17. The Artificial Formation from Paraffin Wax of Structures resembling Molluscan Shells. By J. T. Cunningham, M.A., F.Z.S.

[Received January 26, 1915 : Read March 23, 1915.]

(Text-figures 1–5.)

In December last Mr. R. H. Burne exhibited before this Society some specimens of forms assumed by paraffin-wax when cooled, which resembled in a striking way in shape and markings the shells of Molluscs. These specimens were presented to Mr. Burne by Herr C. U. Ariens Kappers, of the Senckenbergisches Institut, Frankfurt a. M., and they are described by him in a paper published in the Zeitschrift für Allgemeine Physiologie in 1907. In that paper no information is given concerning the conditions under which these structures are formed, it being merely stated that they are produced when the melted paraffin-wax solidifies. The shells imitated are stated to be Lamellibranchs, Gastropods (operculum of *Turbo*), and Brachiopoda. Seeking the explanation of these resemblances, Herr Kappers adopts the conclusion of Harting and Bedermann that the form and characters of molluscan shells, as well as those of otoliths, egg-shells, and the skeletons of Foraminifera, Alcyonaria, and Echinoderma, are due to the aggregation of crystals of calcium salts formed within a colloid medium, the crystals being of a special kind called sphæro-crystals or calco-sphærites. He maintains that paraffin-wax shares with calcium salts the property of forming sphærocrystals, and that the formation of crystals from a solution takes place in essentially the same way as in the solidification of a molten mass. Moreover, there is a further resemblance in the viscosity of the mother liquid, the form which a crystal assumes being more or less influenced by the resistance which its particles encounter in its formation. In molten substances unequal terminal surfaces of the crystals, causing bending and distortion of the forms of the larger crystals formed by means of the smaller, also occur as in viscous solutions.

Kappers believes that the rapid cooling which is specially effected for histological purposes is favourable to the production of the forms under discussion, because the crystals are then formed in the viscous medium of the cooling substance, whereas in slow cooling normal crystals have time to form. It will be seen below that my experiments are in contradiction to this, for if the melting-point of the paraffin is high it is more difficult to obtain shell-like masses.

In the discussion that followed Mr. Burne's exhibition and description of the specimens exhibited, I expressed the conclusion from the appearance of the specimens that their form and markings were not to be explained by any effect of crystallization, but were due, as in the case of molluscan shells, to the successive addition of accretions in a particular direction. The resemblance to molluscan shells consisted in (*a*) external form, (*b*) markings. In form the plates of paraffin resembled in some cases Lamellibranch shells, varying as these do in the proportion of breadth to length, and the narrower ones were more like Brachiopod shells. In all cases there was a prominence corresponding to the umbo of a shell. One specimen had a spiral twist like that of a Gastropod, only flatter; Kappers compares it with the spiral operculum of *Turbo*. With regard to markings, all the specimens showed parallel or rather concentric lines or striæ, having in the Lamellibranch-like forms the umbo for a common focus, in the spiral forms being parallel to the edge. These lines are closely similar to the lines of growth in molluscan shells, except that they are slighter, not forming such projecting ridges as in true shells, and never as in the latter furnished with spines or processes. One important difference between the paraffin simulacra and real shells, was that while one surface in the former was convex and bore the concentric markings, the other was in all cases flat, though not smooth, in fact was precisely similar to the free surface always formed when a mass of molten paraffin-wax is cooled in a vessel or a mould. In a shell the inner surface is always concave and smooth.

It seemed to me that the paraffin plates or simulacra of shells consisted of successive layers superimposed one on another, each succeeding one being larger in area than the one below, and the lines on the convex surface being the edges of the successive layers. If this were the case, there would be a real, though not an exact, resemblance between the paraffin masses and molluscan shells, for it is well known that in the growth of the latter additions are made both to the edge and to the inner surface; the mantle secretes over its whole surface, and as it grows each successive layer is larger than the preceding and extends beyond its edge.

Something was said by Mr. Burne about the paraffin simulacra having been formed by cooling with water, and I therefore made experiments by pouring molten paraffin-wax into water. The success was immediate: the wax is lighter than water and therefore floats, and when the cooled mass was taken out it was in all respects similar to the specimens obtained by Kappers. The exact shape of the mass depended on the way in which the molten mass was poured into the water. If it was poured down the side of the basin the mass remained attached to the latter, and the flow extended away from it: then the shape resembled that of a Brachiopod shell. When the wax was poured on to the free surface of the water, it spread out more evenly and took the form of a cockle or pecten. The first wax to touch the water forms the umbo, that which follows flows over it and spreads out in ever widening layers. The stream of wax must always be kept running on to the mass already on the surface of the water, otherwise a long irregular band is produced which has no particular interest. I have not been able to make the wax flow equally all round the umbo, to produce a resemblance to the limpet shell, because such a mode of flow would be a case of unstable equilibrium; the force of the flow is never perfectly vertical to the surface of the water, but always tends in one direction or another and drives the mass away from the point of contact with the stream.

In order to produce spiral forms precisely similar to those described by Kappers and exhibited by Mr. Burne, I took a round jar full of water and stirred the latter so that it revolved, and then poured the wax on to the surface near the centre. As the mass is rather flat, the wax being much lighter than water, the form produced resembles, as Kappers mentions, a spiral operculum like that of *Turbo*, and not an ordinary Gastropod shell. When the water is stirred in a right-handed direction, the spiral is right-handed, and when the water is stirred in the opposite way the spiral of the paraffin plate is left-handed. This alone is sufficient to prove that the resemblance to a shell has nothing to do with crystallization, since the direction of the spiral merely depends on the direction in which the water is revolving. It is to be noted that as one looks down on the paraffin plate, the direction of its spiral is opposite to that of the water, for when the water is moving in a right-handed revolution the movement of the water carries the wax that first falls to the right, and the additions are made to the left; but the form of the spiral shows on the *lower* surface of the plate of wax, and, of course, when the plate is reversed after it has solidified the spiral appears right-handed. In some cases I obtained spiral forms which closely resembled the internal surface of the operculum of *Turbo*. The outer surface of this structure is smooth and flat, though it shows the spiral direction of growth, but the inner surface bears a prominent spiral ridge. By pouring the wax at the outer edge of the revolving mass on the water, I obtained plates with a similar prominent spiral ridge.

The concentric lines on the convex surface of the mass are, as in the molluscan shell, lines of growth or accretion, but their formation requires explanation, since a continuous flow over a smooth surface like that of water, while it would account for the shape, would not be expected to show any lines on the surface in contact with the water. The lines are due probably to the combined effect of surface tension and the slight contraction of the edges of the solidified layer in contact with the water. The molten wax is unable to flow immediately over the edge of the solidified layer, but is heaped up above it until its pressure is too great for the surface tension, when it flows over and comes into contact with the water, and then the process is repeated. The vibration of the water caused by the fall of the wax may have some effect in determining the rhythm of these successive flows, but when the wax falls from a slightly greater height the effect of the vibrations is seen in a series of large knobs on the lower surface of the paraffin mass.

Although, as remarked above, Kappers does not describe in his paper how the shell-like masses were formed, he gives some information on this question in a private letter to Mr. Burne, which that gentleman has kindly sent to me. In this letter Kappers states that since he obtained the specimens by accident he has from time to time tried to make them purposely, but always failed. They were formed by molten wax that escaped between the embedding mould and the zinc table on which it rested, the molten wax "coming soon in contact with water (aqueduct water)." I presume that aqueduct water means what we call tap-water. He goes on to say that it must be possible to make the shapes purposely, that he tried to do this in watch-glasses floating on water, and got some "which showed the principle very clearly but were not nearly as nice as those obtained by accident." The paraffin he used was a mixture of 2 parts melting at 58° C. and 1 part melting at 42° C. That which I used melted at 52° C.

From these remarks of Herr Kappers it seems to me quite certain that the specimens he obtained were formed in the same way as mine, namely from molten wax flowing on to the surface of water. He gives a sketch showing the embedding mould resting on the metal table, but I presume from his remark about water that the edge of the zinc table overhung a vessel of water, such as a sink, and that the escaping wax flowed from the edge of the table on to the surface of the water. It is certain that no shell-like forms are produced by the wax cooling on a solid surface; I have tried this, and the only result is a plate of wax of fairly uniform thickness of rounded outline and no special markings either on the upper or lower surface.

I have also tried the effect of pouring the wax into watch-glasses floated in water, and found that concentric lines are produced on the surface in contact with the glass. The lines in this case are more circular round a centre in the middle of the watch-glass, but they are not so distinct and regular as when the wax is poured on to water. Their explanation is I believe the same as in the latter case.

Although I think it is quite evident from the facts and experiments above discussed that the form and markings of the shell-like masses have nothing at all to do with crystallization or the forms of crystals, I have made some investigation of the crystalline structure of the solidified wax, and give here the results of this investigation. The crystals of the wax can be seen in thin sections cut from a block, and have the form of elongated prisms. A simple way of obtaining these crystals is to melt a little of the wax on a microscope-slide and allow it to cool of its own accord, and then examine it with the microscope. The prisms are then seen to be aggregated in star-like clusters, very much like snow-crystals, or the crystals of ice formed on a frosted window-pane. A diagram of this arrangement is shown in text-fig. 1. This is the arrangement assumed by the crystals after slow cooling, when no special methods are used to accelerate the cooling. I have carefully compared by means of sections cut vertically or parallel to the free surfaces, (1) one of my shell-specimens, (2) a block formed by pouring the molten wax into a metal mould, the block being about $\frac{3}{4}$ in. long by $\frac{1}{2}$ in. wide, and cooled

Text-figure 1.

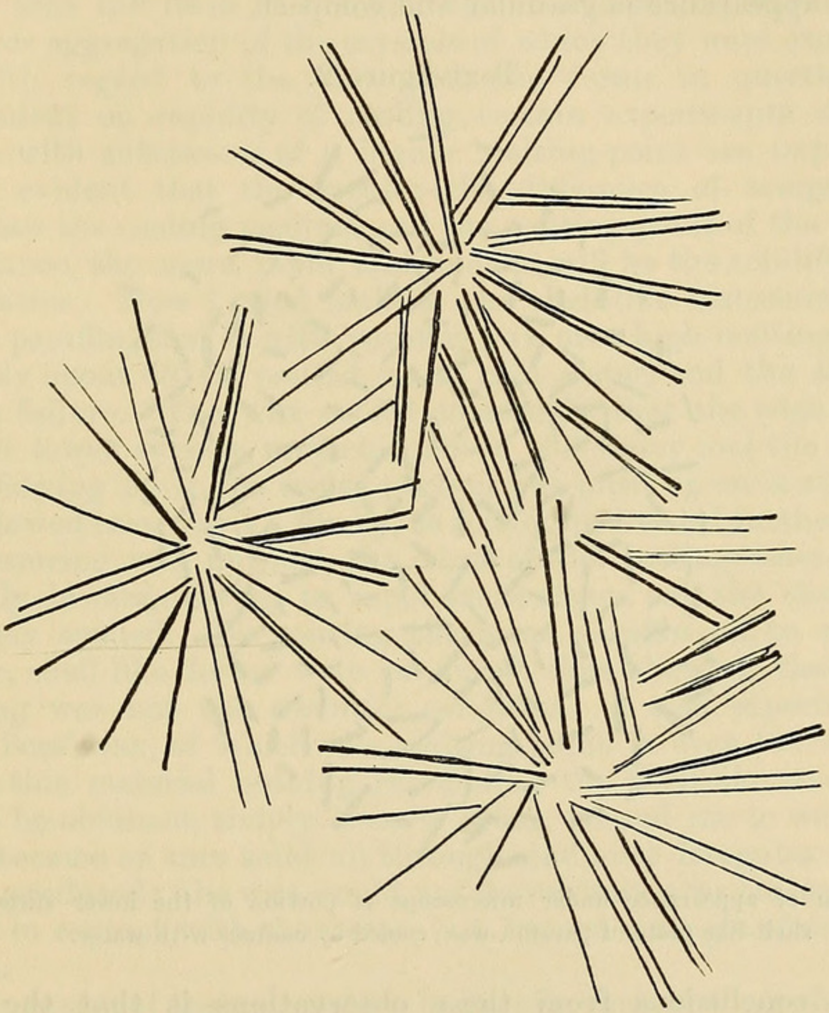


Diagram of stellate arrangement of prismatic crystals of paraffin-wax in the superficial portion of a spontaneously cooled mass.

spontaneously. I find that in a vertical section from the shell-specimen taken about the middle of the mass, the same stellate arrangement of crystals can be seen. The same arrangement also occurs in a section from the exposed surface. A portion of the lower surface, *i. e.* that which is suddenly cooled by contact with water, however, shows a different appearance, namely, a number of short irregular lines at angles to one another, marking out polygonal areas which may be the bases of crystals extending vertically into the interior (text-fig. 2). These lines and areas have no relation whatever to the concentric lines or markings which resemble those of molluscan shells, these markings consisting of ridges and depressions on the surface, while the others are microscopic and in the substance of the wax.

In a vertical section from the central part of the block cooled slowly in a metal mould, the stellate arrangement of the crystals is visible near the free surface, and a portion of the surface shows the same structure. When a superficial section of one of the lateral surfaces, or the base is examined no such structure can be seen, in fact crystals cannot be made out distinctly at all, the whole appearance is granular and compact.

Text-figure 2.

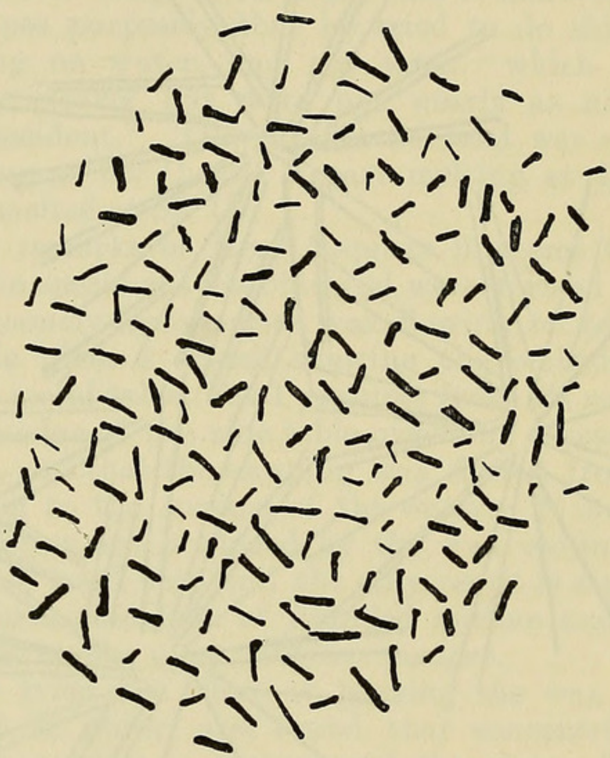


Diagram of appearance under microscope of portion of the lower surface of a shell-like plate of paraffin-wax, cooled by contact with water.

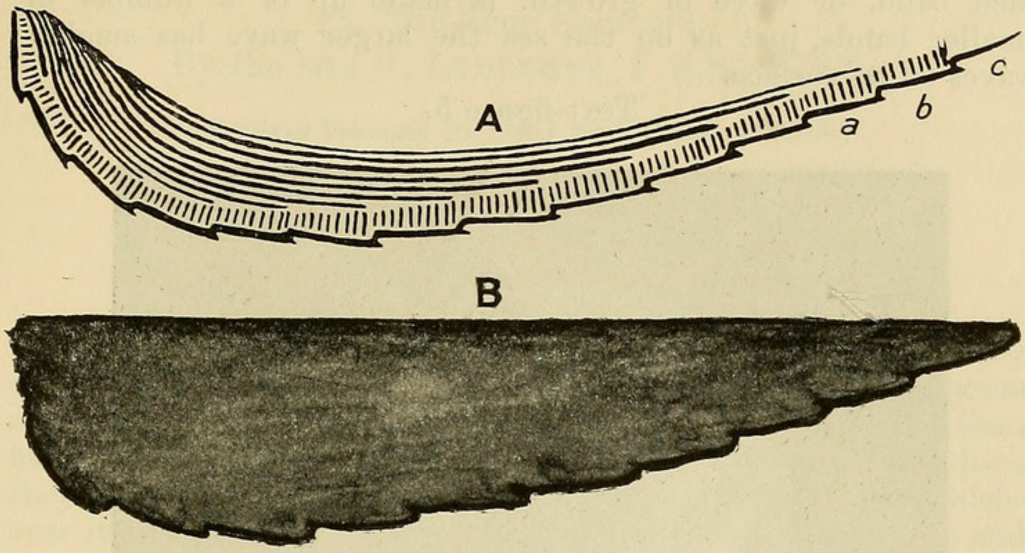
My conclusions from these observations is that the large prismatic crystals are formed where the cooling is slow and that they assume the stellate arrangement where there is most freedom of movement, *i.e.* near or at the free surface, as on a glass slide or at the surface of a block, or floating shell-like mass. On the other hand, where the cooling is rapid, as at the surface in contact with water or in contact with the metal of the mould, neither large crystals nor stellate arrangement is to be seen, the structure is more compact, apparently because the wax becomes solid at numerous closely crowded points at the same time, and crystals if formed at all are very minute. I have not been able to see any indications of crystals having any approximation to a spherical form, which I presume is the meaning of sphæro-crystals. I am inclined to think that the surface of a block of paraffin-wax in contact with a metal mould is cooled as quickly or even more so than that in contact with water, at least in a cold room in January, for the metal is a better conductor of heat than water, and is at a low temperature to start with. If the form assumed by the block was determined by the form of crystals the effect should be visible on the free surface of either a block in a mould, or a mass on the surface of water, for here the wax is free to take any form, whereas elsewhere it takes the form of the surface in contact with it. It is to be noted that Kappers gives no observations on the form of crystals in paraffin-wax, and makes no attempt to show that the form of his shell-like masses corresponded to the form or aggregation of the crystals of which they were composed.

With regard to the view that the forms in question are dependent on rapidity of cooling, certain experiments which I made with substances of a higher melting-point are important. It is evident that the greater the difference of temperature between the cooling medium and the melting-point of the molten substance, the more rapid and sudden will be the solidifying of the latter. Now I tried making the shell-like structures with hard paraffin, that is with paraffin-wax of a high melting-point, namely about 60° C., poured on to cold water, and the attempt was a failure. The wax cooled so rapidly that the edge of the cooled lower surface projected above the water and the molten wax flowing on to the cooled portion was piled up on it and then overflowed irregularly ; finally, as cooling proceeded further, after the pouring was finished, the edges of the cooling mass curled rapidly inwards owing to rapid contraction, and the shape was entirely spoiled. By pouring the same paraffin on to *warmed* water, shell-like forms were produced, thus showing that rapid cooling was not the essential condition. I also experimented with bees'-wax, of which the melting-point is over 100° C., and with this material nothing resembling the shell-like structures could be obtained, simply because when poured on to water the wax became at once solid all through and only irregular masses were produced : the wax would not flow evenly over the solidified layer in contact with the water, but formed a tangle of solidified cords.

The causes of the assumption by paraffin-wax of these shell-like forms are, as I think I have shown, purely physical, and in itself the subject may seem to be of slight importance and to have little bearing upon zoology. But the subject acquires considerable zoological importance from the fact that the phenomena have been adduced in support of the view that the forms of molluscan shells are determined by the form and behaviour of the crystals of which their inorganic part is composed. For such a view the phenomena discussed in this paper afford no support whatever, and the doctrine itself has no scientific foundation. Considering the diversity of molluscan shells in general, the different shapes of Lamellibranch shells, the torsion of the Gastropod shell, and the variety of the spirals shown among the Gastropoda, the third type and included diversity in the shells of Cephalopoda, etc., it is impossible to suppose that crystals or sphæro-crystals should aggregate themselves in modes of corresponding diversity of type and detail merely because they were formed in a colloid medium. Moreover, we know that the form of the shell is determined by the mantle, the border of which secretes an organic layer of conchiolin, and this has the specific form of the shell before calcification takes place in it at all. Lastly, no reason has been given why the form or aggregation of crystals should produce the characteristic parallel or concentric markings on molluscan shells, which correspond to the edge at which growth takes place, each of which has, in fact, at some previous moment in the growth of the shell been its extreme edge. These markings are in fact evidence that the growth of the shell is not perfectly continuous but intermittent, although we do not know fully the causes of this rhythmical periodicity in the growth except in the annual markings. That the forms of spicules such as the three-, four-, or six-rayed spicules of sponges, may be determined by the form and aggregation of crystals, seems probable enough, but this is quite a different question from that of the form and markings of molluscan shells, which are determined by the extent and the physiological activities of the shell-secreting epithelium.

In text-figs. 3 & 4 I have given diagrams which show on an enlarged scale the mode in which growth takes place in a molluscan shell, and in one of the imitation shells of paraffin-wax, respectively. In the mollusc the edge of the mantle secretes conchiolin only, the periostracum; and for reasons, not so far as I know discovered, the growth of this edge is not uniform and continuous, but is stationary for a time, and then starts again not quite in the same direction, but the mantle leaves the extreme edge of the periostracum projecting and secretes a new band starting from the lower surface of the preceding band. In certain cases, as is well known, the edge of a band at certain intervals may be fringed with long spines or processes, as in *Cardium echinatum*. When the extreme border of the mantle has extended to a certain distance beyond its former limit, the next internal band of the mantle comes into contact with the band of periostracum just secreted, and forms on the inner surface of this an addition to the prismatic layer of the shell. When the next growth-movement of the mantle takes place, the prismatic-forming region passes out to the new border of periostracum, and the prismatic band just formed becomes covered by the region of the mantle which secretes the nacreous layer. The successive processes of secretion are shown in text-fig. 3 A, where *c* is the extreme band of periostracum in process of secretion, *b* the preceding band with the prismatic layer added to it, *a* the band preceding *b*, to which a single layer of nacreous shell-substance has been added. It is to be noted that in the true shell, as also in the wax imitation, between the more conspicuous lines of growth, which alone are indicated in the

Text-figure 3.

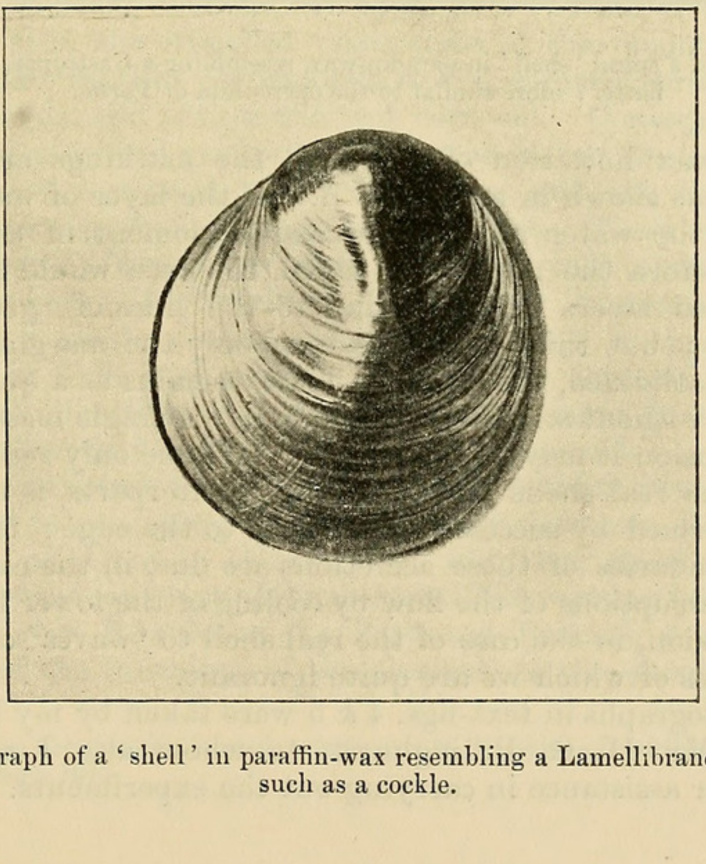


Comparison of form, markings, and structure in a molluscan shell, and artificial mitation of the same in paraffin-wax.

A. Diagram of section of a Lamellibranch shell. The outer line represents the periostracum which is uncalcified, and usually worn away except near the growing edge, which is on the right of the diagram. The layer indicated by vertical strokes is the prismatic layer, the curved continuous lines represent successive layers of the nacreous substance which lines the inner surface of the shell.

B. Section of a shell-like plate of paraffin-wax. The convex surface marked with depressions at regular intervals, is the lower surface in contact with the water; the horizontal surface is the upper surface, exposed to the air.

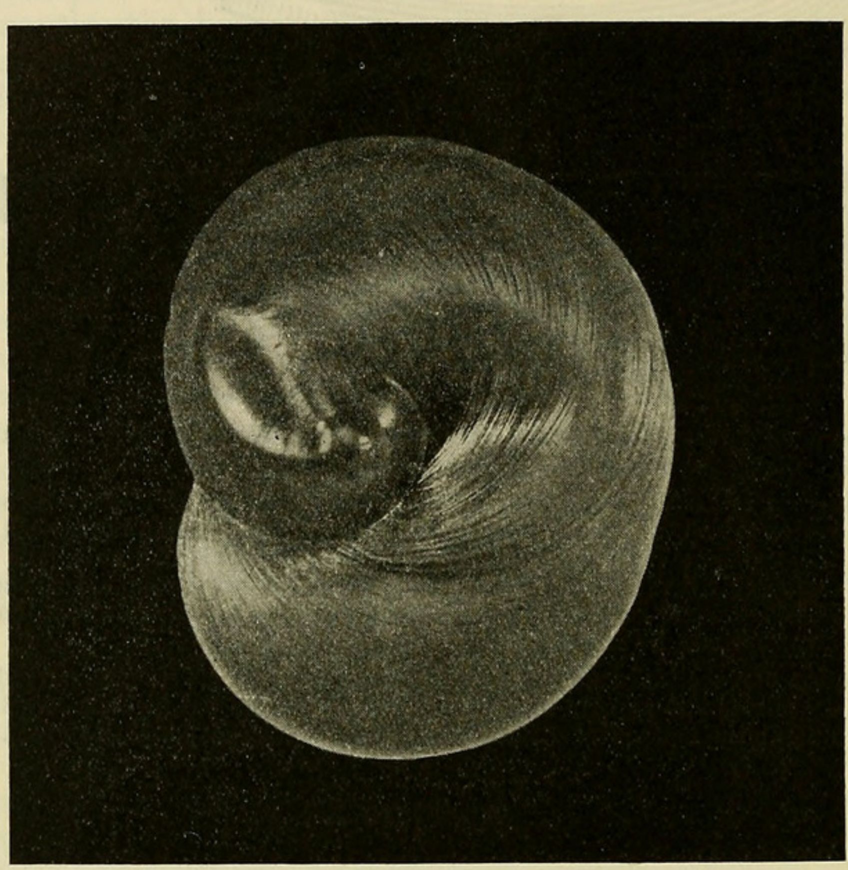
Text-figure 4.



Photograph of a 'shell' in paraffin-wax resembling a Lamellibranch shell, such as a cockle.

diagrams, there are numerous minor or secondary lines, so that each band, or wave of growth, is made up of a number of smaller bands, just as on the sea the larger wave has smaller waves on its surface.

Text-figure 5.



Photograph of a spiral 'shell' in paraffin-wax, resembling a Gastropod, but much flatter: more similar to the operculum of *Turbo*.

In the wax imitation of the shell the markings are purely superficial, as shown in text-fig. 3 B. If the layer of wax on the surface of the water at each successive moment of time were solidified before the next were added, the mass would consist of superimposed layers corresponding to the lines of 'growth' on the surface; but this is not the case, only the marginal increments are solidified, the internal mass remains as a quantity of liquid wax without structure and cools into a single mass.

In conclusion it may be pointed out that the only resemblance between the real shells and their wax counterparts, is that they are both formed by successive accretions to the edge: the marks of the boundaries of these accretions are due, in the case of the wax to interruptions of the flow by cooling of the lower layer and surface tension, in the case of the real shell to 'waves' of growth of the causes of which we are quite ignorant.

The photographs in text-figs. 4 & 5 were taken by my honorary assistant, Mr. H. G. Billinghurst, to whom also I am much indebted for assistance in carrying out the experiments.