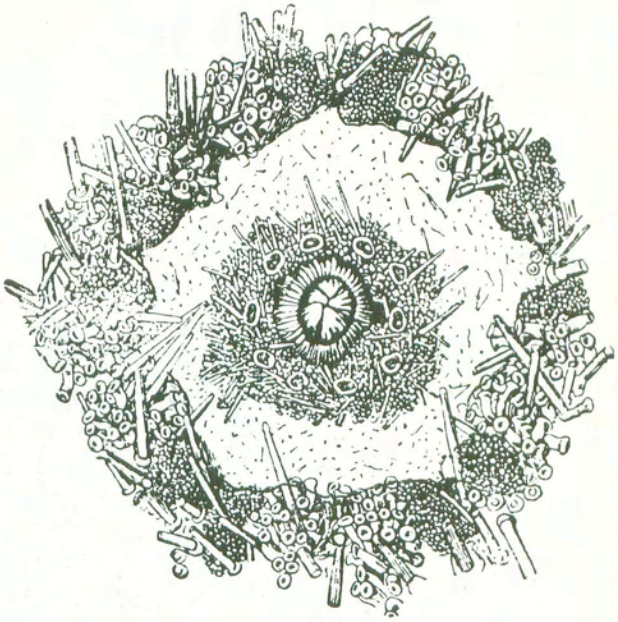


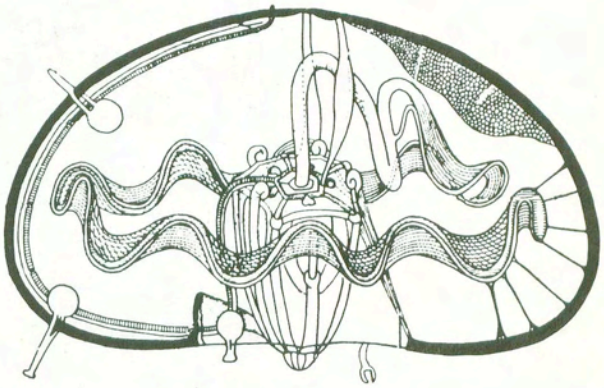
THE SEA URCHIN

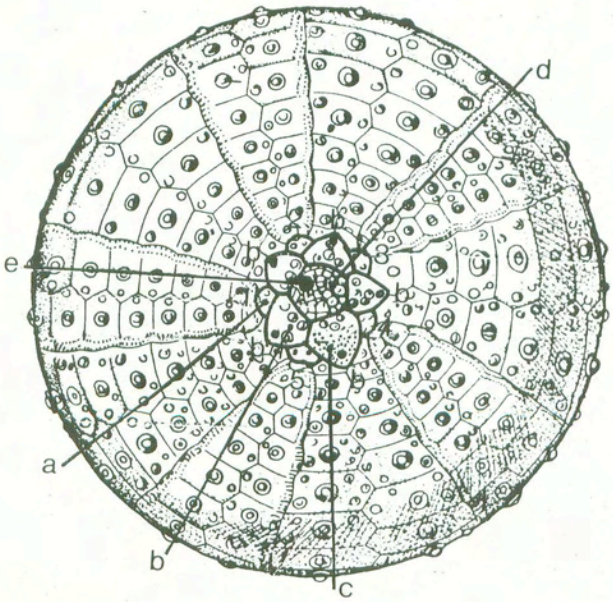
Sea urchin and starfish are among the most well-known of all the sea inhabitants belonging to the echinoidea.
The echinoidea, or sea urchins, have a few fundamental characteristics in their structure. Their body can be sphereoidal, chord-like, or resemble a flattened disk. Their shell is made up of numerous calcareous plates found in the inner part of the skin. Sometimes they are connected to the skin to give rigidity to the shell. At other times, these connections allow the shell increased flexibility.
The small plates usually carry spines which can be rigid, thin, or flexible, or even take the shape of thick short sticks.

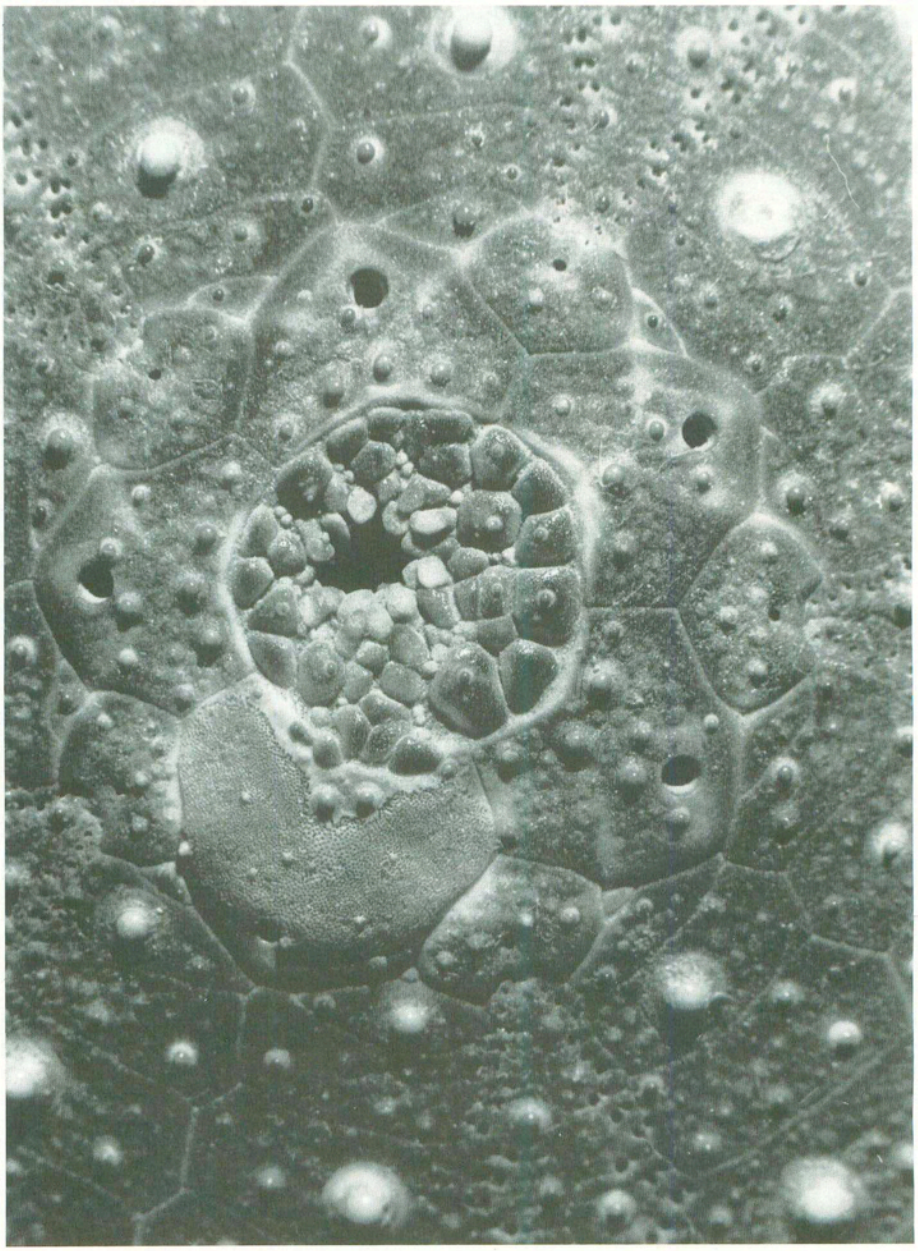
The organization systems of the plates constituting the shell of the sea urchin are quite diversified:
I. five ocellar plates (a), five genital plates (b) of which one is a madreporite or madreporic plate (c), form the so-called apical system.
2. small membraneous plates (d) which include the anus (e) form the periproctal system.
3. the membraneous area surrounding the mouth forms the peristomial system.
4. the coronal system makes up for almost all of the shell. It is composed of meridian lanes of plates which extend from mouth to anus; these latter two constitute the two top and bottom poles of the shell.
In the sea urchins which have a regular and globe-like form, like those chosen for this study, the subdivision of the shell gives origin to a series of similar zones.
These zones are arranged in a radial way around a central axis passing in the mouth. Zones, or sectors, are radial and inter-radial. Altogether they are 20, perfectly joined together.
The plates which form these 20 meridian lanes are arranged in alternate pairs.

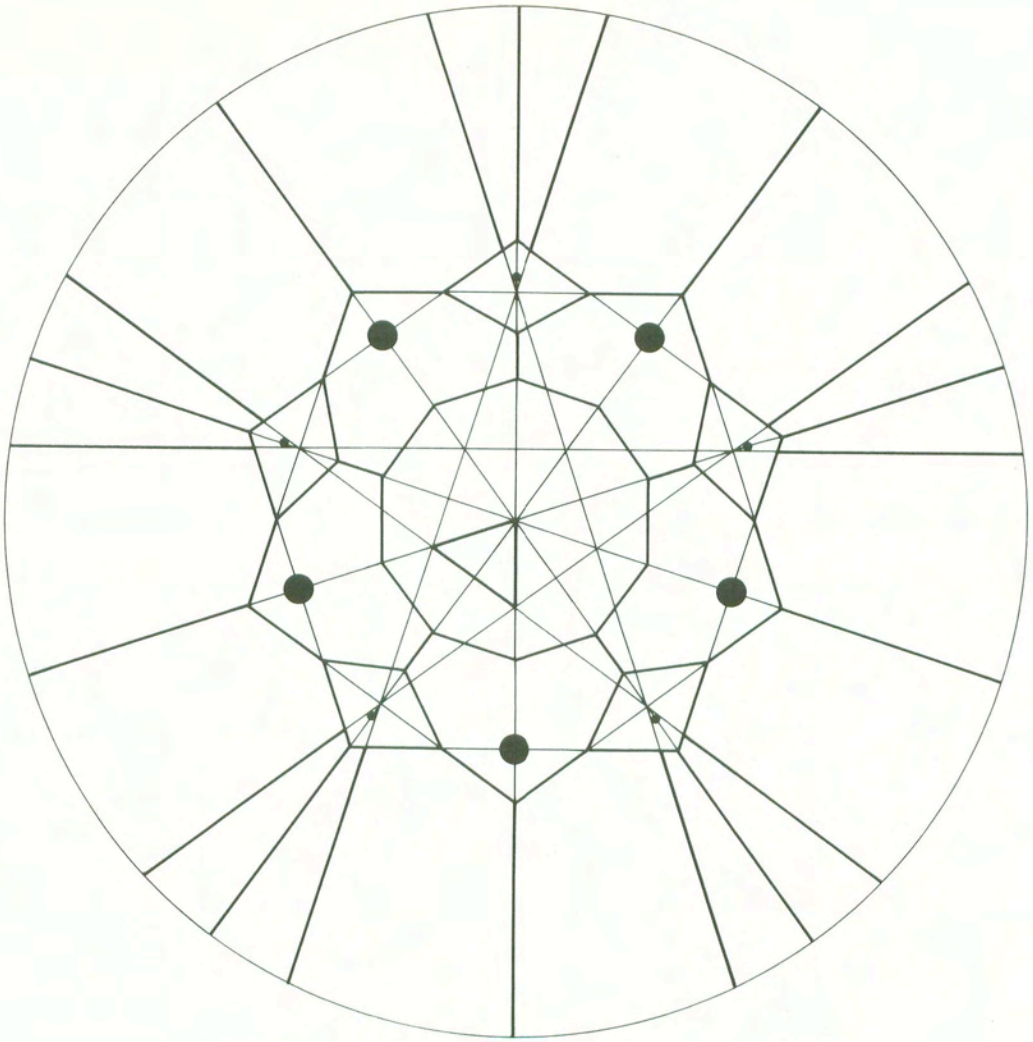
In the sea urchin, the number of sectors derives from the apparent, more or less regular, penta-radial symmetry in which the animal seems to be divided.
In reality, this animal's original symmetry is bilateral.
An evident bilaterality can be observed in larvae.
At the bottom end of the internal surfaces of the sectors, we find five calcareous attachment points or bridges, on which the powerful retractor muscles of Aristotele's lantern are inserted.
The lantern owes its name to Aristotele who studied it first.
It is a skeletal structure that supports five powerful teeth which enable the sea urchin to swallow food and dig niches into underwater rocks, where it then can station.
The mouth opens in the center of the lower pole of the shell and is constituted by the mentioned skeletal structure, by pedicels, by muscles and other soft parts.
The sea urchin uses the spines, which have movable joints at their base, to "walk" and slowly move on submerged rocks, or on the muddy or sandy sea bottom.
It uses the pedicels, which are like long, extendable and flexible tentacles, to bring the food to the mouth.





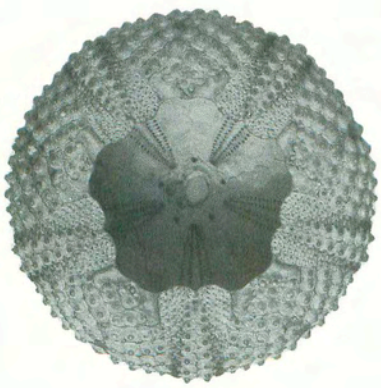






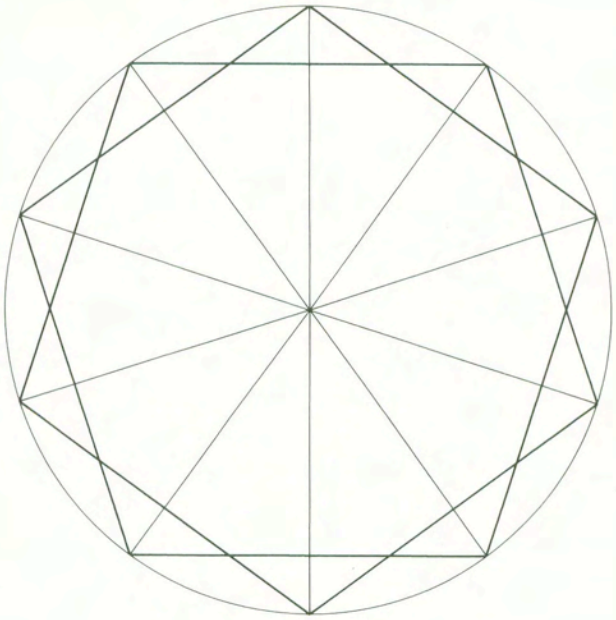
Subdivision of the sea urchin's shell.
This drawing shows a hypothetical geometric construction of the apical pole of the sea urchin's shell.
According to this interpretation, with respect to two of the five symmetry axes around which the twenty sectors composing the shell are arranged, the pentagonal body of an adult sea urchin can be divided in four parts.
None of these parts though, satisfy the necessary conditions to support a regular bilateral and specular symmetry.
According to the drawing, if a symmetry axis divides the madreporic plate in two parts, one of the two parts of the resulting shell division includes the anal pole, thus breaking the symmetry.

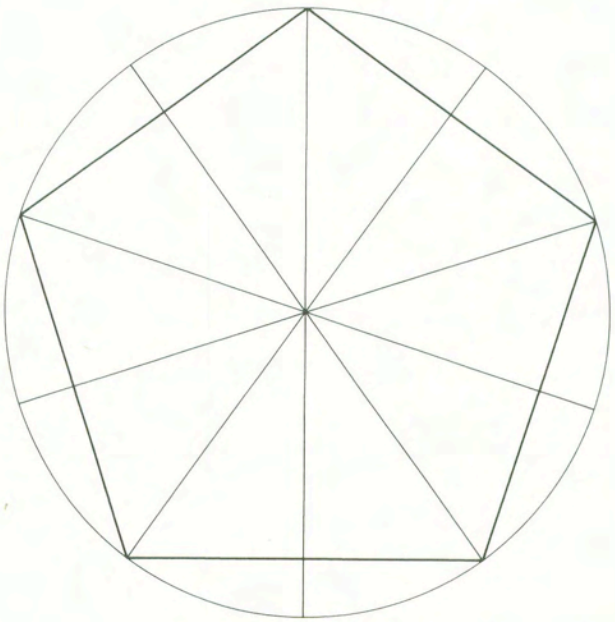
Vice-versa, if the symmetry axis divides the anal pole in two parts (represented in the drawing by the heavy-bordered triangle), one of the two parts of the resulting shell division includes the madreporic plate as a component of asymmetry.
The result does not change if the same operation is performed on the three other axes.

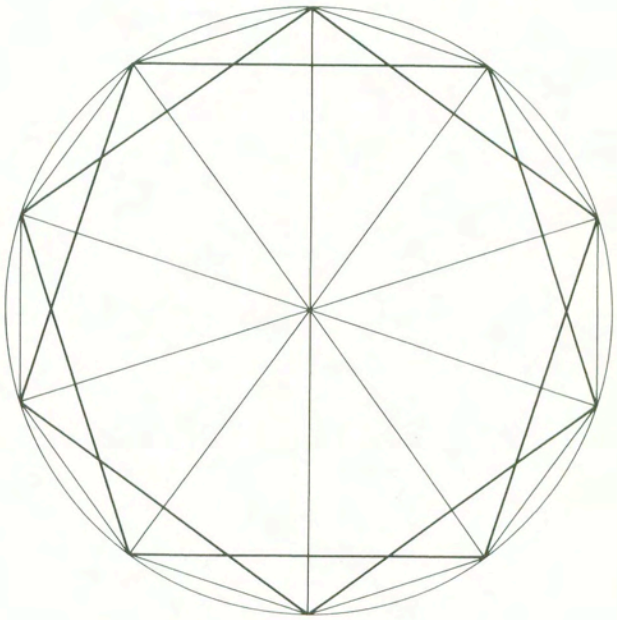


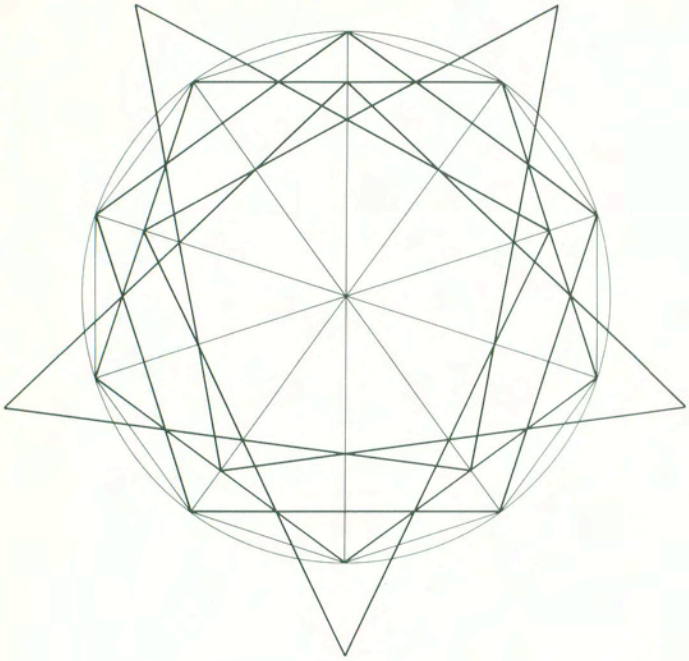
The drawing shows the articulation of the curves which make up the perimeter inclosing the membrane-like area. The mouth of the sea urchin is located in the center of this area.

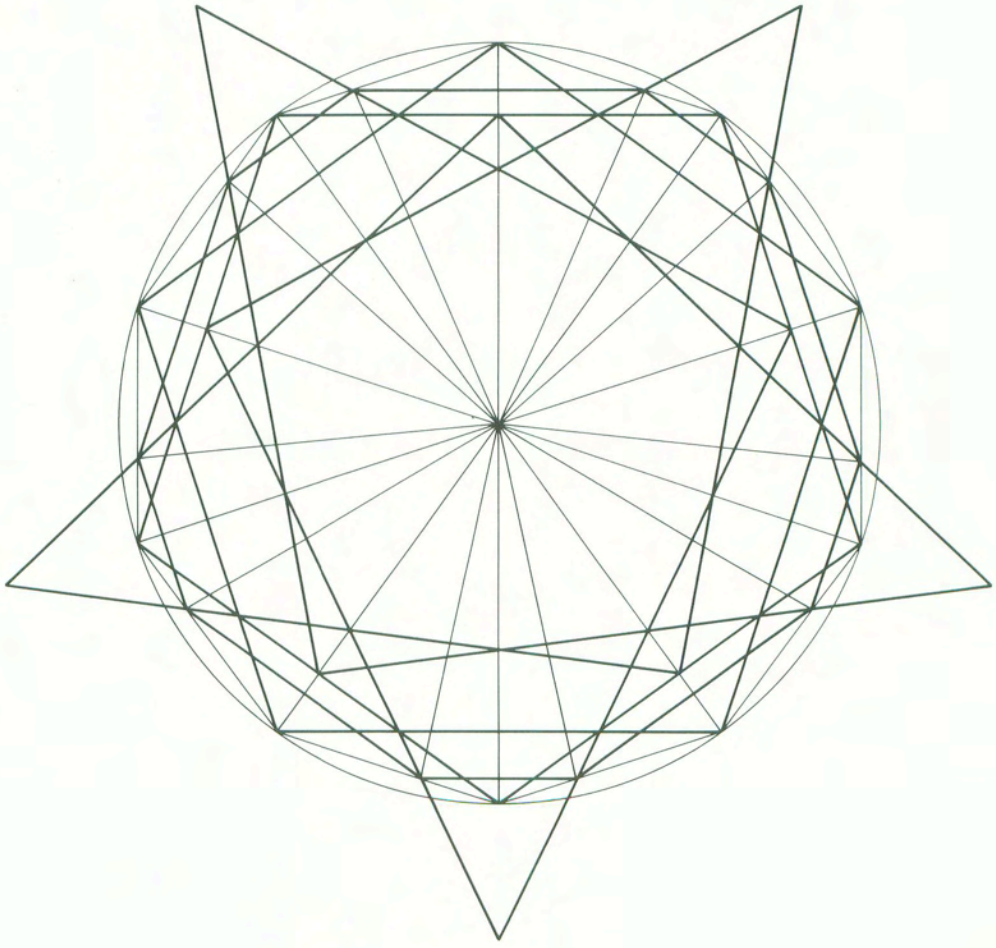
Geometric interpretation of the apical pole of the shell.
Study of the course of the division lines of the shell. We start with a pentagon being rotated around its own center. Then we continue with geometric operations which are co-related and consequential, keeping a constant reference to meaningful points of the pentagonal module. The angular values determining the course of the division lines of the shell are then established. Next, we find the perimeter of the polygon which includes the area hosting the urchin's mouth, and the beginning and end of each division line: connections from point to point of the two poles of the shell.
Points and lines establish a relationship between the two poles of the shell - between the apical system and the peristomial system.

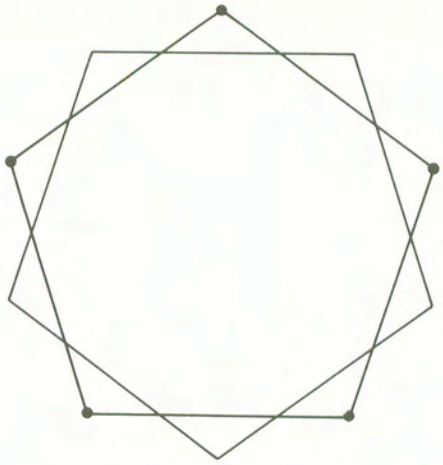


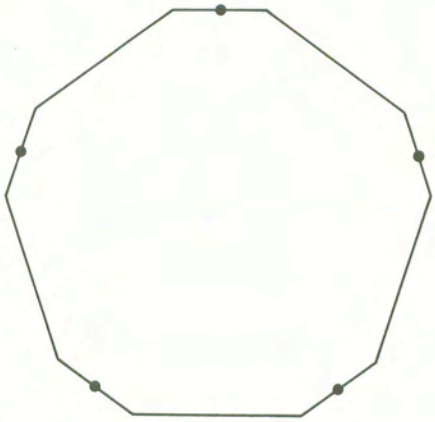


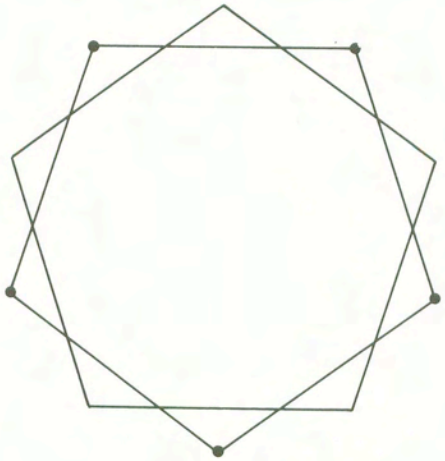


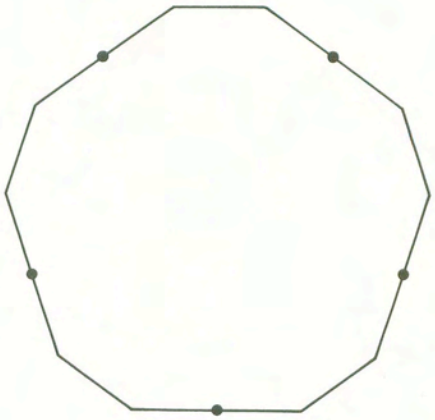


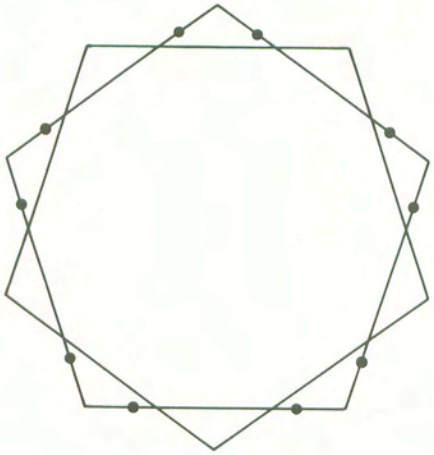


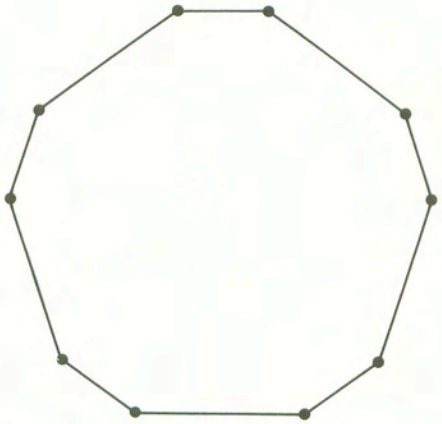


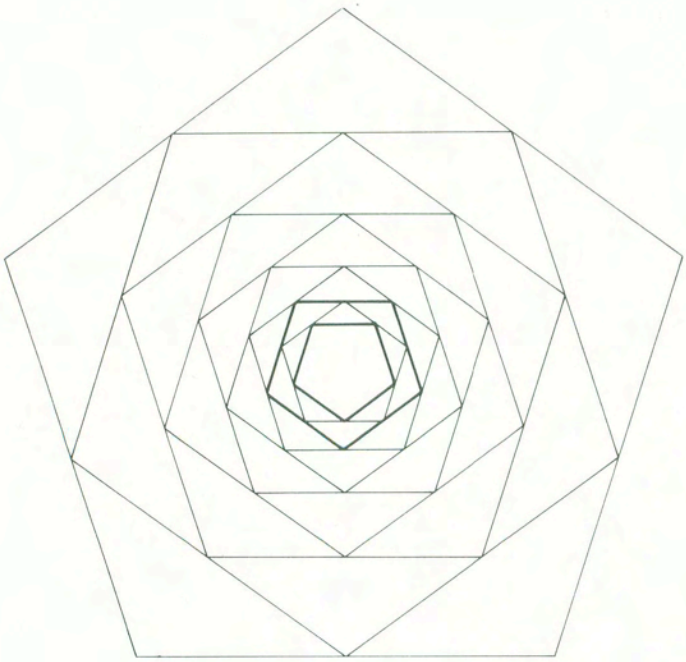




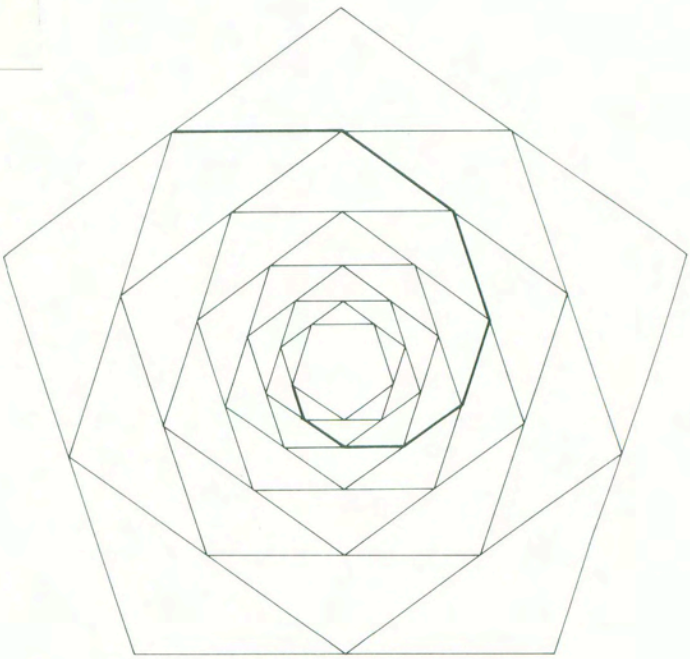


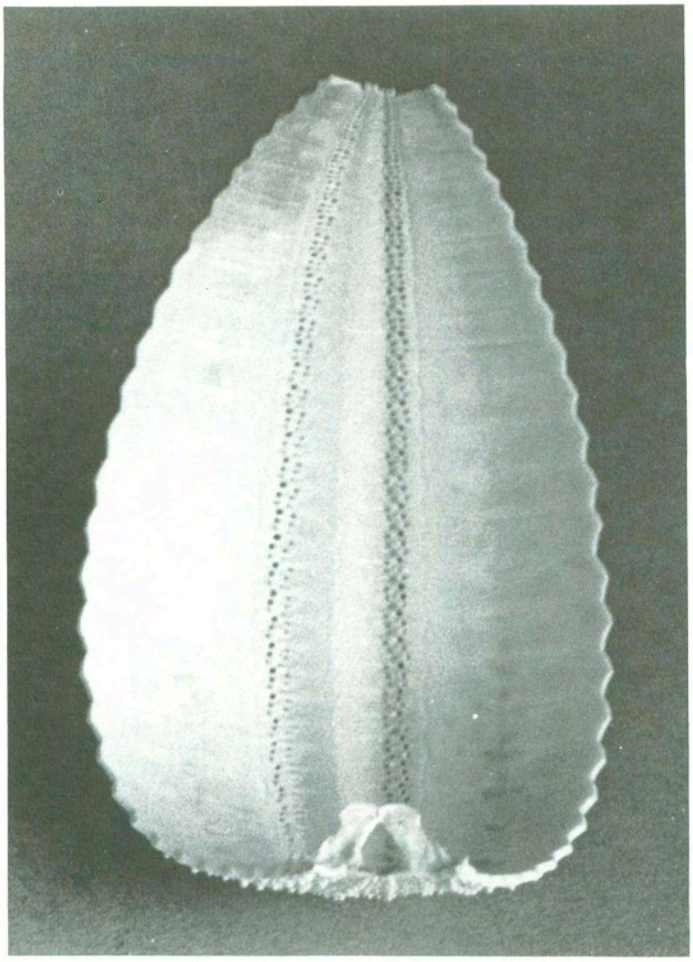




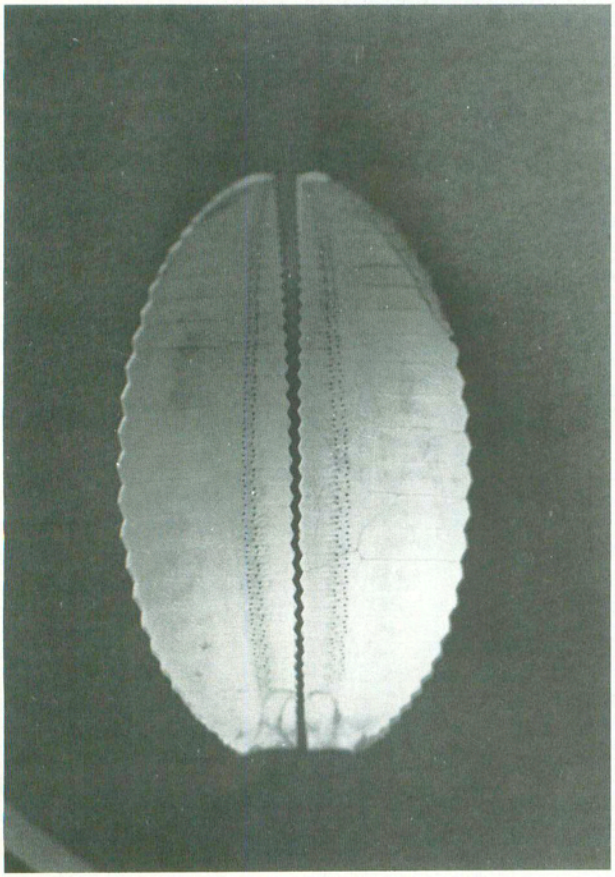


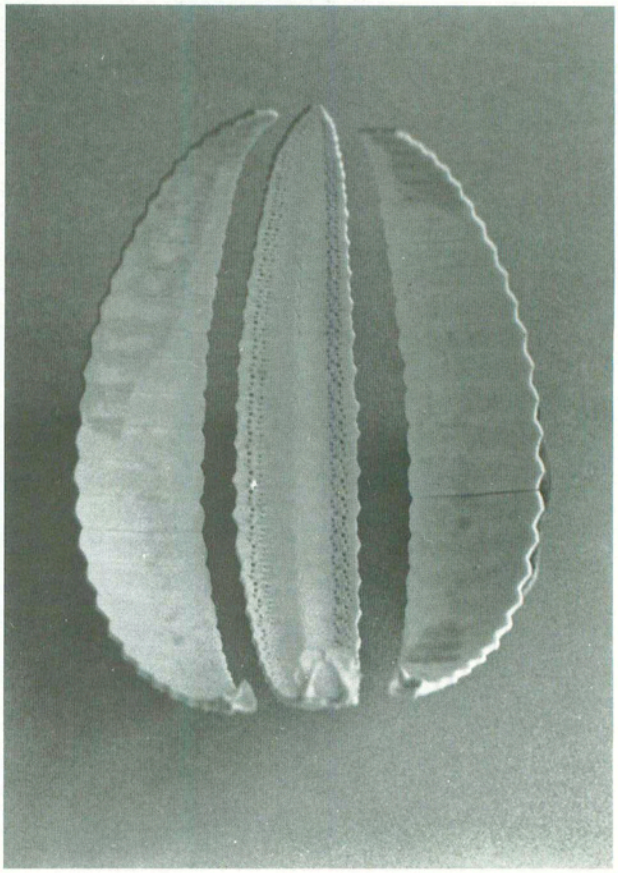
Shematic of the shift, rotation, and expansion movements.

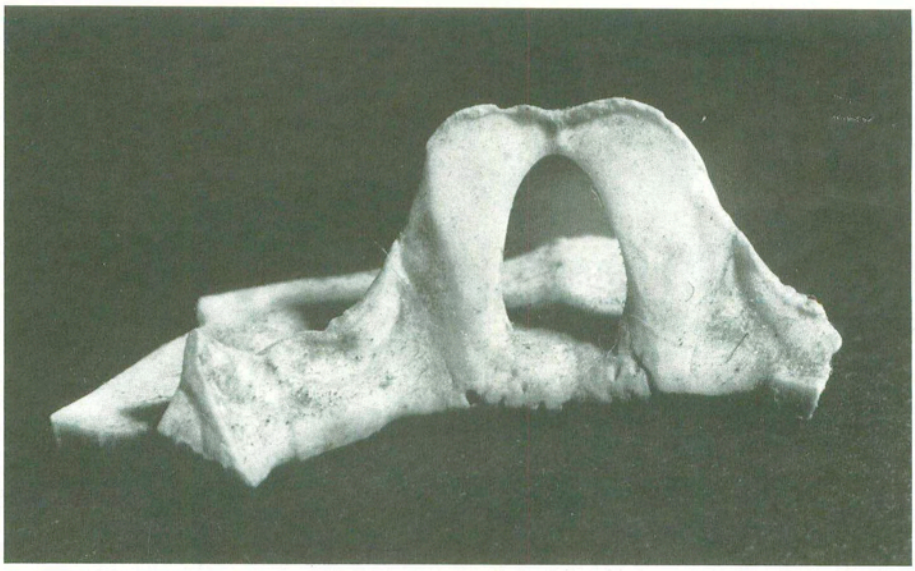


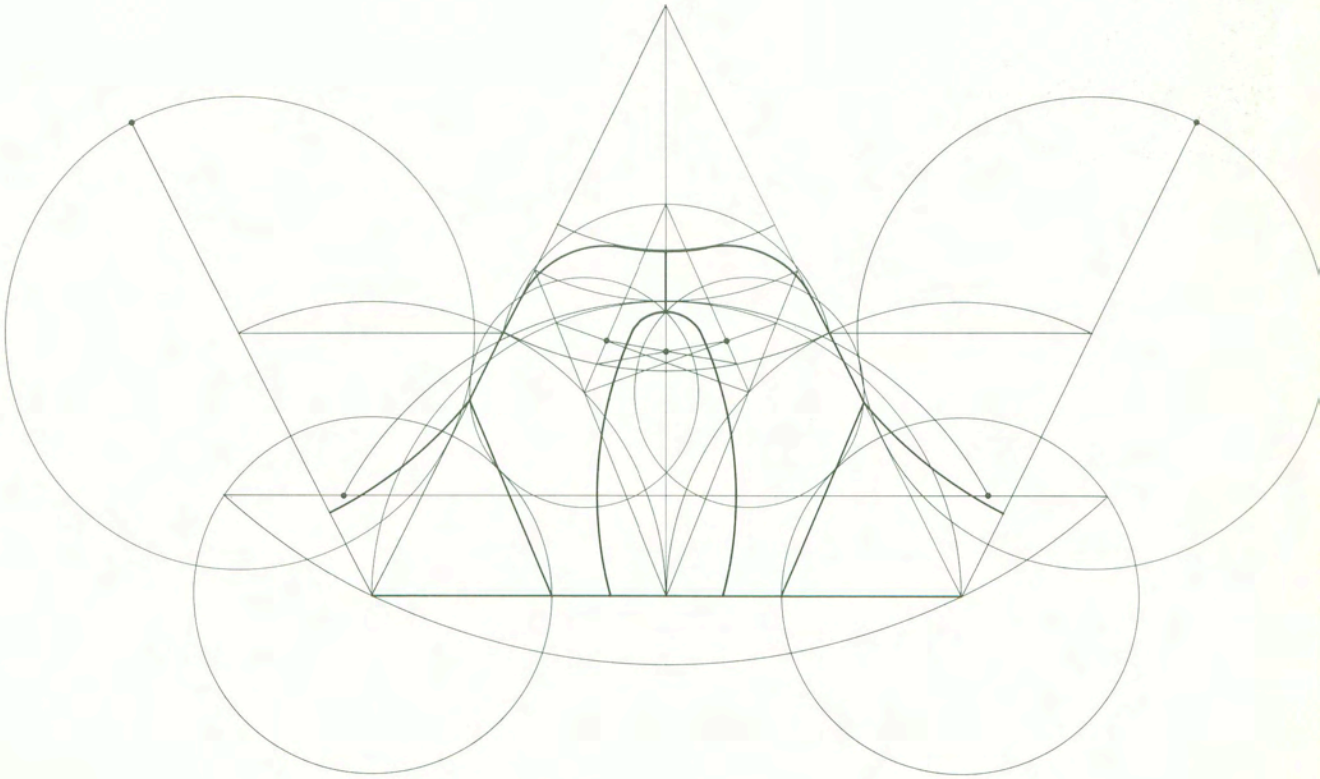


By carefully applying finger pressure on the shell, close to the joining lines, it is possible to separate the sectors forming the shell.
We will then be able to see the section of the small plates composing the shell, as it grows in thickness while moving from the top pole to the mouth located on the opposite pole.
Moreover, we will notice how the shell breaks up into twenty complementary sectors. The design of the sectionof the sectors reveals a tendency to favor solidity, mechanical strength, and lightness in all the components.
The photographs show how the attachment-points of the lantern's retractor muscles are sectioned along the same geodetic lines which divide the shell into sectors. This can be observed in the drawing showing a hypothetical geometric reconstruction.

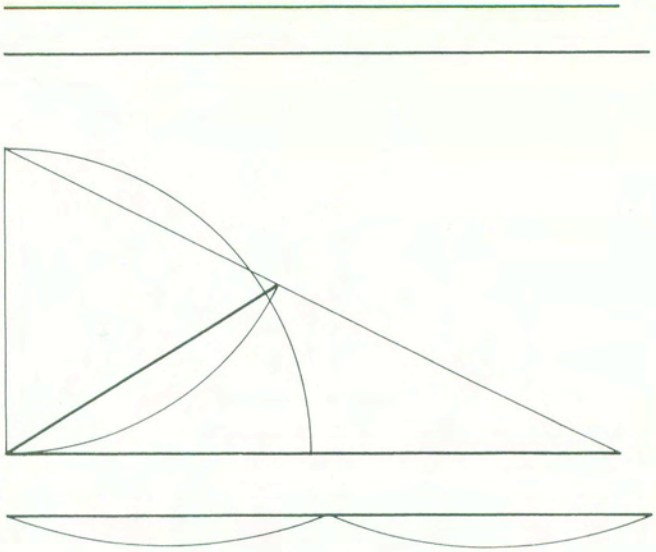


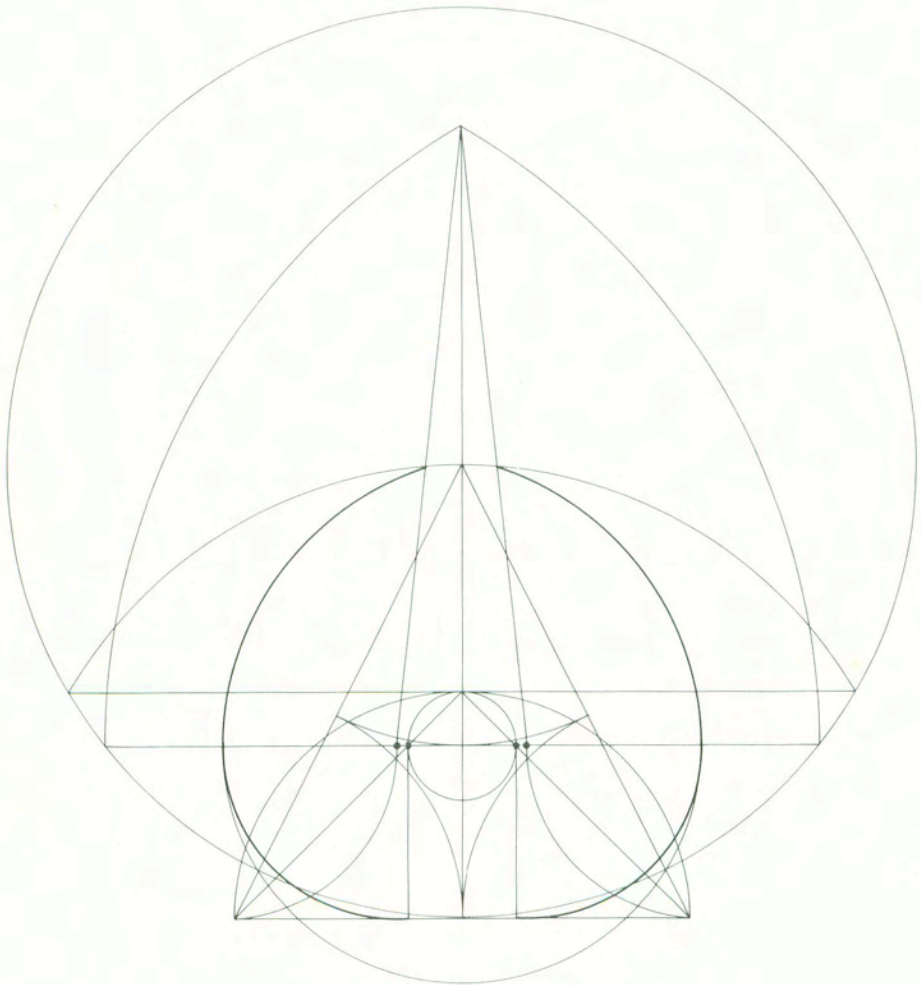


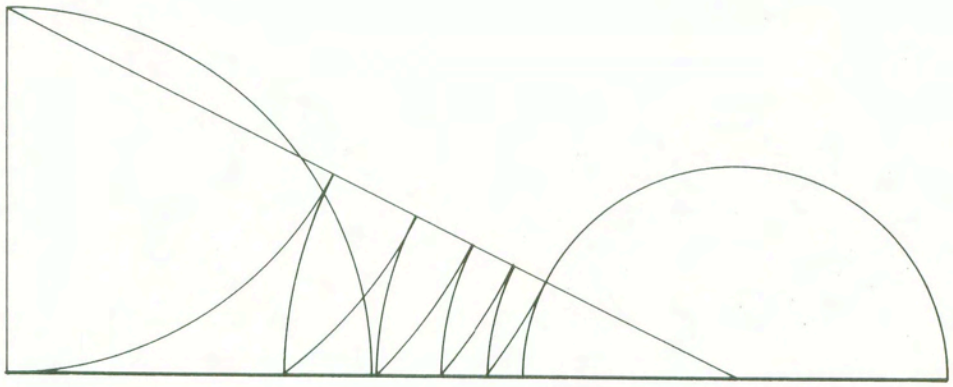


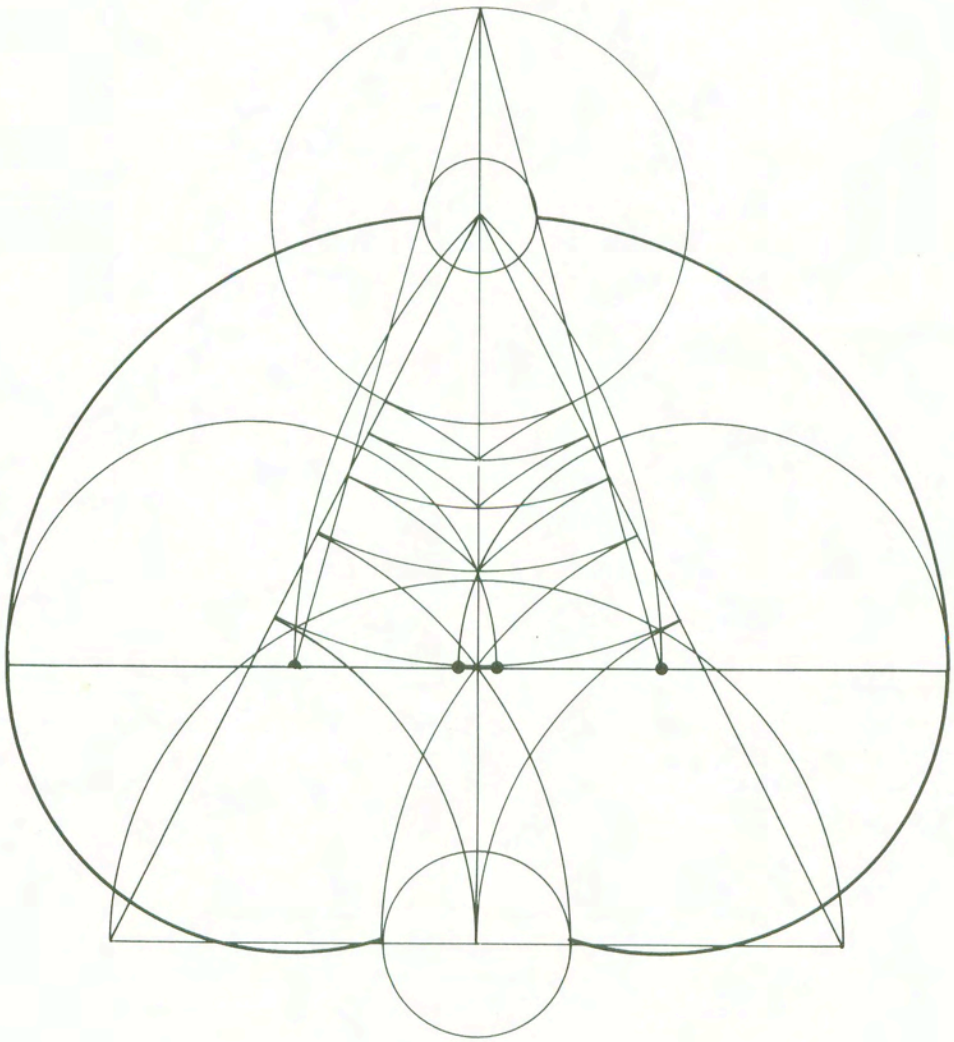


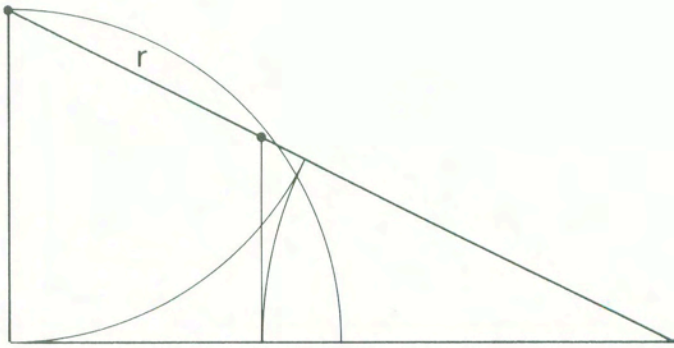
Study of the shell's profile.
Measurements of the height and of the maximum diameter are taken on each subject we want to study.
Given these two dimensions as the base for work, the profiles of the shells are drawn, trying to geometrically define curve-profiles which are closest to the real ones.

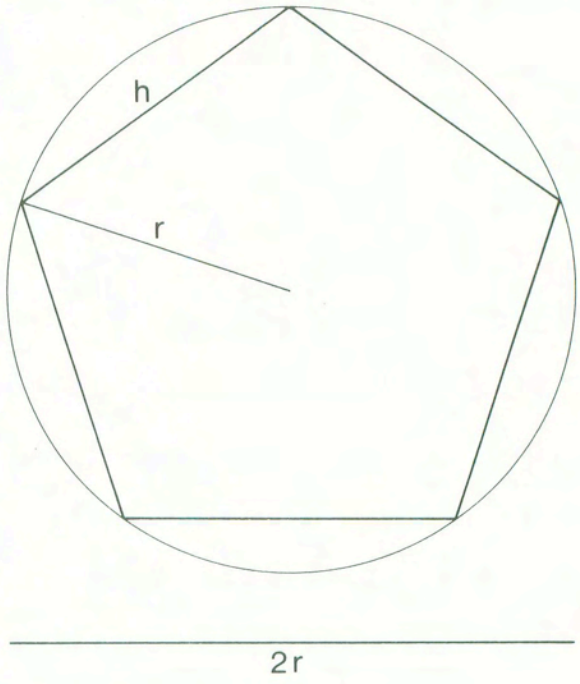




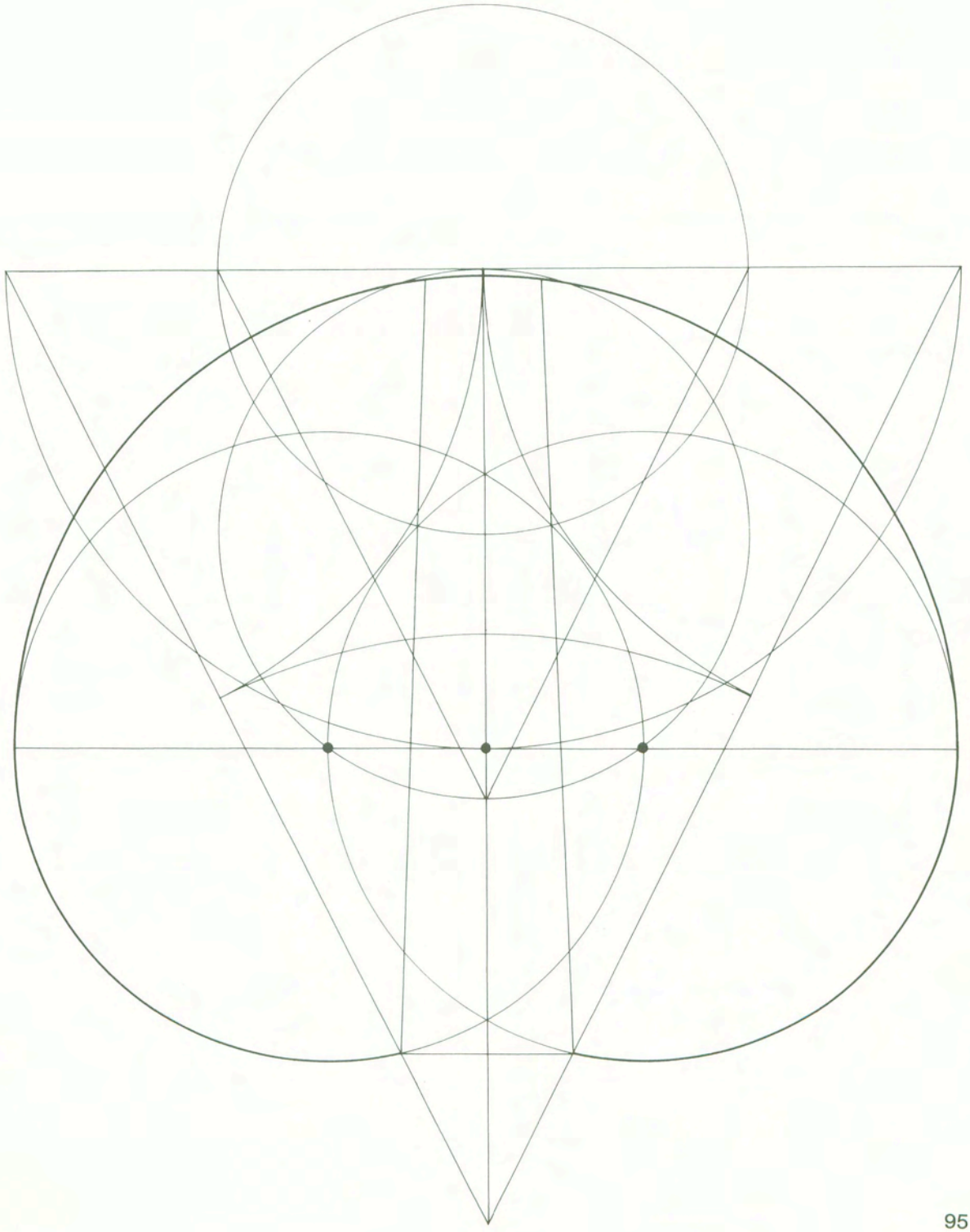


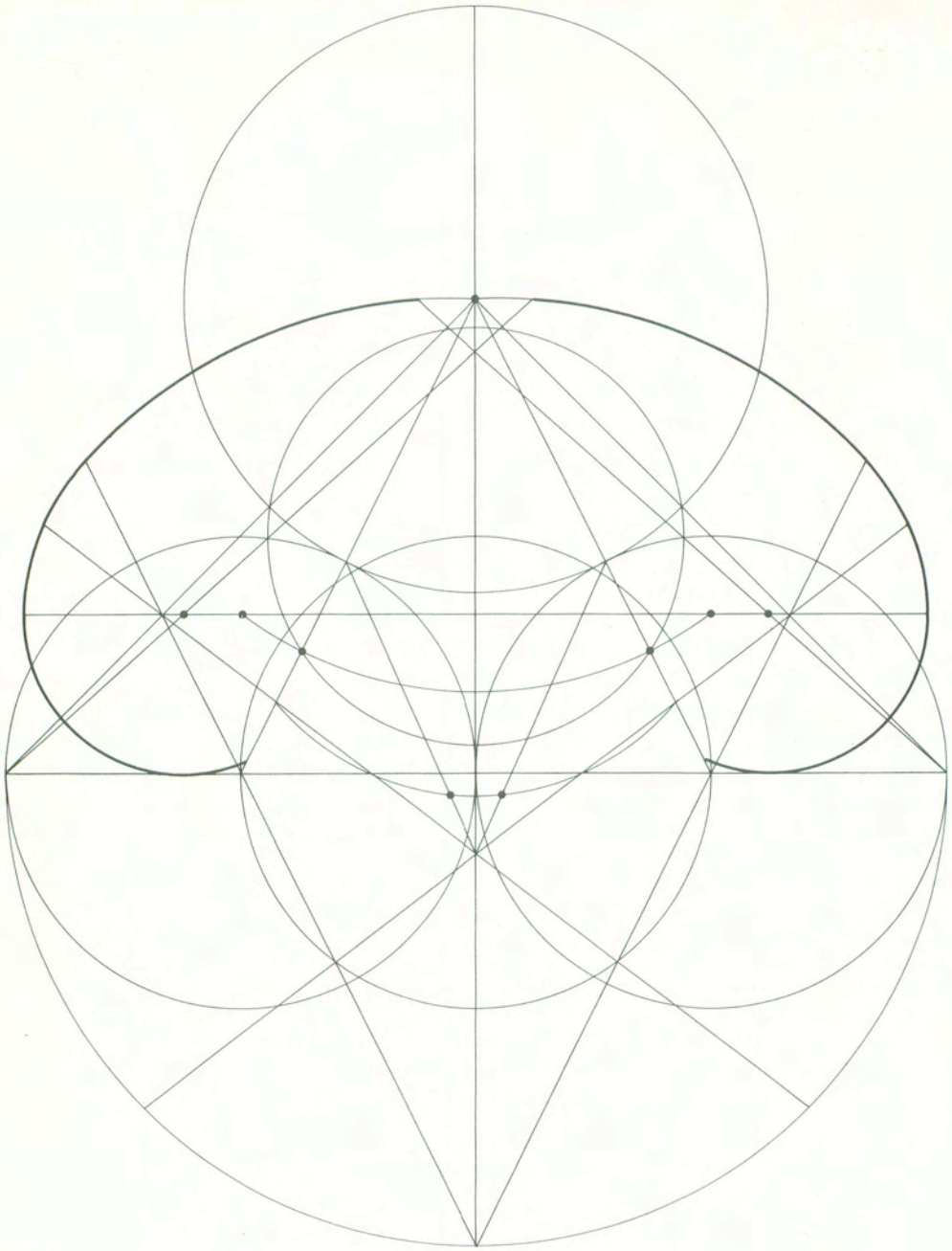


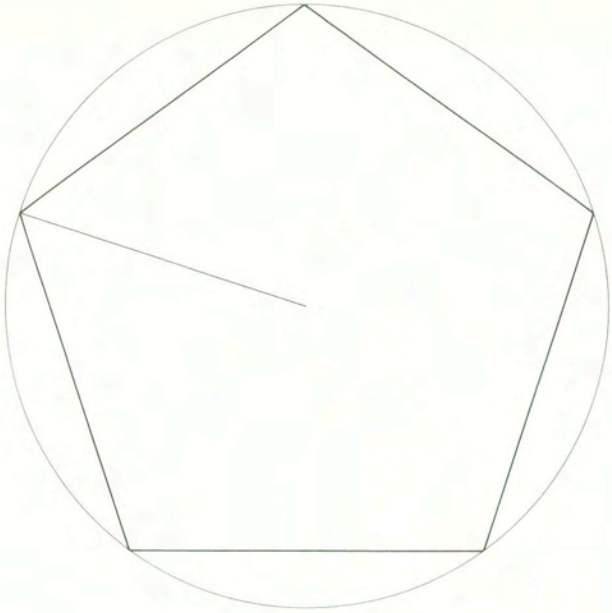


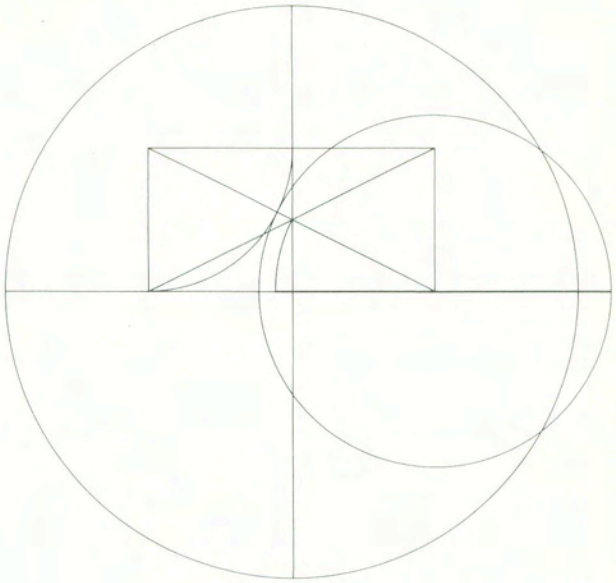


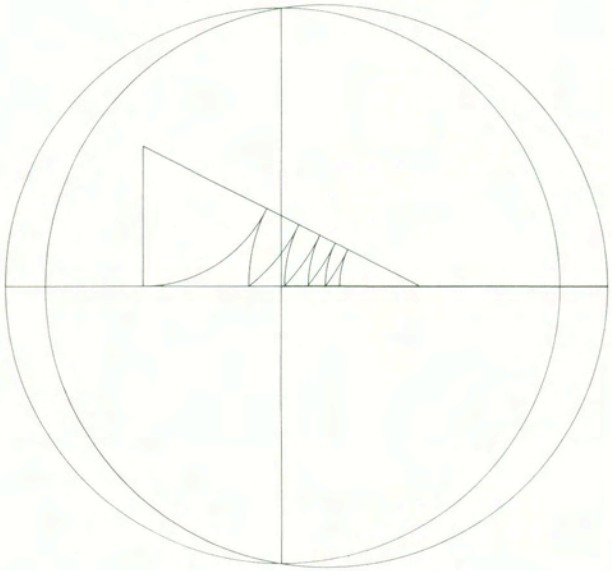
In this case the height of the shell is equal to the side of the pentagon inscribed in the maximum circumference of the shell.

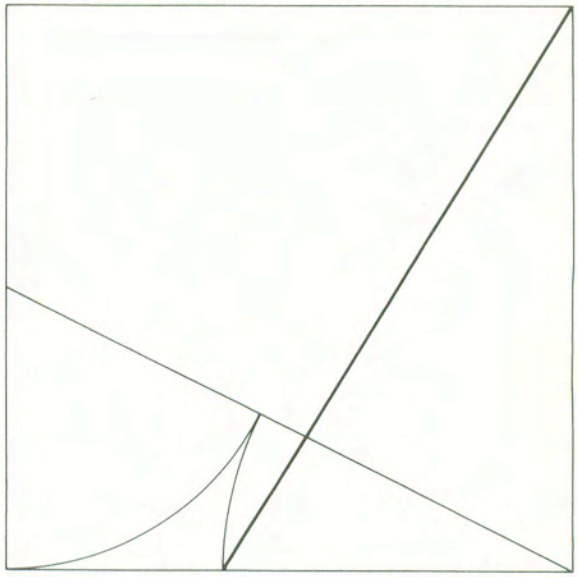




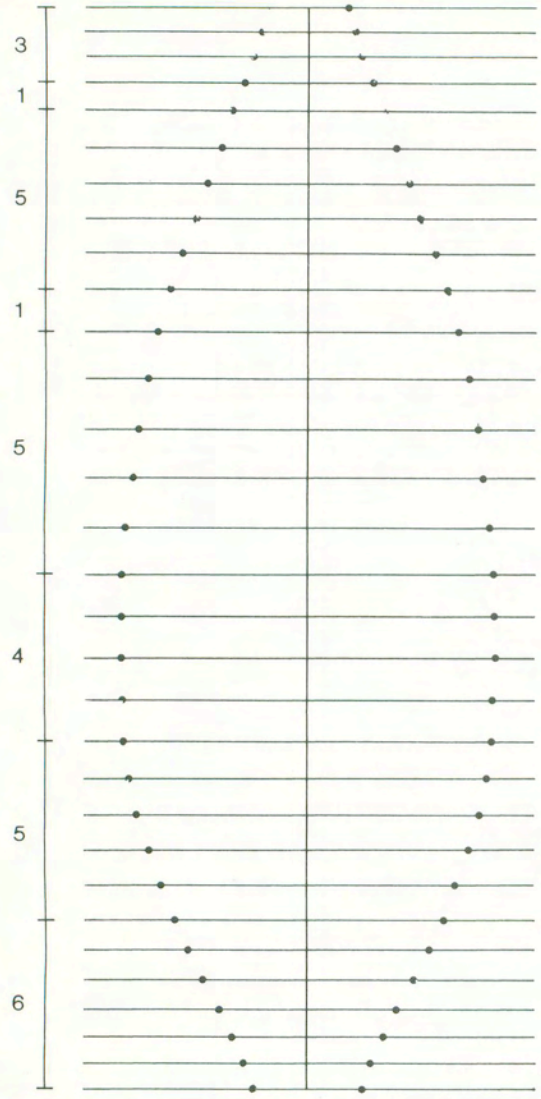


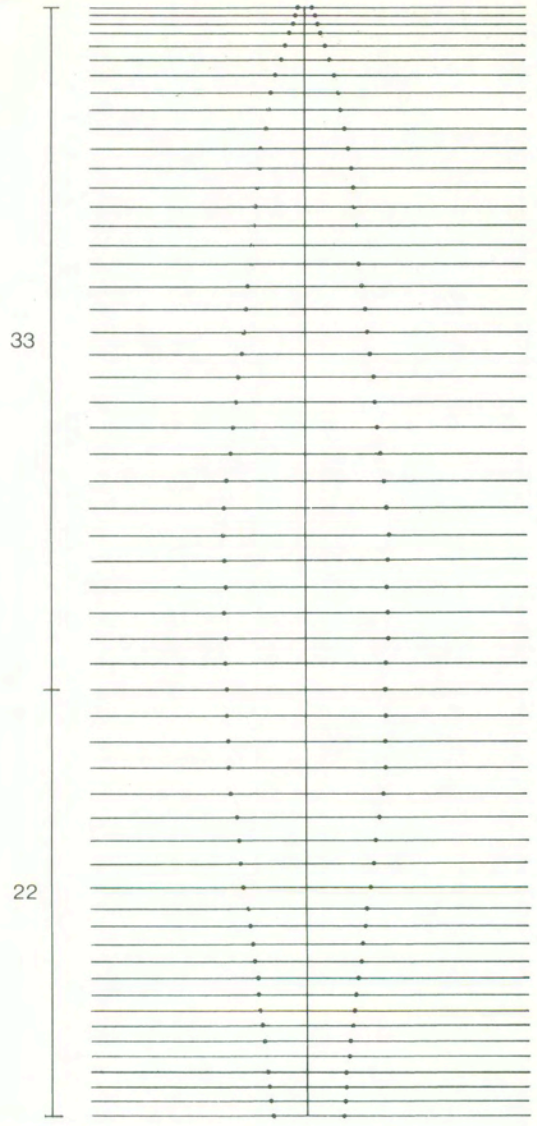






A few ways to construct the regular pentagon inscribed in a circumference.
The thicker line indicates the side of the pentagon.

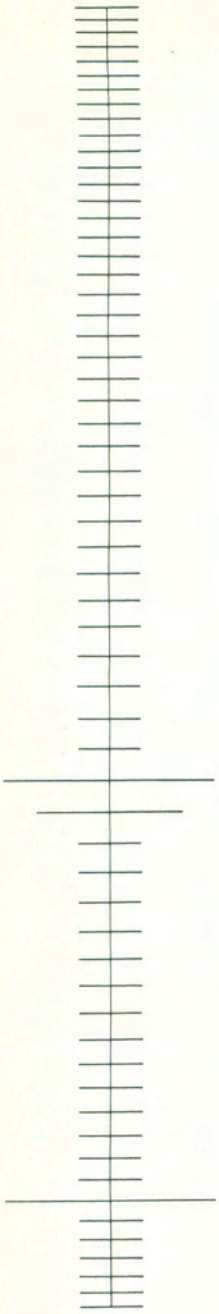




Survey of points of larger and smaller sector.

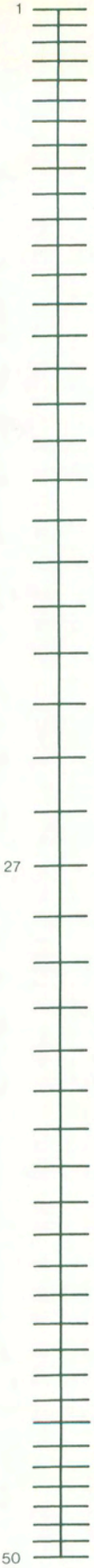
A sea urchin's shell is picked.
The small plates which form the shell are analyzed.
We try to find out how they are connected, both as a whole and as in detail. What is their size, their number, their shape.
Surveys are conducted in order to obtain all the necessary measurements needed to understand if there are groups of plates which have the same dimension, if all the plates are different, what is their mutual relationship.

After having repeatedly checked the dimensions of each plate, and found out that the possible differences between a given plate, a preceding and a following one, are often unperceivable, we try to find an increase/decrease point on the surface of the shell.
That is where the plates, which increased in size as they moved further away from the apical pole, stop their growth and start decreasing in size as they approach the peristomial pole.
The drawings visualize the growth and shrink factors of plates which are dimensionally different from each other.

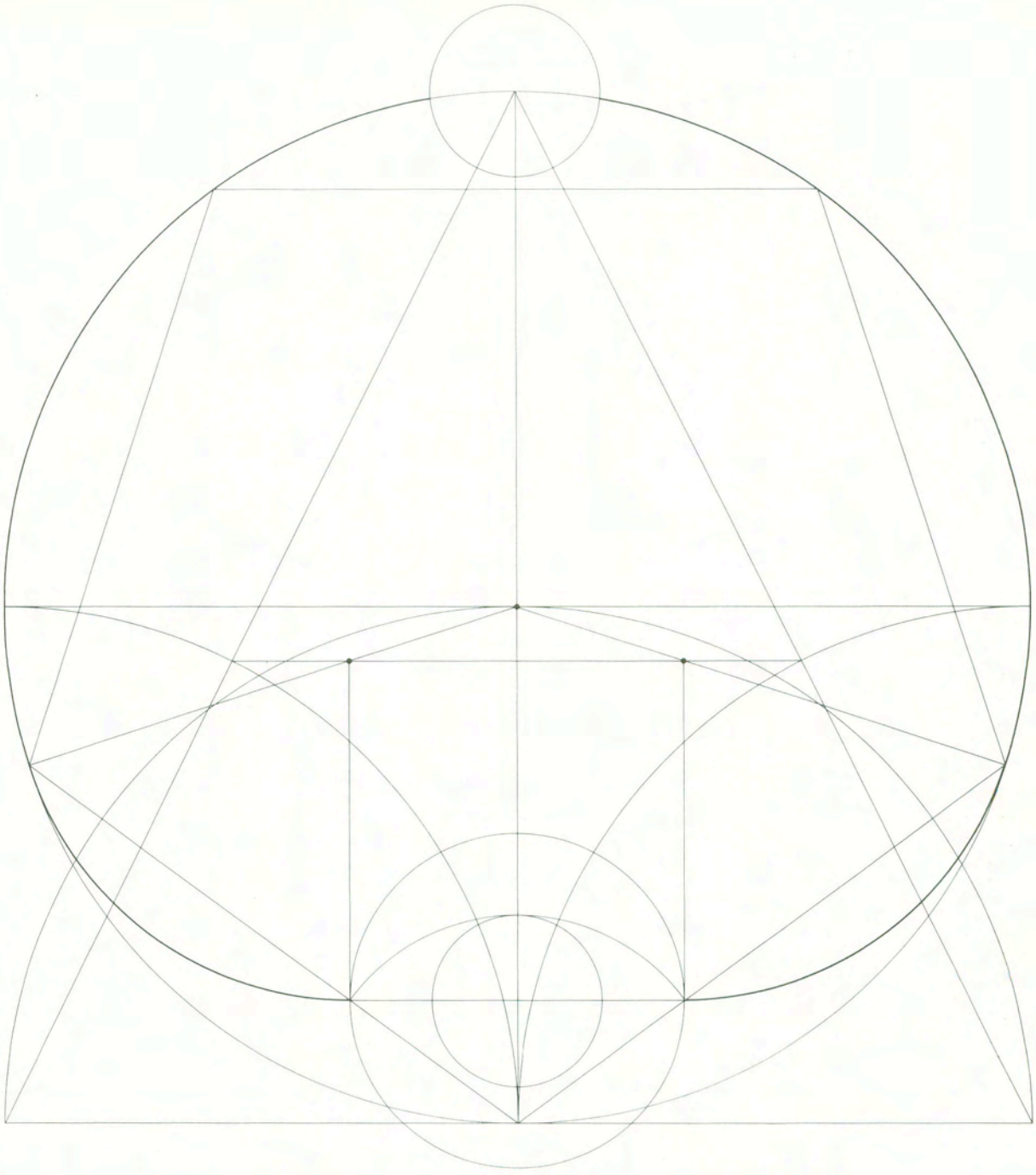



37
15


1
14
32

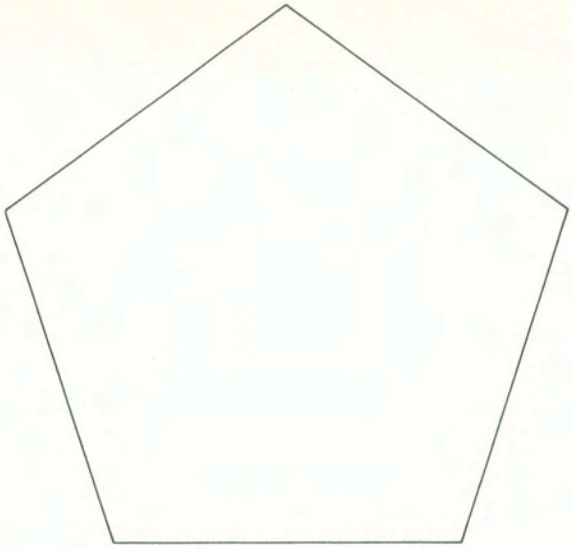

1
27
50

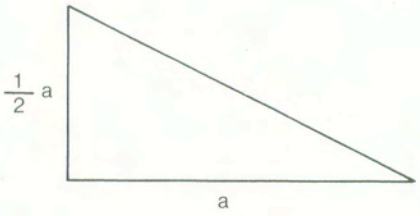

1
19
31



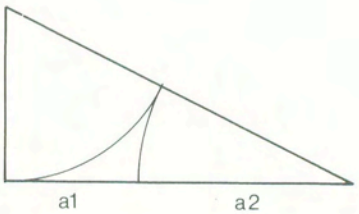
Keeping in mind the increase/decrease relationship of the plates, we construct a new shell profile. The task consists of evenly distributing a precise number of segments - all different from each other - on the shell, and without any left over segment.

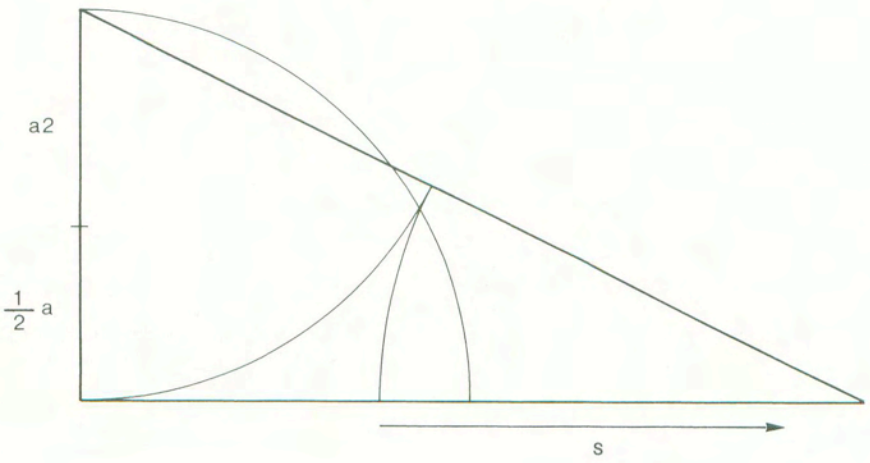
The solution of this problem will allow the construction of models of the shell structure by adopting a horizontal parallel-plane system.

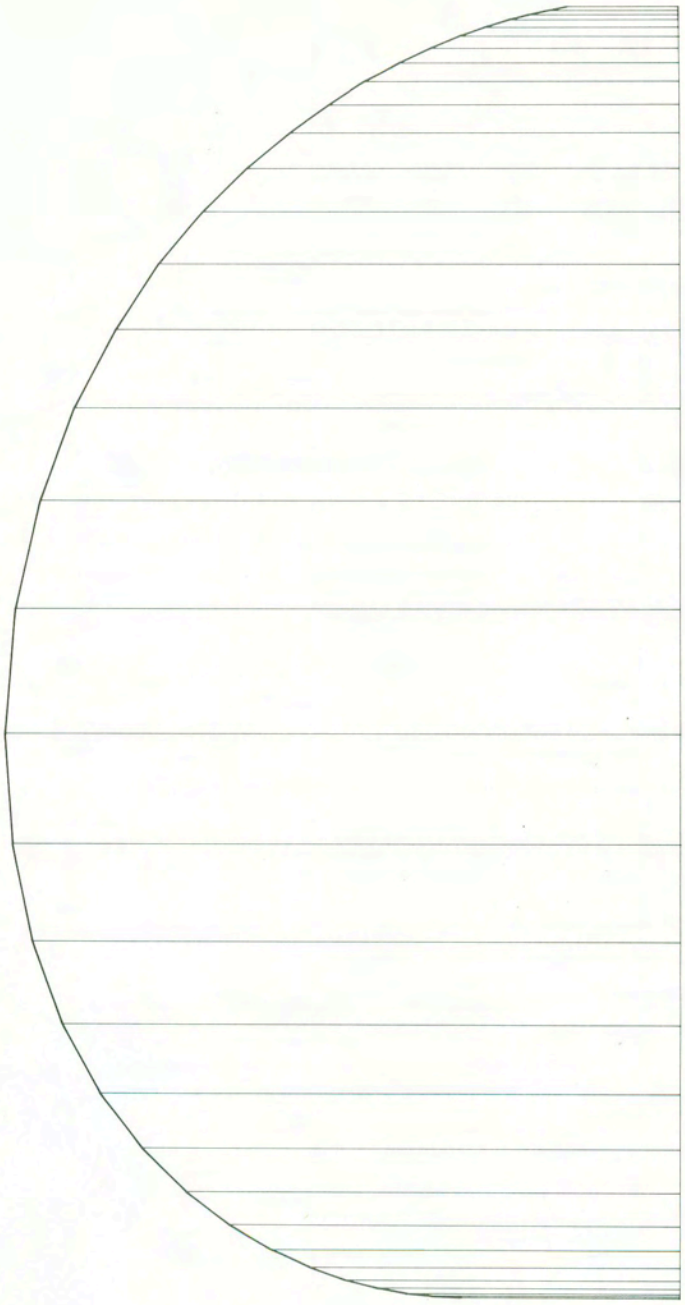




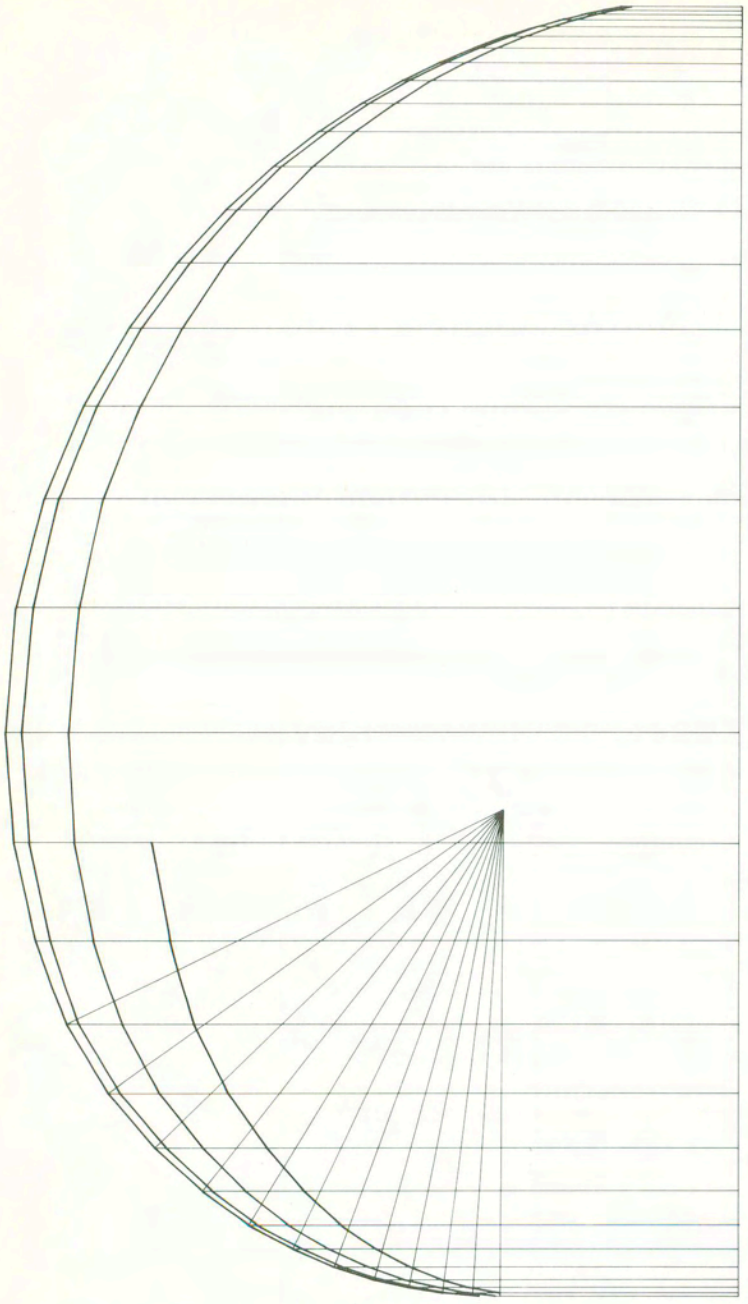
Subdivision of the shell into segments.
This operation enables us to obtain a number of segments which exactly fill-in the shell profile.
The increase/decrease point coincides with the golden section point of the curve construction.



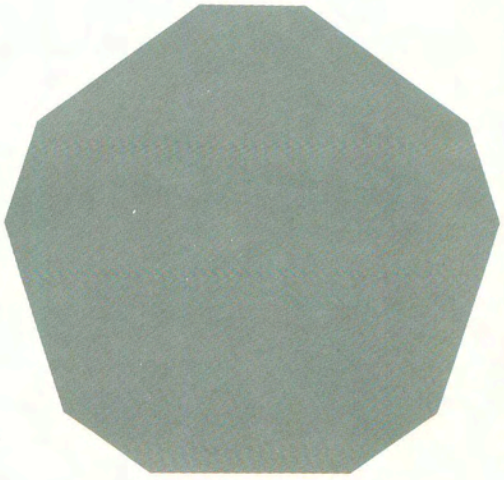




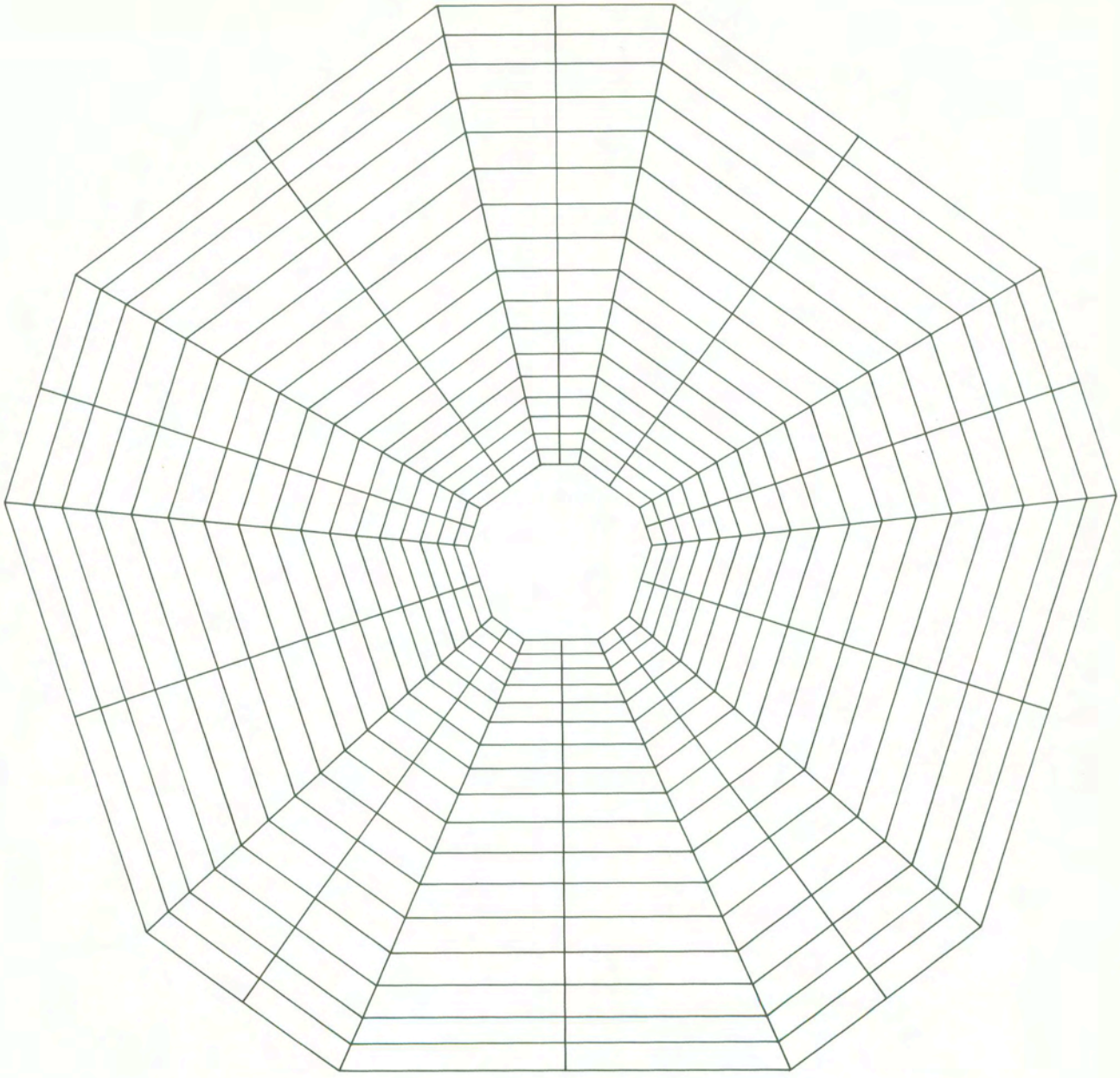
We will now draw an equal number of parallel lines from the points we found. These lines are also perpendicular to the axis of the shell's profile. It is as if we sectioned the profile with various planes.



Now we must give a shape to those planes. The choice of a pentagon-derived shape will characterize the overall three-dimensional form of the various models.
To complete this choice, we will also use the line configurations which divide the shell into sectors.
The course of these lines has been already precisely defined in the subdivision study of the apical pole.

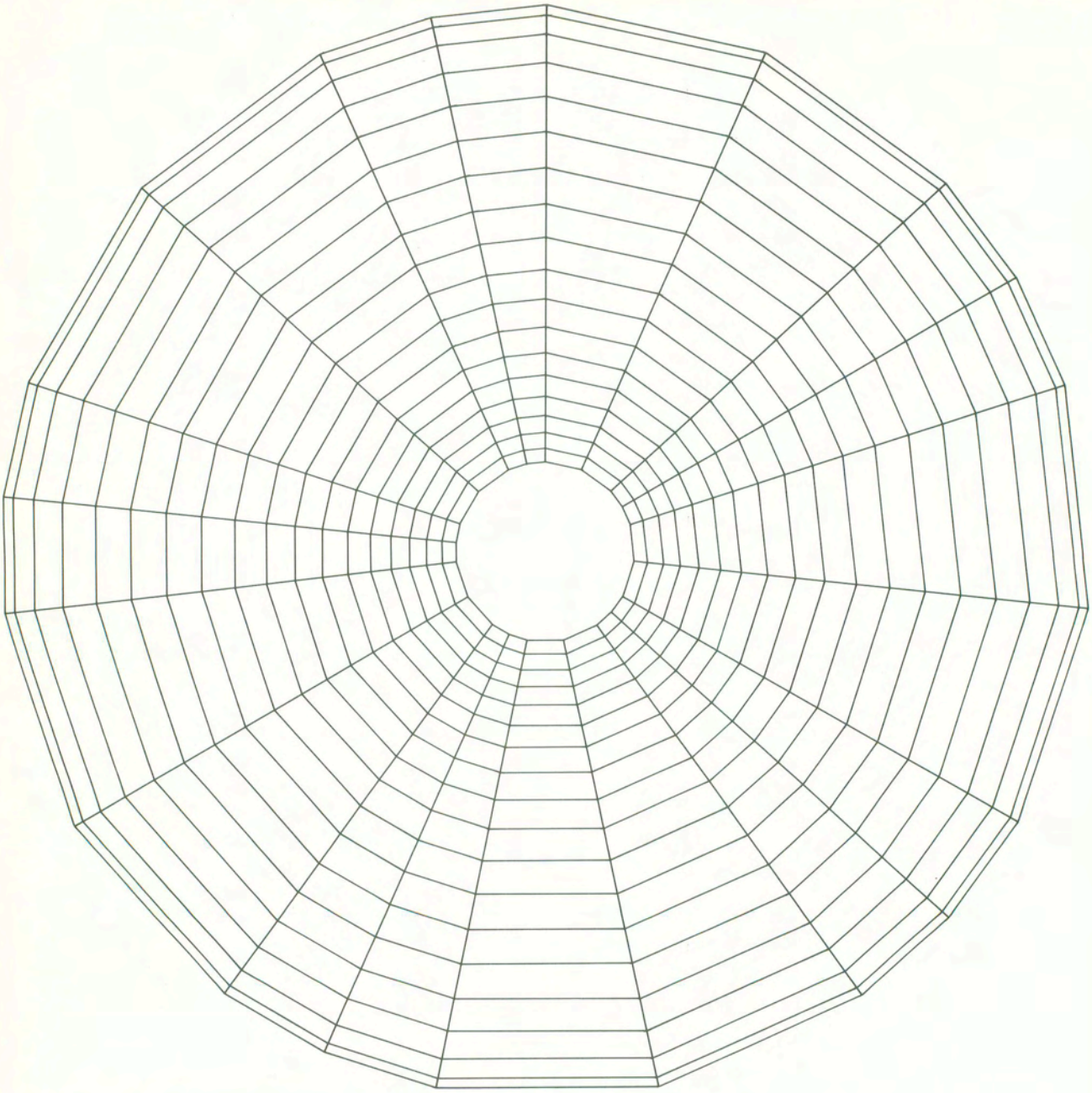


If this is the resulting shape, then we have to construct many similar shapes with a varying radius. Each radius will be as long as each of the lines connecting the points with the profile axis.

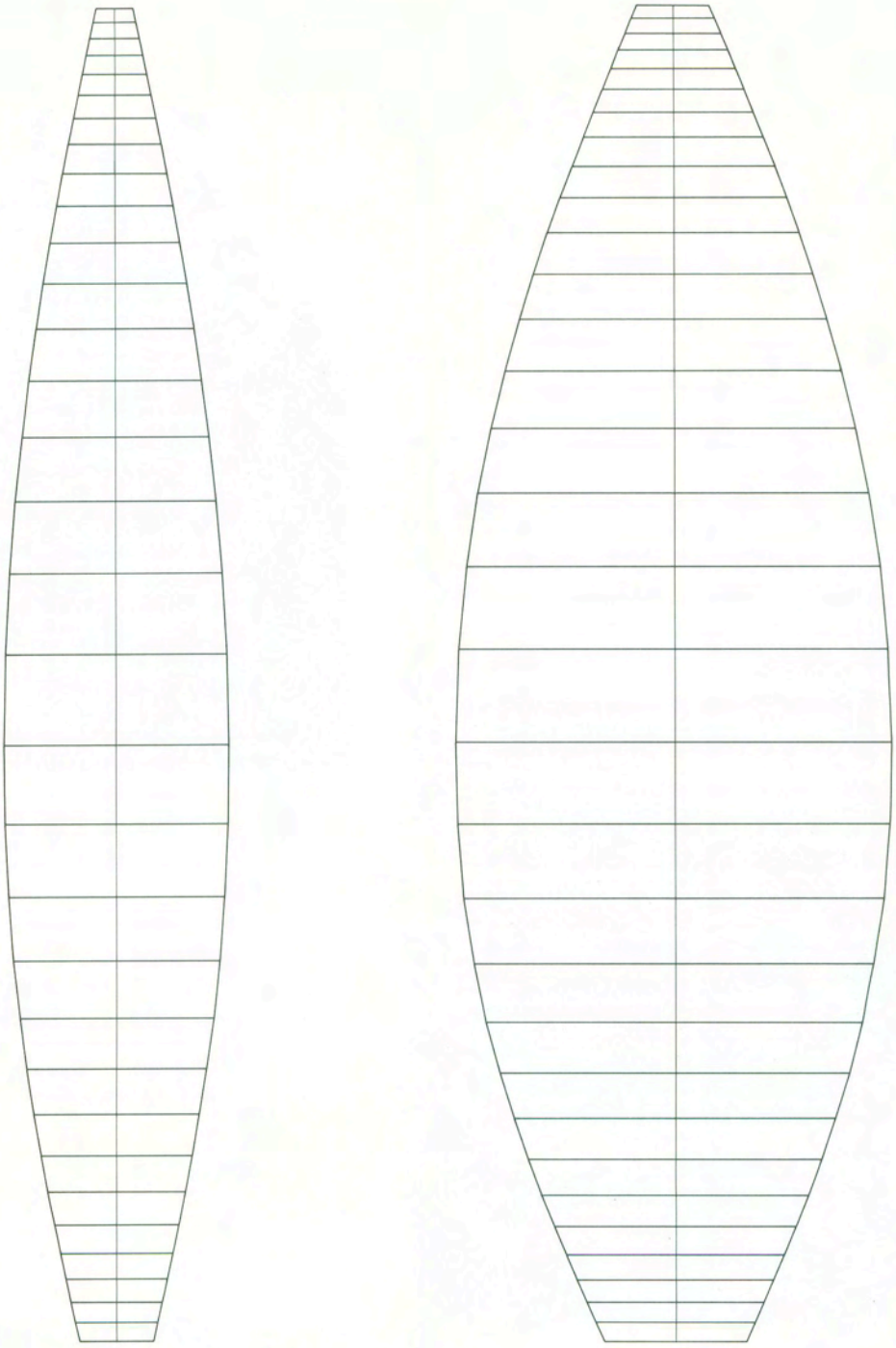


Top view of shell model.

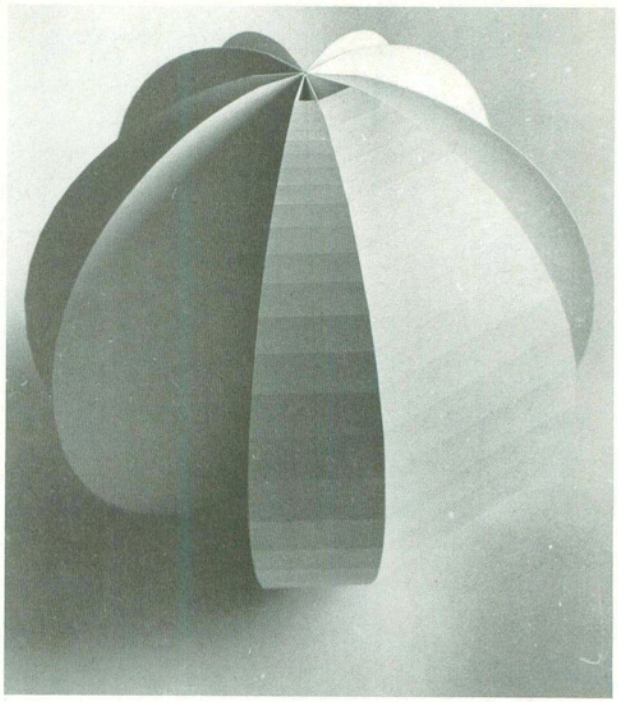
While keeping in mind the chosen polygonal shape, we can have profiles, that is geodetic lines, which vary in size. The new profiles can be constructed by using the first profile as a base. In this way it is also possible to construct sectors which will perfectly jive with each other.

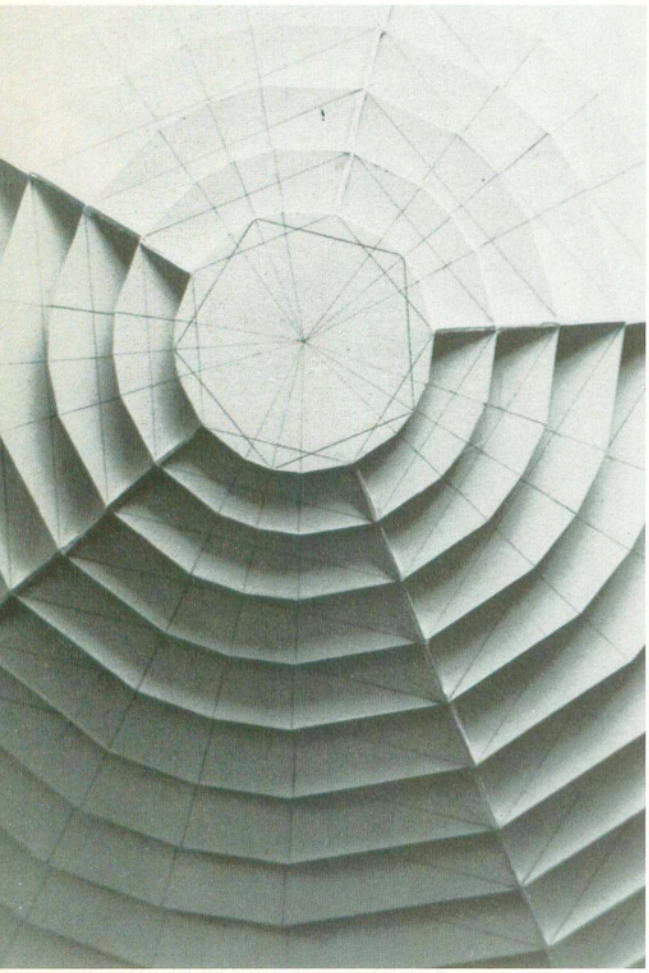


Top view of the same shell model, with profile variations.



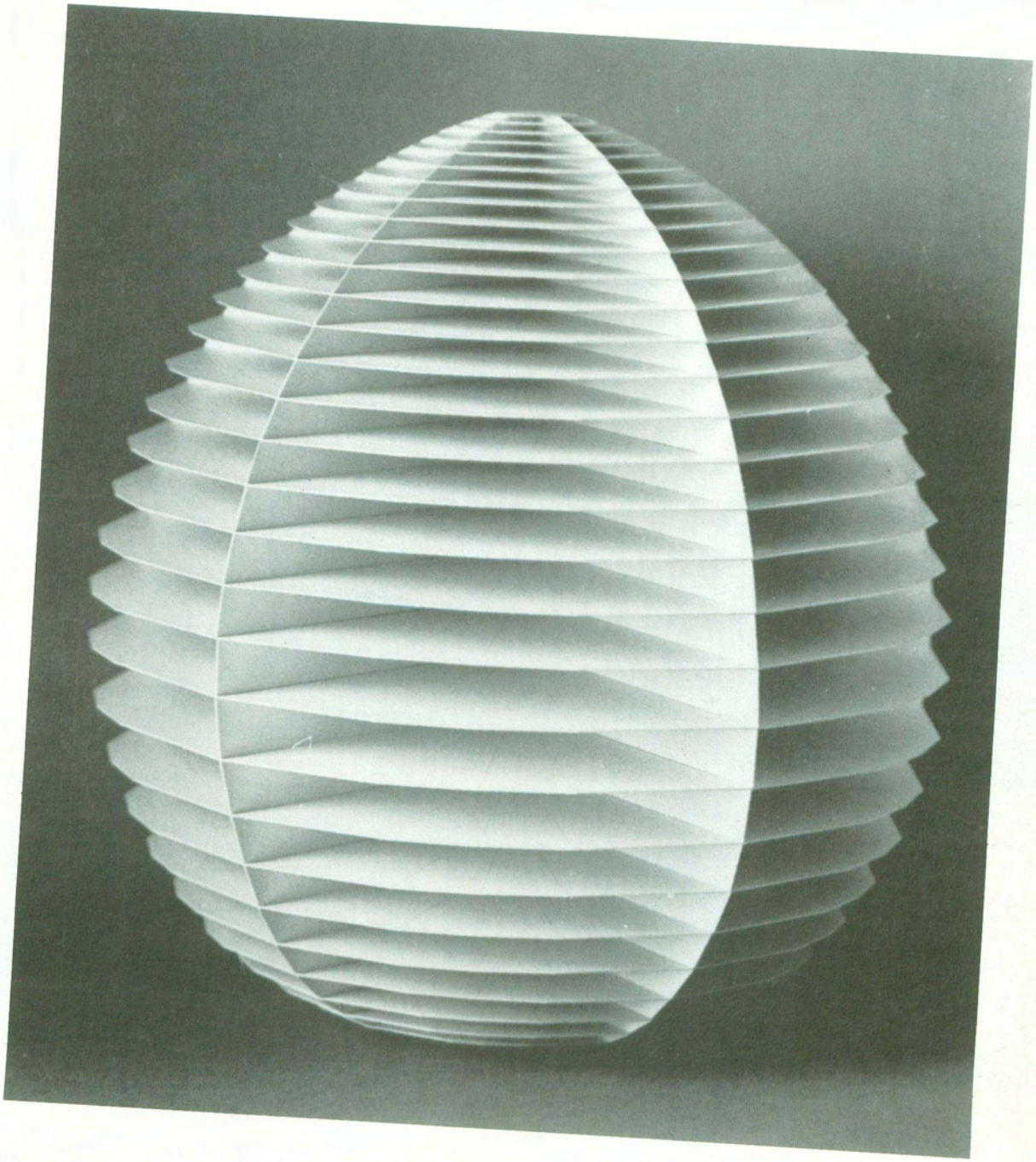
Drawings of the smaller and of the larger sectors.

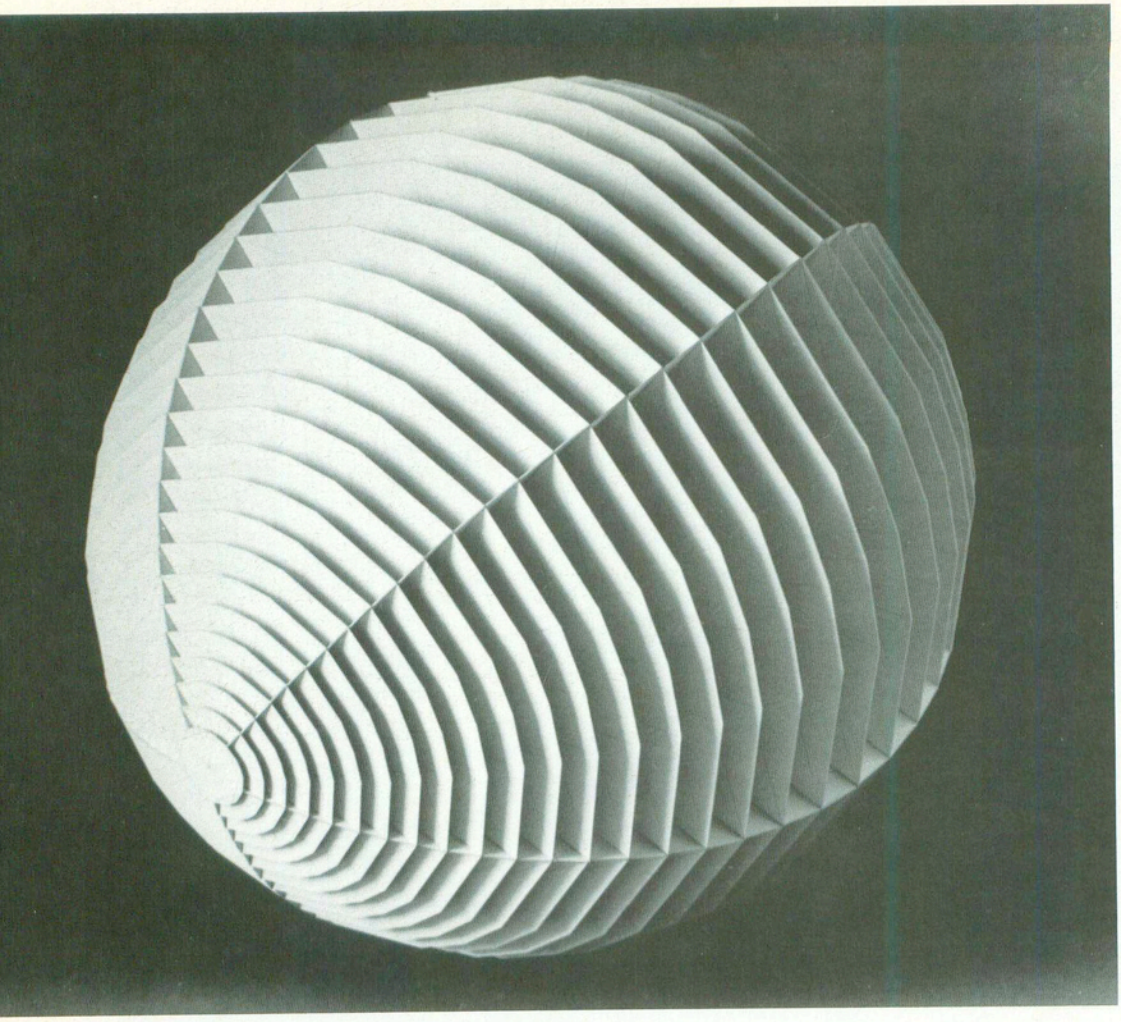


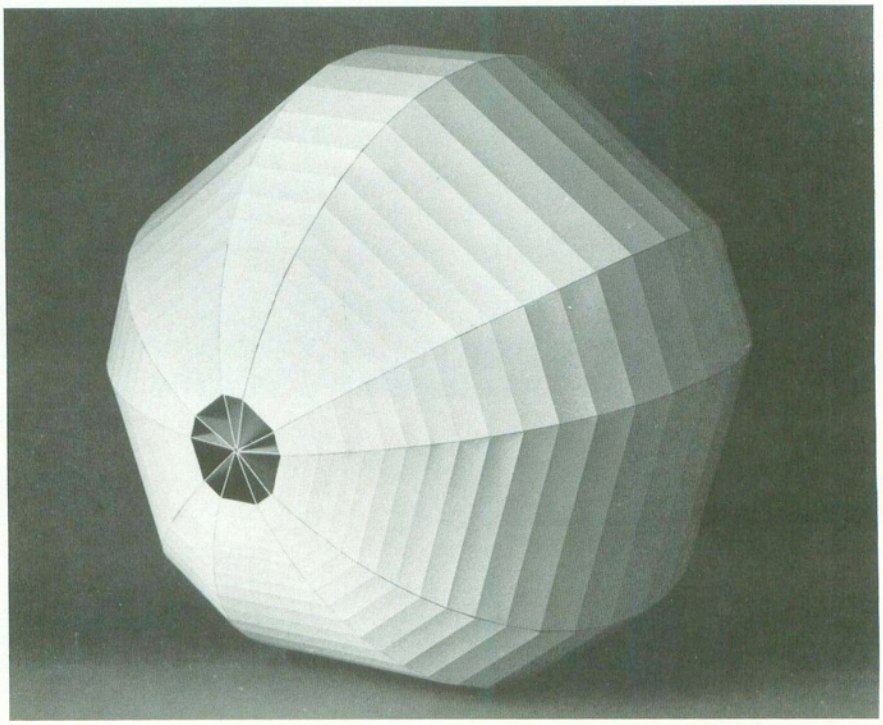


Detail of the shell model, seen from the top.

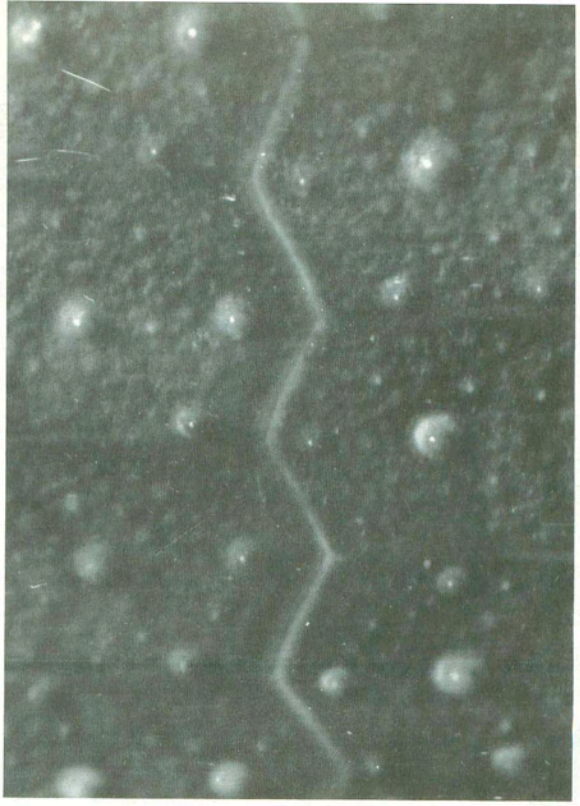
These first models are helpful mainly for studying the spatial arrangement, the configuration of the parallel and radial planes.
The next step is trying to define the overall shape of the system arranging the plates together and how they support each other.

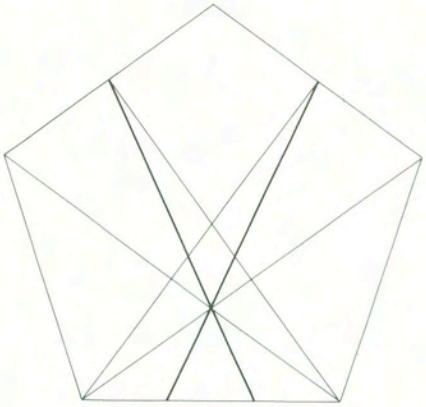


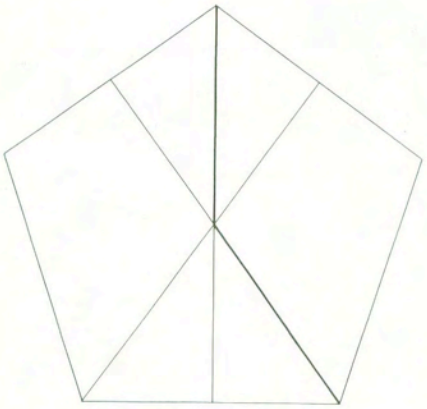


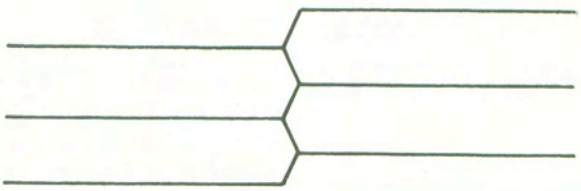


In the natural model, the plates which make up a sector are not lined up on the same axis.
One row of plates is shifted in relation to its corresponding lateral row.
This determines a zig-zag line that moves from one pole of the shell to the other.
The angular values of the joining lines of the sectors are then studied.
In the end part of the shell, near the mouth, the plates face each other in such a way as to form a 145-degree angle, (this value is in accordance with the radial lines of the pentagon).

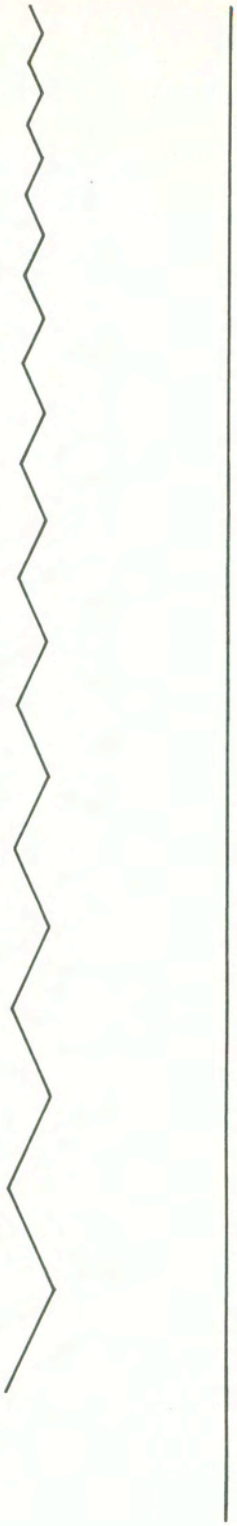




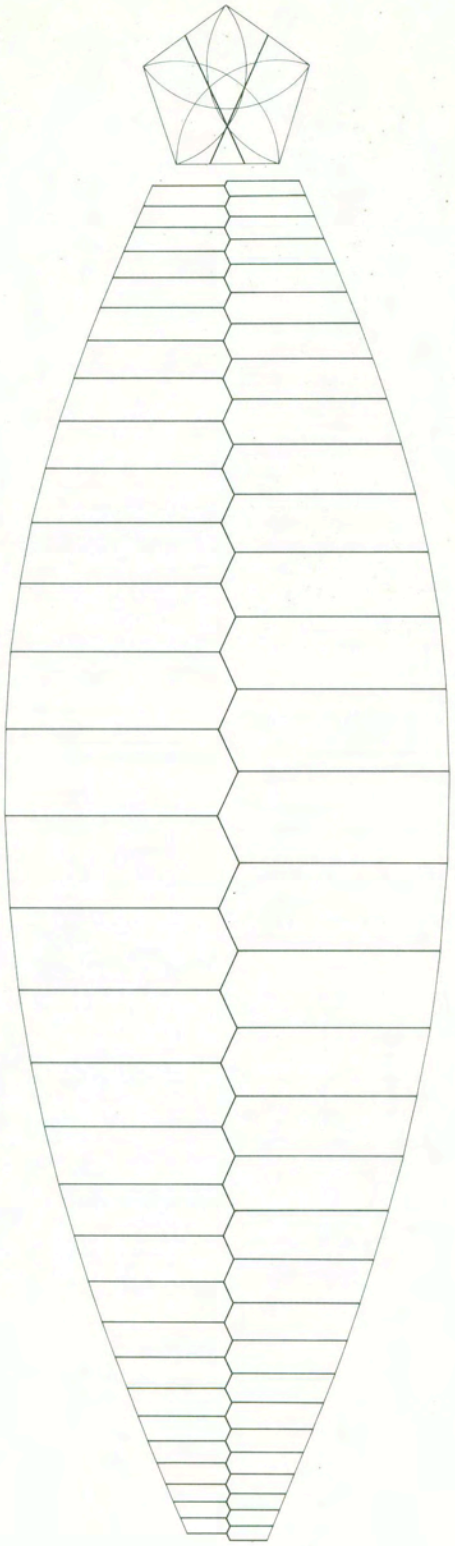


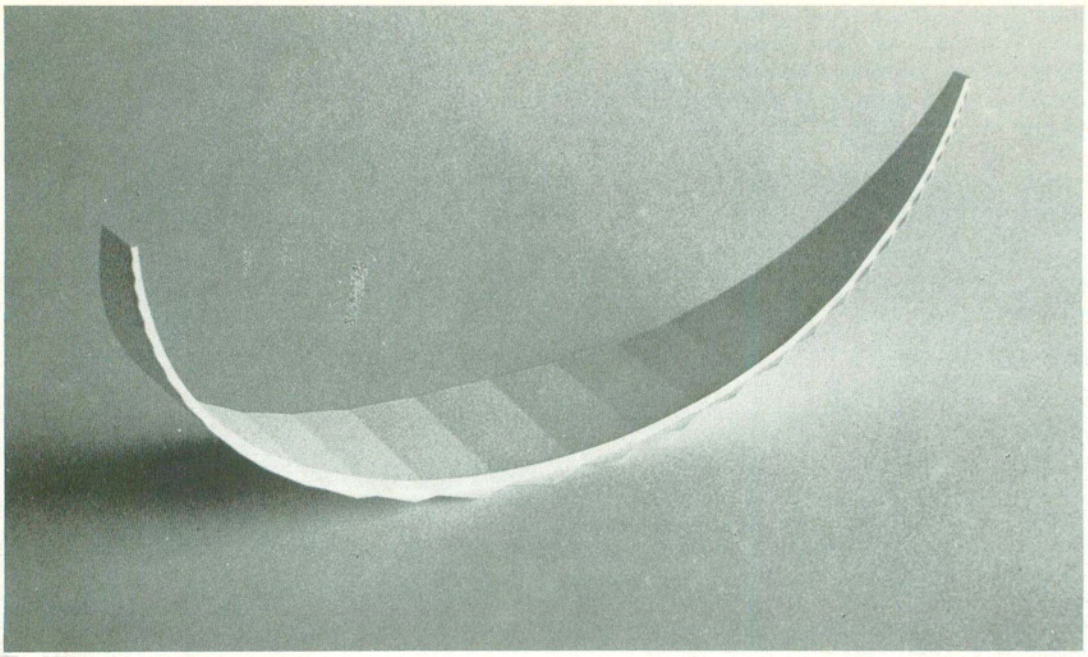


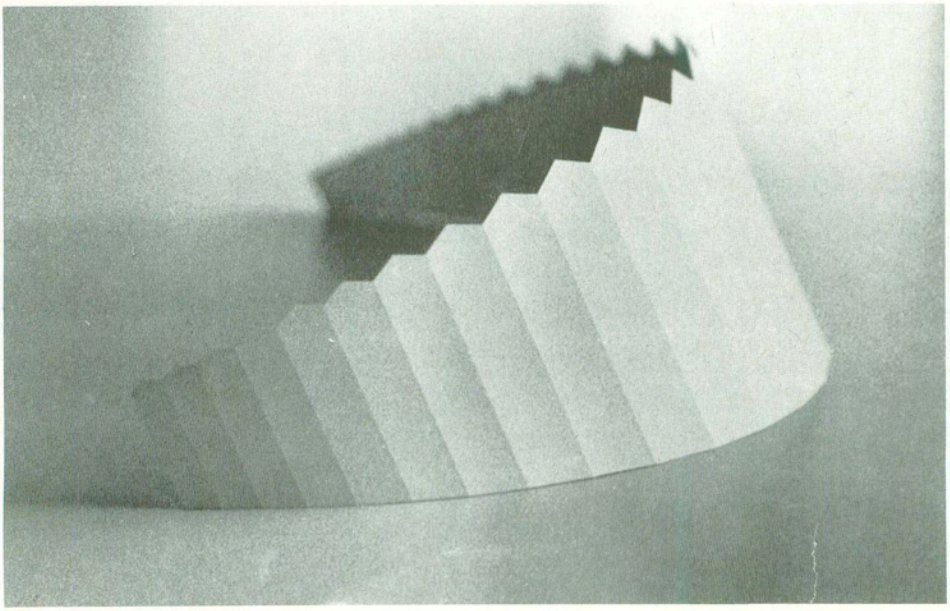
The zig-zag drawing of the joining line of the sectors is determined, in its overall shape, by the profile of the two ends of each plate.
This makes any sliding or shifting movement of the plates practically impossible; it is the longest possible contact line; at the same time, it greatly favors the resistance of the shell to outside forces, i.e. water pressure, knocking, etc.
We can give a visual explanation of this fact by "unrolling" the little segments which form the sector-joining zig-zag line onto a straight line.
The set of segments obviously makes up a longer line than that for which we could substitute the zig-zag one, simply connecting, in the most direct way, for example with a line called geodetic, the north and south poles of the shell.



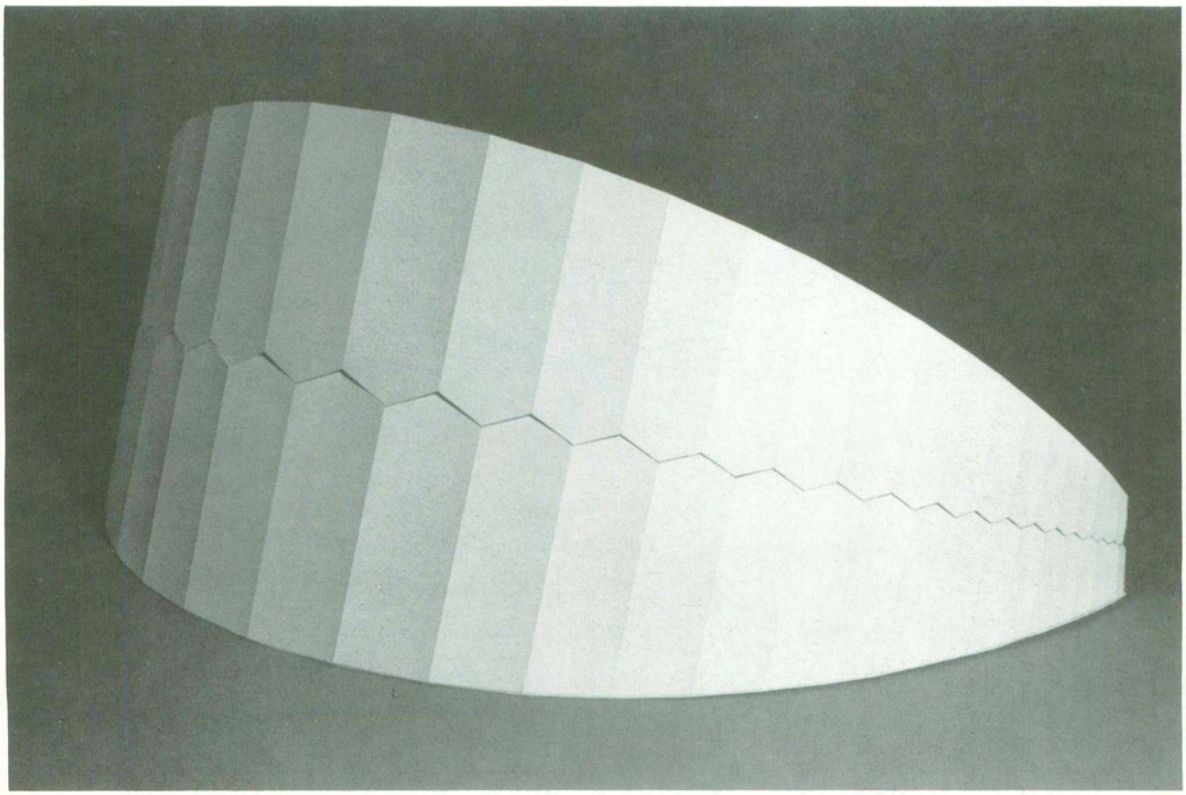
Drawing of a sector in which the angular values and the "hinge" line find a rythmic justapposition, determined by the intersections of the sets of horizontal spaces (plates) in which the sector is divided.



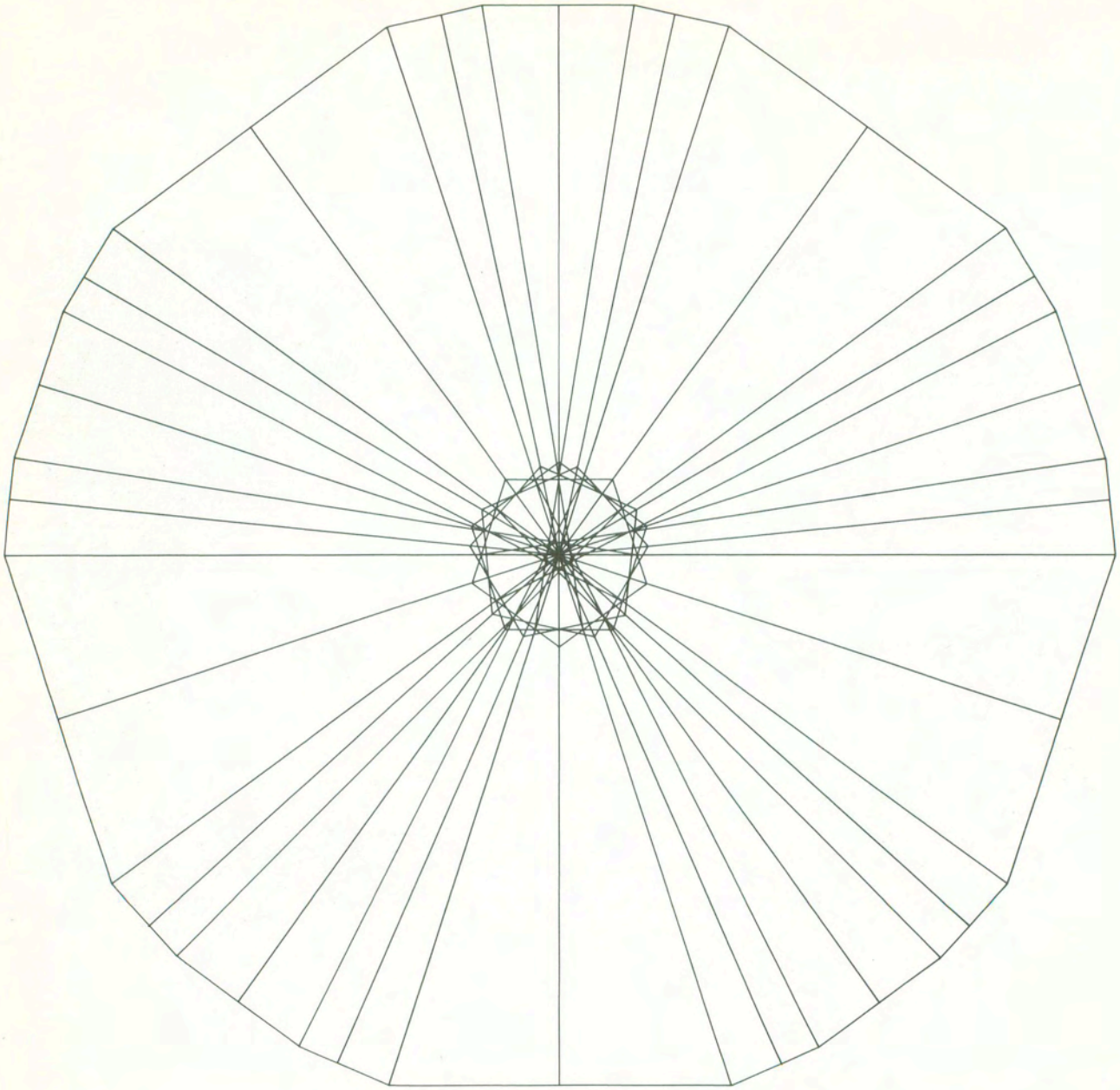




Models of sector.

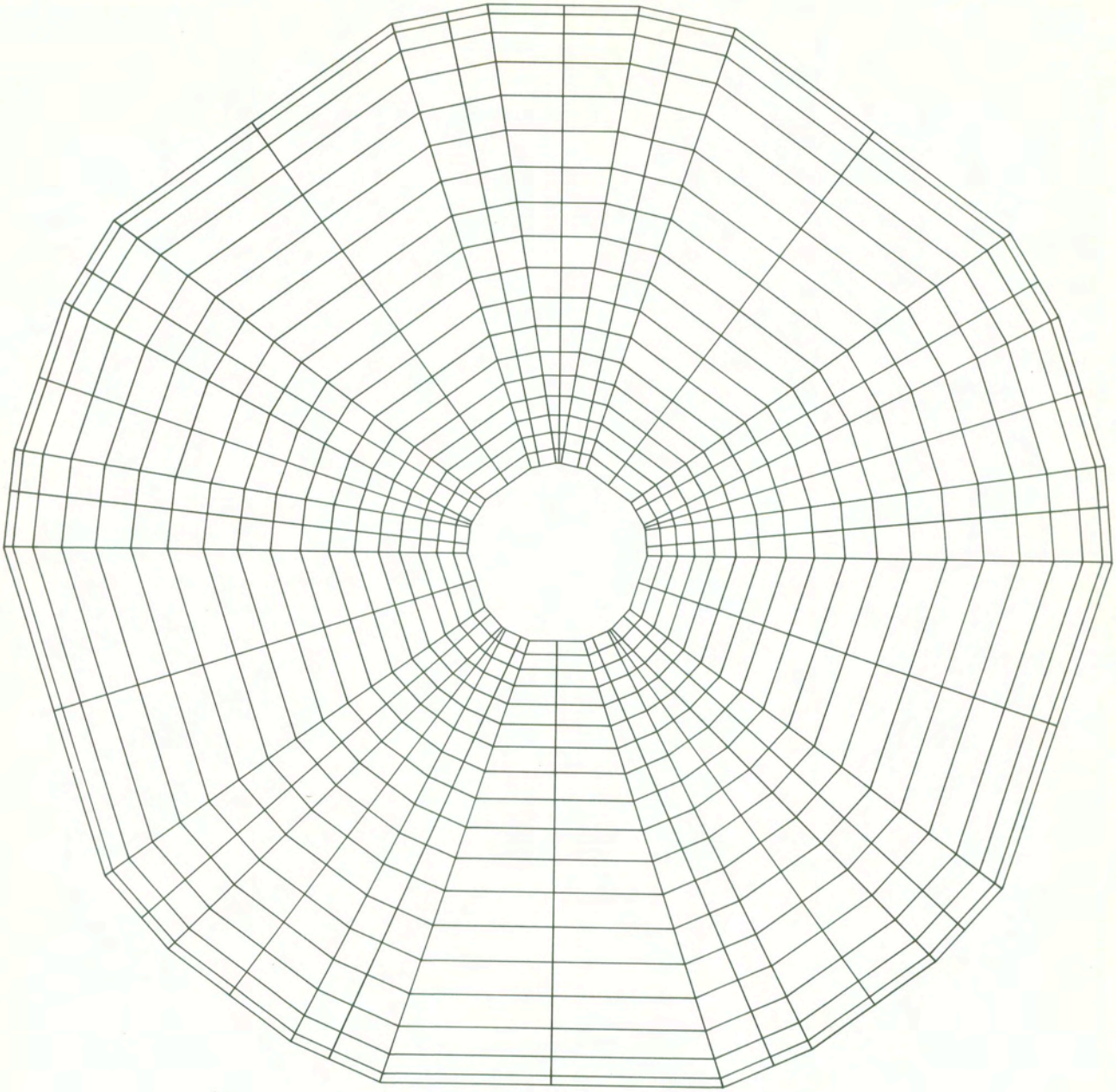


Two adjoining sectors hinged together.



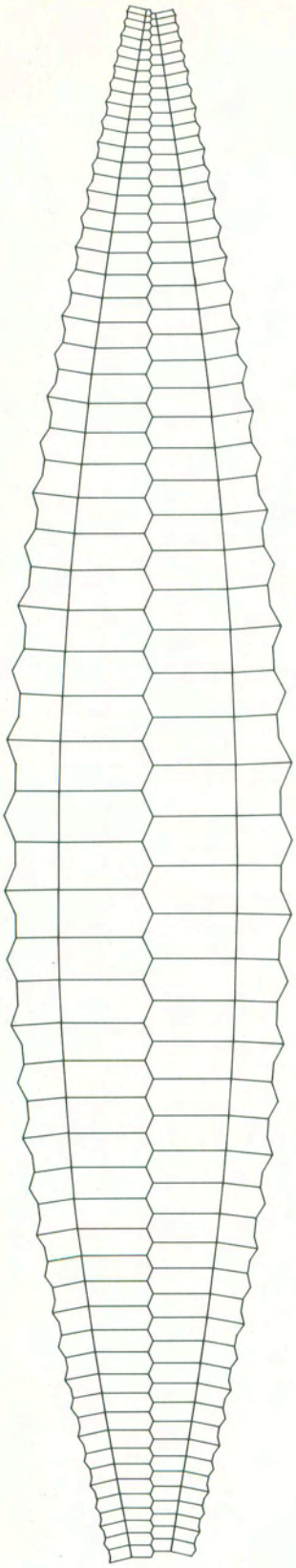
Of course, not all the hinge lines have the same design.
The five major sectors are divided in two parts by five hinge lines which, in the natural model, appear to be similar to each other. In a geometric sense, we can simplify this and consider them equal.
The drawing and the model of the preceding page are the actual construction, that is they attempt to represent this kind of hinge.

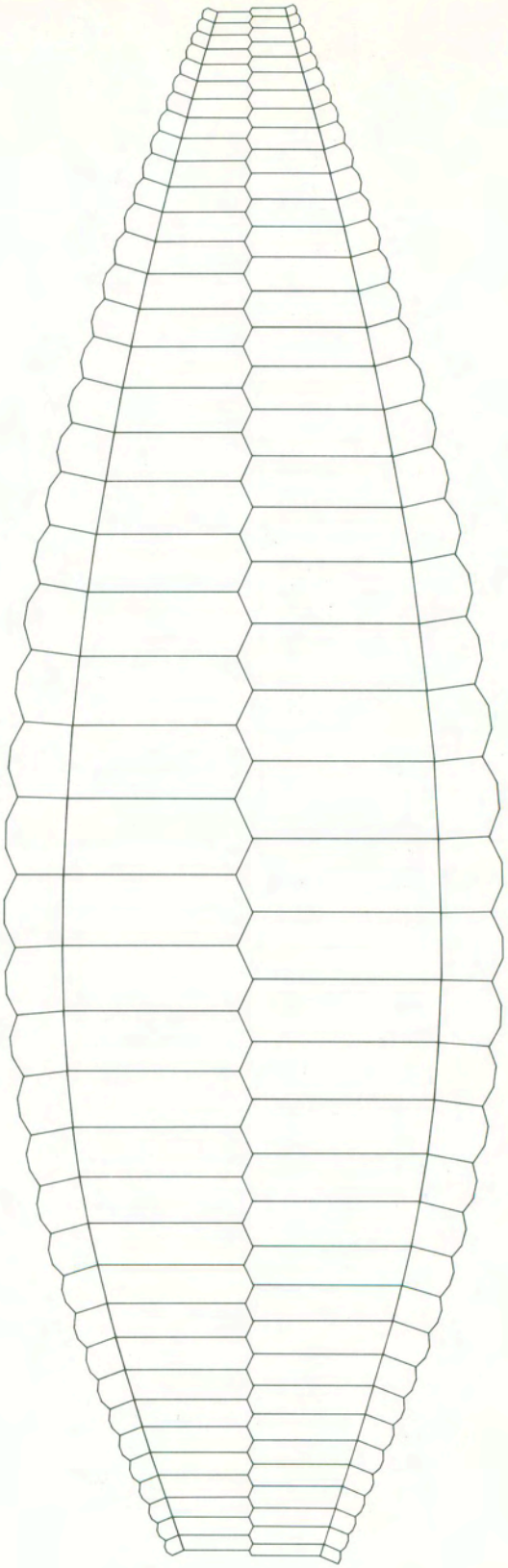
The five minor sectors are also divided in two parts by five hinges which have the same angular values. Therefore their overall form (the hinges' form) is similar to the hinge that divides the major sectors.
Obviously though, they are smaller in size because the plates of each sector are smaller as well.

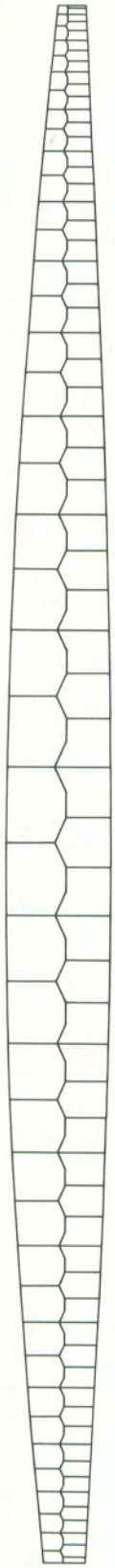
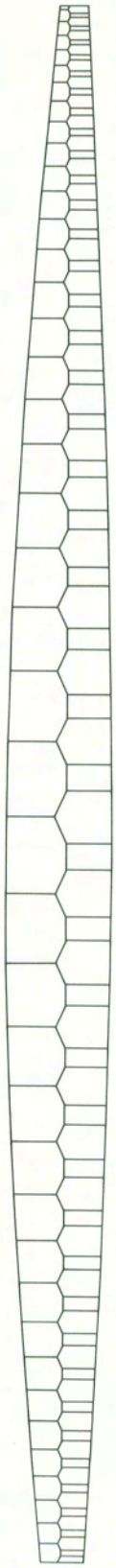


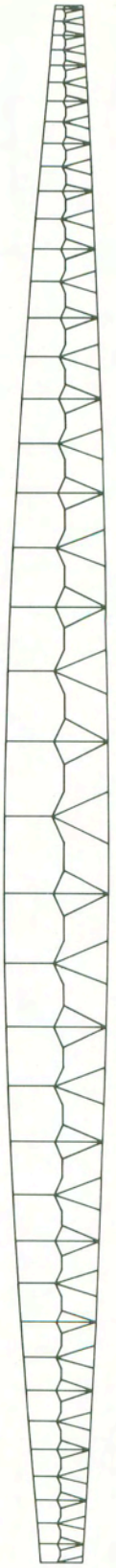
The contact lines between the large sectors and the small sectors are defined by ten other hinges.
These ten hinges have a different shape from the other type of hinges and form a "one-of-a-kind" type. Their peculiar formal characteristics are visualized in the following drawings.

The drawings shown in these pages constitute the overall fold-out of a three-dimensional curved surface divided into 20 sectors. This surface is, in an approximate way, an analogy to the overall fold-out surface of a sea urchin's shell.







LIST OF PARTS TO BE STUDIED

I) Spines.
2) Structure of the articulated joints of the spines.
3) Thickness of the plates forming the shell.
4) Comb-like forms on the internal surface of the jaws.
5) Attachment points of the thin, transparent membrane which wraps around Aristotele's lantern.

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