Chapter 1

Crystallotics (= The Science of Crystals)[1]

The task of *crystallotics*

The most important and interesting domain of natural science, which until now, as "crystallography", forms a major part of the so-called "science of inorganic nature"—or in the narrow sense "mineralogy"—has achieved, through Lehmann's discovery of "liquid crystals" (1904) a completely changed position and a much extended significance. Hitherto, the science of crystals has usually been left to be the "crystallography" of the mineralogists, physicists and chemists and for them the main task was seen to be the systematic classification of crystals and the description of their numerous crystal forms, their physical properties and their chemical constitutions. In the outstanding "Grundriss der Kristallographie" of Gottlob Linek[2], who presents the most recent state of this science comprehensively in a clear form, the greater part is dedicated to the systematic description of the 32 symmetry classes and their optical properties[3]. Just as biology was earlier considered to be "descriptive", so also crystallography (as a part of mineralogy) had the predominant character of a "descriptive science".

Through the great progress, which physical and chemical research on crystals has made since the beginning of the twentieth century, most notably through the fundamental recognition of "living crystals", the general significance of the science of crystals, and its relationship to the other branches of natural science, has substantially altered. Looking from our monistic standpoint we now treat crystals as "living natural bodies" and in retrospect also regard their psycho-mechanical properties also as "inspired". We are permitted to denote "*crystallology*" in the widest sense as *crystallotics* and its most important branch, morphology (—descriptive crystallography—) as equivalent branches to be set alongside the "physiology" and *psychomatics* of crystals. As the earliest of the forms of crystals were described and classified, there appeared "*crystallogenics*"—the investigation of their development. The "physiology of crystals", just as that of organisms, must study their chemical and physical properties, and the "*psychomatics* of crystals", must study their "inorganic psychic activity" (Seelenleben), the *psychomatic* laws of their feeling and willing and the direction of the secret molecular forces.

Crystalline order

The broadening of our general *crystallotic* outlook, which since 1904 was brought about by the deeper recognition of liquid crystals and their close connections with the lowest organisms, has allowed us effectively to distinguish the following four main groups or orders of crystals (not to be confused with the "symmetry classes of the crystal forms"):

I. *Sterro-crystals*: the true "rigid crystals", which, until the beginning of the twentieth century were almost always treated as "typical or real crystals".

II. *Collo-crystals*: gelatinous crystals which in water can swell up and alter their volumes or their typical crystal forms: (albumin crystals in plant cells, animal blood, etc.).

III. Bio-crystals: solid mixed crystals which result from the usual operations of living plasma and mineral substances (chalk, silica, etc.).

IV. *Rheo-crystals*: the liquid or "apparently living" crystals of Otto Lehmann.

Sterro-crystals

The rigid crystals, which until the beginning of the twentieth century were the only objects to be designated as "true crystals", are characterised by their solid state of aggregation and their inflexible prismatic external form. This rigid prismatic shape is accessible to clear geometric definition and mathematical calculation. Their surfaces are defined by flat parallel planes whose edges meet at constant angles; these edges meet at corners, which correspond to the poles of ideal axes intersecting at the midpoint (of the crystal). This symmetrical external form indicates a characteristic inner structure which is manifest in the cleavage properties and in the various properties of the molecules as regards light, heat, electricity and other physical influences. Through the ideal axes, whose proportions determine the stereometric fundamental form, constant symmetry planes can be located. In spite of the great multiplicity of forms which *sterro-crystals* individually show, all can be traced back to the basic forms of six systems. These are therefore of significance for our comparative treatment of inorganic materials and organisms, because they also determine, in a quite similar way, the basic geometrical shapes of some of the protists, especially among the Radiolaria.

Symmetry systems

The six morphological crystal systems, which are shown in summary in Table 1, possess different *promorphological* values. The first, tesseral (cubic) or regular system, stands out from the other five and is distinguished by three equal and equivalent mutually perpendicular axes; its inner construction is isotropic like the sphere; the molecules are oriented in all directions of space equivalently, as in amorphous bodies and in liquids[4] (see Figs. 1–3; Plate C, Fig. 3)—in contradiction to these isotropic regular crystals, the other five systems are anisotropic; their inner molecular ordering is different in the three directions of space; the inner structure behaves differently in different directions for pressure, heat, light, etc. Of these five anisotropic systems the first two are distinguished in having a principal axis, which we may think of as being vertical, determining the basic form. In the tetragonal or quadratic system, this principal axis, (longer or shorter than the others) is perpendicular to the two other axes which are also at right angles to each other, so that the mid-plane of the crystal forms a square. The basic form is a "tetragonal double pyramid", composed of eight equal isosceles triangles. In the hexagonal system, on the other hand, (for example in snowflakes, Plate B) the vertical principal axis is at right angles to two other axes at sixty degrees to each other; so that the basic form is a six-sided double pyramid composed of twelve equal isosceles triangles. The horizontal section is here a regular hexagon (Plate B, Figs. 12–14).

The three other symmetry systems have a narrower *promorphological* interest for us and exhibit complicated properties; they appear more rarely in the organic shape repertoire of protists than the first three symmetry systems. The fourth, orthorhombic system, is characterised by three unequal axes, mutually at right angles, and these correspond to three

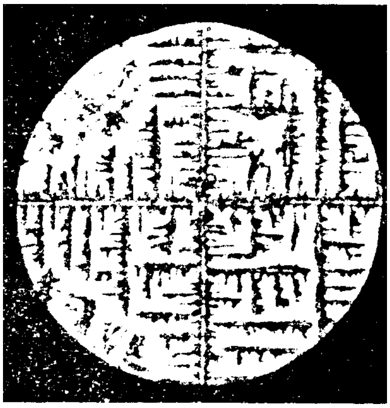


Fig. 1.

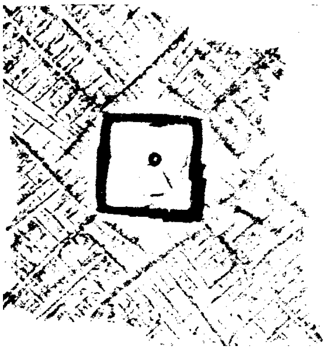


Fig. 2.

Fig. 3.

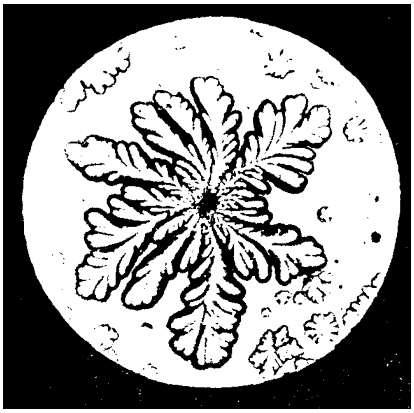


Fig. 4.

Figs. 1–4. Crystallisation of sodium chloride. Cubes in the cubic system. After Leduc (Nantes), "Théorie de la Vie", 1910.

Fig. 1. Primary crystal skeleton. The "living" field of crystallisation in which the molecules of sodium chloride, extending from a central nucleus in the directions of the three axes, link with each other. From the three "directed molecular fields" (Haeckel's *molethyn*) of the first order, there grow secondary structures, and from these, also at right angles, growth continues with tertiary structures.

Fig. 2. A growing crystal in a field of crystallisation, in which the central nucleus is formed from a pre-existing sodium chloride cube. The four primary rays, corresponding to the molecular axes or "directed molecular fields" (*molethyn*) extend from the eight corners of the cube.

Fig. 3. A Crystallisation field with three sodium chloride cubes. From the eight corners of the primary cubes there grow, in extension of their axes, short primary "directed molecular fields" and from these further secondary growths emerge.

Fig. 4. The Pathology of Crystal Life. Abnormal Sodium Chloride Crystals. ("sick") crystals formed like feathery leaves in a colloidal solution.

symmetry planes also at right angles to each other. The fifth, clino-rhombic or monoclinic system shows three unequal axes; two intersect at an acute angle and lie at right angles to the third. In the sixth, triclinic or asymmetric system, all three axes are unequal and intersect at acute angles; no plane of symmetry is present. (See the first synoptic table in the appendix.)

Individual crystals (Single crystals)

The main subject of crystallography is the individual crystal, the single crystal as a body with a definite shape and of homogeneous chemical composition. One can, in fact, in the last analysis, distinguish between pure crystals and mixed crystals, and, as a transitional form between the two, the "layer crystals"[5] (as clays). As regards our present task, the comparison of individual crystals with *probionts* and Radiolaria, this difference is not significant. Thus we can deal with the simplest forms of Chromacea, the homogeneous plasma spheres from Chroococcus, as spherical "layer crystals", in so far as the growing *cytode*, a structure-less plasma sphere, forms a gelatinous shell or membrane as a "surface product". If we deal here with the morphological individuality of the crystal in general, in anatomical and ontogenetic relationship, then it is first of all to be emphasised that every monocrystal is limited in space and time. Every crystal form as an individual (whether chemically homogeneous or mixed) passes, during its formation from a "seed", that is from a central molecular group, and grows up to a determinate size. Individual maximum sizes are very different, even for a single species, but cannot be exceeded. Thus, there are very numerous crystals (namely bio-crystals) which remain microscopically small and do not reach even 1 mm. On the other hand gigantic inorganic crystals (for example of various alums) may grow up to be one metre across. Many ancient single crystals (for example in mines) reach a circumference of several metres and weights of more than 50 kg.

Just as each individual crystal is bounded in space so it is bounded in time; it has a finite lifetime, either because of its inner chemical composition or because its development is determined by external circumstances. Here a determinate boundary is imposed, not from below but from above. Geology teaches us that even if the oldest sediments are more than a hundred million years old, there can be no "eternal life" in crystals included in them. Even when we wake them from their "apparent death", and stimulate them to further grown by bringing new nourishing material, this (life) will also remain limited in time and in space. Every single crystal, just as each organic *plastid*, is the historical size it once was and does not return.

Crystal aggregates

By social aggregation of many monocrystals, crystal collectives or *coeno-crystals* result[6]. For comparison with the coenobia of protists, the most important of these are the crystal chains which arise by catenation. Like the beads of a chain or pearl necklace, many individuals lie in a row one after the other in a determined direction. The smallest of these chains are the *margarites*, pearl necklace-like forms, whose single members are the so-called *globulites*, sphere crystals (or amorphous spherulites) of very small dimensions. Objects bigger than such crystal chains occur also in rigid and in liquid crystals. They completely correspond to the *cytode* chains of *probionts*, as well as to the Chromacea (Oscillaria, Nostocacea, etc.) and to the Bacteria (Streptococci, Crenothrix, etc.). These include the real cell chains of the true “thread Algae” (Conferva, Ulothrix, etc.). On the other hand the important question arises as to whether in these concatenations other forces prevail, such as are operative in the invisible world of molecules in the formation of the “space lattice” of rigid crystals. The parallel lining up of equivalent units in a definite direction is in any case a phenomenon which, in its *psychomatic* significance, throws light on many apparently widely disparate processes of social organisation.

Dendrites

When the simple chains of rigid crystals branch, tree-like forms result, which often show the greatest resemblance to the ramified stems of plants and lower animals (polyps, Bryozoa). The best known are the dainty ice flowers, which in winter decorate the glass window panes of our rooms. These most diverse, often fantastic, ice formations are none other than many-branched chains of small ice crystals which have been rapidly deposited from the water vapour of the warm room air on to the cold glass sheet. Thousands of such small water crystals sit in rows and the chains branch according to the conditions of their surroundings. Mineral dendrites form still more delicate “art forms of nature”, ramified crystal aggregates, which take on the forms of richly branched plant stalks of the Algae, mosses, conifers, etc. They occur in the cleavages and clefts of many chalks (e.g. Solenhofen slates) and sandstones; they occur also in meteorites; they consist mainly of *coeno-crystals* of hydrated iron oxides, siliceous magnesia etc. and can also be produced artificially. The dainty “metal trees” which can be grown by evaporating metal salt solutions (Saturnus trees) from lead acetate solution, Diana trees from silver solutions, etc., are such similarly richly branched small bushes and trees, that they were often held to be direct products of the plant kingdom.

Concrescence (*Syn-crystals*)

The regular growth of *syn-crystals* should be distinguished from the irregular growth of gregarious crystals, as in the above-mentioned aggregates, from which the greater part of *coeno-crystals* result by chance by other circumstances, and the latter are designated as “twin, triple and multiple crystals”. This concrescence can be defined both by parallel as well as by symmetrical positioning of the molecules in twinned- (or in multiple-) single crystals. In each case a stable state or an equilibrium positioning is reached, which indicates a “desire” of the joined twins (or multiples). This can be compared with the copulation of *cytodes* and of cells among the protists. For the “feelings” of the crystal psyche, these concrescences indicate, as far as their *psychomatic* meaning is concerned, the determinate “directions” of the growing monocrystal and their symmetrical disposition in space. In the copulation of cells (as widely occurs in the gamete formation of protists), the new biology assumes correctly, that their growth is determined by the feeling and “inclinations” of the two copulating individuals. The same is the case for the rarer concrescence of fabric-forming plants and animals, of *histones* (e.g. diplozoa). The same *psychomatic* origins may also be assumed for the appearance of *syn-crystals*.

The development of *sterro-crystals*

The precursors of crystallisation are now to be interpreted as real “life phenomena”. When a chemically simple body passes from the liquid state (melt or solution) to the solid state, for example, by the cooling of a molten mass or the evaporation of solvent from the dissolved mass, there is first formed a so-called “crystal seed” or “crystal nucleus”, a more dense aggregate of molecules, which then acts to attract the surrounding particles. In a determinate direction—corresponding to a stereometric axis—the oriented molecules lie parallel to the seed in regular symmetry. Since the seed has the characteristic form of the appropriate crystal system, the growing individual appears as a steadily growing image of the nucleus. This growth happens in *sterro-crystals* through external docking (apposition or juxtaposition), while in *rheo-crystals* an inner uptake (intussusception) can also occur, as in organisms. In “liquid crystals” there is also a real distinction, which existed earlier between organic and inorganic bodies, both in relation to their aggregated condition and also in their growth. Moreover, for crystals it is generally the practice—as for organisms—to treat growth (*crescentia*) as that “phenomenon of life” which, in the main, determines the evolution of the individual.

Crystal skeletons

Of greater significance for the *psychomatic* assessment of the crystallisation processes are those crystal forms which nowadays are designated by the crystallographers as crystal skeletons. When a *sterro-crystal* crystallises out quickly from a melt (on rapid cooling) or from a solution (on rapid evaporation), the nucleus grows preferentially in the direction of the axes towards their poles, and shapes itself according to these vertices and the edges connecting them. After this, the formation of the faces is retarded or proceeds slowly. Since for descriptive crystallography the regular formation of these polygonal faces and the multiplicity of the edges separating them is of special interest, the fixed formation of the axes and their immediate neighbourhood is less emphasised. But, just this “incomplete or rushed crystallisation” is of especial importance for the comparison of *sterro-crystals* with Radiolaria and other crystal-like protists. It throws a bright light on the *psychomatic* forces of molecular movement, which as *molethyn*[7] (directional forces between molecules), determine the geometrical shape of the single crystal. The inner axial star is more important for the development and for the character of the prismatic crystal form than the special formation of the external faces in their numerous single modifications[8]. Just as, in the estimation of the vertebrate body, the exact knowledge and the comparative anatomy of the inner skeleton are the first conditions for the understanding and the systematic classification of the external form, so it is the same for the morphology of *sterro-crystals.*

The life of *sterro-crystals*

The solid, inorganic, stereometrically defined crystal, which hitherto has been usually regarded at lifeless and dead, possesses real “life” just as much as the “organism” of the simplest kind among the protists. The single crystal lives and preserves itself as an independent individual, insofar as in its substance, the physical and chemical forces—or “energy forms”—which are determined by its elemental constitution, preserve themselves. This ‘life force’ (in the physical sense) leads us directly and visibly towards a “living force” or “actual energy” as long as the *sterro-crystal* grows and develops. It does not disappear, however, when this growth ceases and a stationary state sets in. It remains then as a latent force of “potential energy” in the “apparently dead” crystal, as long as internal and external conditions permit this. The real death of the individual sets in when these conditions stop and the inner constitution is destroyed.

Almost a hundred years ago, C. G. Carus had interpreted the real "life of the crystals" in the same sense, and this was also in agreement with Goethe's view. In his "Foundations of a general treatment of nature"[9] (1823) Carus said: "Crystallisation itself, which results from the inner principles of the motion of material, we must always call life; but this life expires in the endless rigid form of the crystal." Thus it is particularly to be emphasised, that Goethe was especially qualified, on the basis of his mineralogical and biological studies over many years, for the critical comparison of organic and inorganic life, and was not limited by the boundaries, which hinder the short-sighted and limited specialists, in his natural judgment of the great general principles of the formation of structure. As Goethe, in his morphological studies on the comparative anatomy of the skull and on the metamorphoses of plants, was far above the ruling outlooks of the professional zoologists and botanists, so also was he superior in his outlooks on "the life of crystals" with respect to the mineralogists.

Adaptation of *sterro-crystals*

The characteristic symmetry in the inner structure of rigid crystals, the relationship of their defining axes and poles, and especially the constancy of the angles between their edges, is determined by their chemical constitution, by the elective affinities[10] of the atoms and by the directionality of the juxtaposed molecules. Thus the external form and size, as well as the special facial forms, of the individual crystal depend on the external conditions of its development, in the first place on its nutrition. This dependence is above all on the influence of the conditions of the immediate surroundings, the temperature, the pressure and the effects of disturbing objects. For rigid crystals, which are formed from solutions, the concentration, the conditions of the co-solutes, the stillness of the mother liquor and the physical constitution of the surroundings are important. The most beautiful and most regular rigid crystals are obtained with very slow and undisturbed crystallisation carried out in a large vessel over a long period of time. If the development process is disturbed, for example by shaking, then "crystal flour", a powder composed of many small crystals results. The symmetry of the normal rigid crystal is most fully evinced when it is kept in the middle of the solution; if it lies on the bottom, then the face on which it lies becomes abnormal. Thus the most favourable formation of the inorganic individual crystal is as dependent on space and time as it is for organic individuals.

The regeneration of *sterro-crystals*

An outstanding phenomenon in the life of crystals is to be seen in their possibilities of regeneration—in the restoration of damaged parts. This event has a clear relationship with the well-known regenerative properties of many organisms. Not only the lower but also the higher plants and animals can restore lost or damaged body parts by partial growth. Damaged crystals, both solid and liquid crystals, can also repair damage. Old experiments by Lavalle on crystallisation relating to this have recently been successfully repeated. If you cut away one edge during the formation of a definite octahedron and thus, by "wounding" produce an artificial face, a related face forms by itself at the exactly corresponding opposite edge, while the other edges develop the normal form. This demonstrates an inner correlation of the parts, which the unitary formative force[11] shows physiologically, and the feeling for symmetry of the individual shows *psychomatically* (see "Symmetry" in Chapter 4).

The deaths of *sterro-crystals*

Just as their chemical composition and their characteristic basic form sets a limit to the growth for each individually, so also the life of the individual crystal is finished when this limit is reached. The finished rigid crystal is dead when it can no longer grow and become bigger. Many crystals, especially salts, contain water, often in significant quantity. This water of crystallisation can only be stored loosely between the molecules and is then readily removed by heating; it may explode the *sterro-crystal* by producing steam and kill it ("decrepitation water"). Other water-containing *sterro-crystals* are so changeable that they lose water and fall to powder just by standing in the air; they die by "weathering" (as do organic individuals by "decay"). In other *sterro-crystals* the water is in a definite chemical proportion, is bound chemically to the mineral substance and is necessary to the individual existence of the crystal. "Blue vitriol" (hydrated copper sulphate) is weathered as it loses its five molecules of water; it breaks up into a white powder; but when this "dead" (amorphous) powder is just dissolved in water, the substance can again take up five molecules of water and again form new blue individuals by crystallisation. Between this firm and that loose binding of the water of crystallisation there is no sharp division.

The apparent death of *sterro-crystals*[12]

When, during the "living" crystallisation process, the growing individual is not supplied with enough nourishment ("mother liquor"), further growth stops; it falls into "apparent death"; the actual "life force" goes over to being a "potential force". In this state the apparently dead *sterro-crystal* can persist for a long time—hundreds or thousands of years. If new nourishment is again applied, then the slumbering life can be again awakened and the interrupted growth can be continued. *Sterro-crystals* stand in this respect quite like organisms (protists: dried Chromacea and Bacteria, Algae, infusoria)—even higher plants and animals (seed grains of plants, rotifers, and nematodes, tardigrades, etc.). These organisms also can remain for years in motionless apparent death (ceasing to metabolise) or frozen in ice; they wake to new life when water is added or when the frozen tissue is thawed out again. Here it is unambiguously demonstrated, that "life"—in organic as in inorganic bodies—is not a product of a special "life force", but is a physical process, converting itself by "vigour" into "driving force" or from potential energy into actual energy.

The working of the snow-psyche

Pure water is not only of the highest physical significance for various natural phenomena—above all as the first condition for the existence and development of organic life—but it stimulates also our lively morphological interest because of the unparalleled multiplicity of forms which it assumes as a *sterro-crystal* goes over from the liquid or vapour states to the solid state of aggregation. Above all it is snow which, with by its delicate and most multiform crystal shapes, has, for more than 200 years, enchanted the microscopists. Up to now more than a thousand different forms of snow crystals have been distinguished and photographed. The group of 20 snow crystals, which has been assembled here, offers only a small selection from the fabulous realm of shapes—all the more remarkable, since water is one of the simplest chemical compounds and its molecules are always composed of two atoms of hydrogen and one atom of oxygen. The symmetry system, which the *sterro-crystals* of snow always follow, is the hexagonal system, characterised by a vertical hexagonal axis and three equal horizontal axes, which intersect the hexagonal axis and which make angles of 60 degrees with each other. Sometimes the proportions of these symmetry axes change with the periodically changing deposition of the solidifying water molecules in adaptation to the conditions of external existence (temperature, air pressure, surroundings, speed of growth, etc.) and diverse and delicate shapes develop with the process of sublimation of the atmospheric water vapour.

The ideal basic form in the hexagonal system is the twelve-sided bipyramid, composed of two regular six-sided pyramids joined in the mid-plane, which is perpendicular to the main axis. This ideal symmetry form of extended double pyramid is only very rarely developed in snow crystals. The great majority (over three-quarters of all cases) form flat tablets or regular six-sided discs, with their predominant facial development in the horizontal plane containing the three axes, while the vertical main axis remains short. The most frequent form is the regular six-rayed star, in which six equal rays (simple or branched) grow out from a common centre point (the initial "nucleus of crystallisation" (Figs. 1, 11 in Plate B); it exactly equals the hexagonal bio-crystals, which develop in the siliceous skeletons of the radiolaria and diatoms, as also in the silica needles of many sponges (Hexactinellides), but which also form in many other organic structures. If the development is more dominant in the horizontal mid-plane than at the six corners, flat platelets or six-cornered discs with delicate radial structure (Plate B, Figs. 2, 9, 10, 13 and 14) appear. In half development (hemihedry) regular three-cornered discs develop.

Much more rarely the growth of the main vertical axis dominates during the crystallisation of snow; there result slim pillars, or regular six-sided prisms (with built-out edges, Plate B, Fig. 16) or cylinders (with rounded edges as Plate B, Fig. 17). By the combination of the pillar and the tablet forms of growth there may result rare forms like cuff-links (Plate B, Figs. 6, 7 and 15). Not seldom there are, in the rays of the snow stars (especially in rime and hoar-frost) fine radial channels, which are filled with air or, more rarely, with water (Plate B, Fig. 19). If one breaks the snow crystals their cleavage planes appear and show clearly their inner structure (Plate B, Figs. 18a and 18b). The rare "cuff-links" are quite like the coccoliths, which occur as biocrystals in the chalk shells of the Calcocytes (*cocco-spheres* and *rhabdo-spheres*).

The endless multiplicity in sizes and forms of the snow crystals is thus very instructive, because it shows in how many ways the special forms of the crystals depend on their adaptation to the external conditions. Especially sensitive is the content of the condensed water vapour to the different materials in the solution, which are present near it in the atmospheric air (gases, other vapours, dust particles, etc.).

***Collo-crystals* (swelling crystals)**

We can distinguish a particular order of crystals, especially interesting in many aspects. These are the gelatinous *collo-crystals*, which are formed by many chemical bodies of the group of albumen compounds. They are distinguished from the rigid *sterro-crystals* by their characteristic swelling or imbibition properties; they possess indeed, the

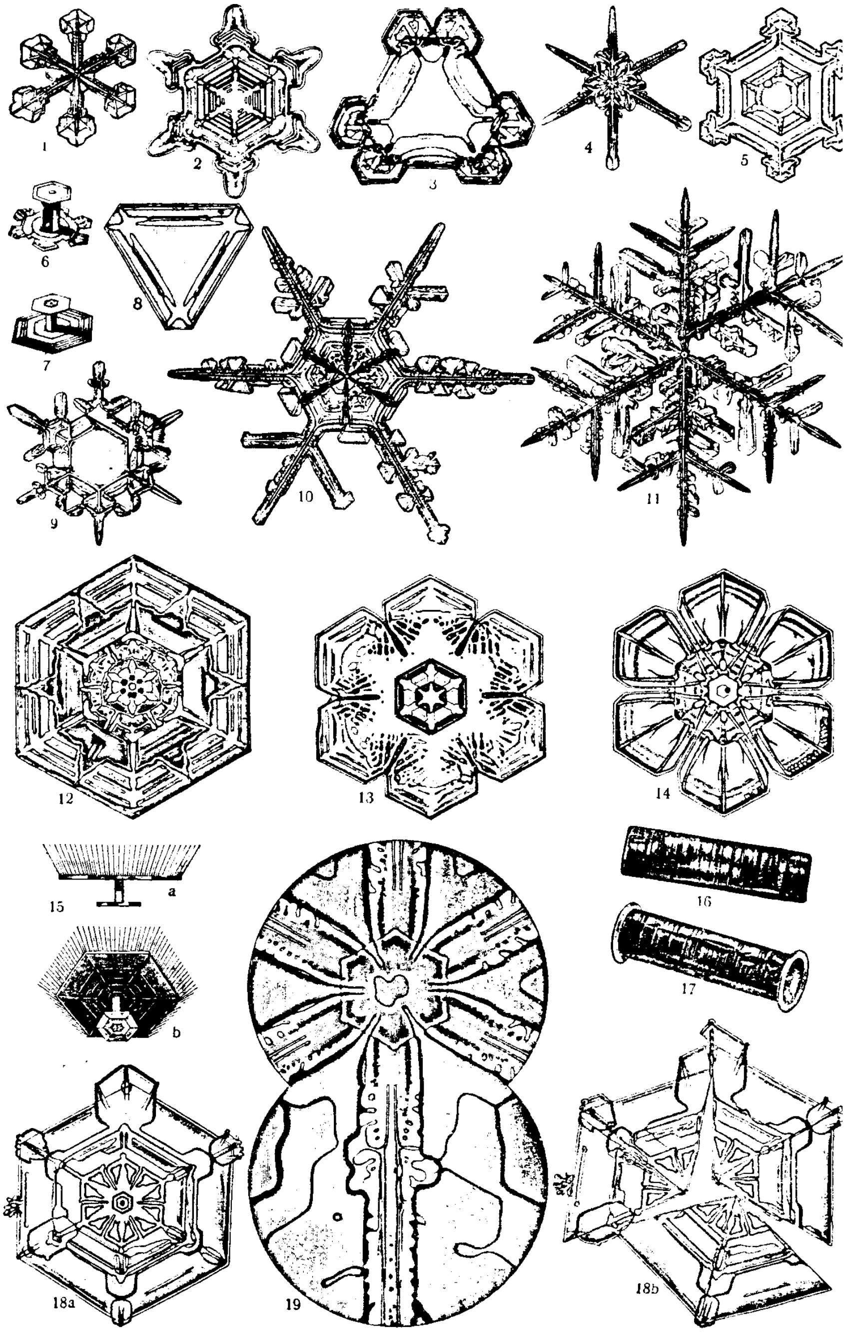


Plate B. Snow crystals (Hexagonal system showing the working of the snow-psyche).

symmetrical prismatic forms of true *sterro-crystals*, but they can take up water in significant quantity without losing these and without dissolving in the water. Thus individual *collo-crystals* may significantly increase their volumes (which may more than double); and often their faces and edges become rounded. By coagulation, by treatment with alcohol, or by drying, the *collo-crystals* can be "denatured" or "poisoned"; they retain their chemical composition, but lose their crystallinity; they "die" or are transformed into "pseudo-crystals"[13].

In the cells of plants, especially in their seeds, *collo-crystals* are frequently present, mostly with the forms of the hexagonal system, both in the cytoplasm and in the cell nucleus, but also inside the *aleurograins* and near the starch grains which are themselves often regarded as "*sphero-crystals*". The swelling crystals of proteins in the red blood of the vertebrates are especially important. Haemoglobin, which forms the major component of our red blood cells and gives them their red colour, but which is also present in the muscles and in other parts, crystallises mostly in the orthorhombic system in the form of prisms or needles; its different forms and solubilities are partly characteristic of the different mammals. In the guinea-pig haemoglobin crystallises in tetrahedra, but in the squirrel in the hexagonal system. Since both rodents are closely related and undoubtedly have derived phyletically from the same branch, there exists here a phylogenetic polymorphism. Thus, in one and the same species, e.g. in human beings, different crystal forms occur and can pass over from one form to another (polymorphism) on re-crystallisation. But also in the cytodes[14] of *probionts* (e.g. Tolypothrix) there are *collo-crystals*, indeed as cubes and octahedra of the cubic system (see also Chapter 2).

The physical interest in *collo-crystals* is because they undergo a direct transition from colloidal to crystalline bodies—the two groups into which Graham divided the solutions of solid bodies. The homogeneous protein bodies can be dissolved readily under various conditions, and occur sometimes as colloids (thin or viscous), and sometimes as *sterro-crystals*. These albumen crystals belong mostly to the hexagonal system (as do snow crystals). They possess moreover to a high degree the faculty of taking up into themselves, foreign dissolved bodies of various kinds, salts, dyes, etc., and of forming mixed crystals with these materials—they "eat and drink"—just as (on denaturation) they "die" and can lose the faculty of regeneration. The *collo-crystals* pass on one hand without sharp boundaries into solid *sterro-crystals*, and on the other hand into rigid bio-crystals, and finally also into liquid *rheo-crystals*. In that the protein bodies are reckoned as the most important "living matter" and in the plasma are the active "carriers of life", here is presented again a direct transition from inorganic to organic life. Between then there is no sharp boundary.

Sphero-crystals (Rounded crystals or spherulites)

The most different bodies, both organic and inorganic, can take up the rounded form, when they pass from the fluid into the solid state independently of other influences. These solid balls can be designated as real "spherical crystals" or spherulites, and have a radial fibrous, and often at the same time a concentric shell, structure. Water takes such forms when it crystallises rapidly as hailstones or sleet. So also for the so-called "glass heads", balls which result in the over-rapid crystallisation of liquid glass or molten iron and manganese, —or when gelatinous precipitates transform themselves into crystalline—

these can exhibit the same structure. Most often these “radially structured glass balls” can be regarded as aggregates of many small rod-like crystallites, which radiate from a common centre point towards the rounded surface. When their outer ends extend beyond this surface, spiky spheres result, which are like mulberries and blackberries (and also the morula of the metazoa). Such silica balls are to be found, as massive as “spherical bio-crystals”, in the tissues of Astrophora, a group of silica sponges (Stelleta, Geodia). Related stellate spicules of carbonates occur as forming skeletons in the mantles of many Synascidia and especially of Didemnea.[15] Liquid crystals also often have such “spherulitic” forms, aggregates of many small rounded “crystal droplets” all the same way round, which, in polarised light and between crossed polarisers, show the dark crosses for all droplets in the same direction. Cholesterol propionate does this (Title plate, Fig. 6). While here each sphere of the spherical aggregate shows a liquid “single crystal” of drop form, so can such homogeneous drops in other *rheo-crystals* transform themselves into bubbles, in which the molecules in the surface are packed more closely together and form a “solid” membrane. The liquid content of this hollow *sphero-crystal* can however become more dense in the centre; in this way round bubbles result, where each resembles a true nucleated cell (Title plate, Fig. 6). It all depends, as regards the content of *sphero-crystals*, on the surface energy of the “membrane” (which can later become separated into concentric shells by external thickening)—or on the centripetal energy of the radial rodlets, whether further different modifications of the round crystal take place. If the growth is stronger in one cross-section, the sphere changes into an ellipsoid of revolution—a uniaxial crystal shape.

Between these spherical *rheo-crystals* and the solid *sterro-crystals* no sharp boundary can be drawn. It is also often difficult to decide whether the “spherulite” should be counted as a single crystal (individual) or as a *coeno-crystal* (aggregate).

Amylum (starch) crystals

Many botanists treat starch grains, which are formed in most plants inside the cells by the chloroplasts, as true *sphero-crystals*. Often these rounded grains are fully spherical and are made of concentric sheets, which are themselves composed of radial fibres running from the centre outwards, as for example in beans and in other legumes (Fig. 5). More

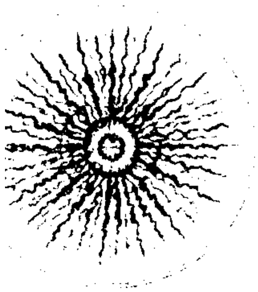


Fig. 5. Spherical crystal of starch. The spherical starch grain (here quite regular but more usually irregularly rounded) is built up of many concentric layers with radial clefts. (It resembles the otoliths or statoliths of many animals.)

usually, however, the form is not fully spherical, but lenticular, flattened or ellipsoidal, or irregularly rounded; the rays may run not from the middle point but from some eccentrically placed point. In polarised light the starch grains are doubly-refracting and show the optic axial cross characteristic of true crystals (Title plate, Figs. 8 and 9). They can grow in pairs, like liquid “twin crystals” and can be united in greater numbers to form aggregates.

Bio-crystals

The remarkable ordering of crystal-like bodies, which I have distinguished (1872) as “bio-crystals”, is of greater significance for *promorphology* than for physiology. They are like the *sterro-crystals* in their solid state of aggregation and in the regularity or symmetry of their forms, which permits an exact geometrical determination and an exact derivation from a mathematical basic form.

They are distinguished also from true *sterro-crystals*, whose forms are determined merely by the chemical mass composition, in that their form is produced by the united working of the inorganic mineral substance (silica, chalk, etc.) and the organic plasma. This difference is theoretically important in that, for the formative force of the organic components, the most complex processes of heredity during their long historical past, are to be taken into account. Among the inorganic components, the mineral skeleton-building materials (silicon, calcium, strontium) this is not the case; here much simpler, purely physical properties are dominant. Moreover the molecular movements in bio-crystallisation are more various and harder to determine than in the simple *sterro-crystallisation*. We can distinguish the developmental processes in single cell protists and in the multicellular tissue-building *histones* as two different levels of this first class.

Bio-crystals of the protists

The multifarious crystal-like forms of single cell protists are connected with the geometrically determined forms of *sterro-crystals* insofar as, here as there, the single individual —also a *singulate* of the self-organising homogeneous substance—determines the direction of the *molethyn* (the intermolecular ordering forces). The regular ordering of emerging molecules into geometrically determined axes and planes is directly determined by the individual life activity of the organic *singulate*. This is also the case for the *plasmodome* protophytes as for the *plasmophage* protozoa. In both groups of protists it is above all silicon, as silica, which permits, by its wonderful plasticity and its ability to be modelled, an incomparable wealth of delicate forms to be produced. This is the case for diatoms and Radiolaria. The interesting connections between these classes of protists, both in purely morphological and tectonic, and in physiological and psychological aspects, deserve still more thorough physico- mathematical analysis. The coarser calcium, especially the calcium carbonates and oxalates, is much less capable than the fine silica of creating the crystalline skeletons of independent protists. The “psyche of the element” of silicon is based on a far finer atomic structure and it possesses a much higher plasticity than does that of calcium[16]. Here the many forms of chalk shells are of promorphological and systematic interest. Among them are the protophytes of the chalk shelled Algae (Calcocytes and Syphonaea); and among the protozoa the many-formed Thalamophora (Monothalamia and Polythalamia). Since the *psychomatics* of protists in connection with bio-crystallisation is of quite special interest, it will be dealt with intensively in the third chapter.

Bio-crystals of *histones* (*Metaphytes* and metazoa)

Solid single crystals, of numerous rigid forms, based on the geometrically regular forms of the inorganic crystals, play a significant role in the skeleton-formation of *histones*. Here, however, it is not, as it is among the biocrystals of protists, the individual of the independent single-cell biont of the creative producer, but the tissue, which is assembled from many socially connected cells. Also here, in the tissues, the solid bio-crystals result through the collective plastic working of the living plasma and the dissolved mineral material bound in with it, especially silica and the calcium oxalates and carbonates. Mostly the bio-crystals of *histones* are precipitated inside the tissue cells, but often also between them in the intercellular material. They play a significant physiological role in that they lend protection and support to the weak tissue.

Among the metaphytes, the tissue plants, the basic tissue (or filling tissue), of which alone in the lower thallophytes the whole body is built up, is often the site of crystal formation. Sometimes there are large single crystals, which belong to the tetragonal and monoclinic crystal systems, and sometimes there are numerous small crystals, “crystal sand”, which fill up the cell. Acicular bio-crystals of calcium oxalate, in parallel bundles, lie often in a long vacuole filled with a rubbery medium, inside an extended cell (especially in monocoteledons). Drusy crystals, “stellations”, composed of many acicular crystals which radiate from an organic nucleus, often form. In the cytoplasm of many cells of palms and orchids there are multiform silica bodies, which may fill the greater part of the cell space.

In the multiform bodies of multicellular tissue animals, the metazoa, the bio-crystals play a much greater role, since most skeletal structures of their diverse species result from the combined action of the organic plasma and the inorganic mineral substance, in particular calcium; in the invertebrates (corals, molluscs, echinoderms) carbonates predominate and, in the vertebrates, calcium phosphates. The histological construction and the fine structures of this calcium skeleton, even in the single family of Metazoa, show characteristic differences. Sponges stand at the deepest level and use both chalk and silica. The biocrystals of sponges, both the chalk spicules of the calci-sponges, and the silica spicules of the silica sponges, show usually marked geometrical symmetry. Their regular forms belong to the definite symmetry classes of the *sterro-crystals*. They incorporate, however, an axial thread of plasma along their axes, around which the dissolved mineral substance is emplaced in layers. The solid, geometrically determined silica skeleton of many silica sponges, especially of the six-rayed (Hexactinellae), show this tendency to biocrystallisation, not only in the regular crystal forms of the individual pieces of their skeletons (spicules), but also in the regular lattice structure of their organs, in the arrangement of their flagellar chambers and in the construction of their walls. For their special psychomatic significance see Chapter 4 (Figs. 57–61).

Rheo-crystals (liquid or labile crystals)

The discovery of these most remarkable bodies, which lift the last screen between lifeless (inorganic) and living (organic) nature, is the fruit of thirty years persistent work by Otto Lehmann in Karlsruhe. Proof of their existence was achieved through extensive meaningful research which was carried out using a microscope with a heating stage (a “crystallisation microscope”) with polarising attachments[17].

The history of his epoch-making discovery, recounted by Otto Lehmann himself in the book (1911) mentioned below, is very instructive for judging the hindrances, which were laid in the way of the recognition and dissemination of fundamental novelties, by dogmatic tradition. The "liquid, apparently living crystals" required fully thirty years before they could capture the general and due recognition of the immediately interested "professionals" among the physicists, chemists and mineralogists and appear in the textbooks; and even today they are ignored by certain prominent physicists. The power of conservative tradition, which stands against every illuminating step forwards, is not less in science than it is in the practical areas of ethics, politics, religion, etc. The fundamental ideas of the Theory of Inheritance (of acquired characteristics) of Lamarck (1809) needed fully fifty years before it finally received deserved recognition through Darwin (1859). My basic biogenetic law ("ontogeny recapitulates phylogeny") which stands on this theory of inheritance, just as the theses of my "General Morphology" (1866) connected with it, and still more my "Monism" (1892) must now withstand a severe "struggle for existence". The wish, to bring a new force to rescue these ideas, through *rheo-crystals* and their connections with the probionts, is for me a major motive for the publication of these "fragments".

The substance of *rheo-crystals*

The chemical composition of those substances which take on the "liquid crystal" form has recently been carefully investigated by Lehmann, Reinitzer, Vorländer, Schenek and other chemists. The great majority of these substances (of which already above a hundred different modifications are known) consist of organic carbon compounds, sometimes with and sometimes without, nitrogen. Also still more inorganic compounds form "glutinous liquid crystals", among them ammonium nitrate and silver iodide. Corresponding to their various consistencies one can, following Lehmann, distinguish organic *rheo-crystals* as mucous-liquid- and "runny[18]" liquid- crystals. Among the mucous-liquid the fatty acid compounds (oleates of alkalis and ammonia), the cholesterol compounds (cholesteryl benzoate, caprate, glycerate, and others) and lecithin bodies (choline, choline oleate and others) are especially important; but also phosphatides and galactoids (phrenosine, kerasine, protagon) and such like substances present in the protoplasm, build "living crystals", and further, the sulpho-acids (compounded with bromine and chlorine) and the para-azoxy esters. To the class of "runny" liquid rheo-crystals belong hydrates of sulpho-salts, paranisole compounds and para-azoxy-phenol-ethers, etc. There are also many various compounds, among them very complex carbon compounds, which may appear in related forms as "liquid crystals".

State of aggregation

The most outstanding property of the rheo-crystals, which immediately distinguishes them from the solid *sterro-crystals*, is their softness or "liquid" constitution. These different packing densities, determined by the "inner friction" of the constituent molecules, show in the comparison of the various kinds, and in the individual development of one and the same kind, all degrees of order between the liquid and the solid states. On one hand the thin-liquid, (nematic) pourable state goes over through the easy-flowing into the glutinous or viscous, and on the other hand into the semi-rigid (smectic) and into the solid state. A sharp boundary between these different phases among the *rheo-crystals* is also only weakly evident in the cooled glue solutions or in the smectic plasma of organic cells. The differing levels of “fluidity” depend on the temperature, the pressure and other external conditions. That *rheo-crystals* are not amorphous, is indicated by their optical anisotropy and the inner molecular structure of their chemically homogeneous substance.

Molecular structure

Of decisive significance for the crystalline nature of the *rheo-crystals* is neither their state of aggregation nor their external form, but much more their inner molecular structure, the regular positioning of the invisible molecules out of which the homogeneous body is built up. This physical structure is anisotropic, as for *sterro-crystals* and *collo-crystals*: that is, the identical smallest particles are so ordered in determined directions, that the crystals show different physical properties in different directions in space. This anisotropy is most evident in the properties for polarised light. The double refraction then present will be clearly illustrated by the various colours and shapes which one and the same sphero-crystal may show on rotation of the plane of polarisation (see Title plate, Figs. 6–22). The crystal splits the incident light beam into two different rays, whose difference is determined by the different directions of the dielectric constants. In this way the “liquid crystallinity” of our *rheo-crystals* is sharply distinguished from the simple amorphous liquids like water, alcohol, oil, etc. These latter amorphous bodies (and also the solid bodies: resin, pitch, glass, etc.) are isotropic: they do not split up an incident light beam, because their molecules lie equivalently in all directions of space. In this there is also here—as everywhere in nature—no sharp boundary that can be drawn; there are always intermediates which occur between the extreme contraries. “Natura non facit saltus!”

The life phenomena of the *rheo-crystals*

In order to gain a correct understanding of the “living crystals”, it is important to compare them impartially and critically, on one hand with the solid mineral crystals, (*sterro-crystals*) and on the other hand with the simplest organisms living today (probionts, monera). Such an impartially critical comparison, (which on one hand many mineralogists and physicists and on the other hand many biologists and philosophers would find unthinkable), has been recently sought by Walter Hirt in his thoughtful sketches on “Life in the inorganic world” (München, 1914). This fills in and corrects the related trains of thought, which I had stimulated already in 1866 in my “General Morphology” and in 1904 in the “Wonders of Life”. Insofar as I relate myself to these introductory treatments and similarly to my “God-Nature” (1914), I limit myself here, to expounding, in the most concise form, those phenomena in the kingdom of the “apparently living crystals”, which may be compared directly with the vital functions of organisms. A closer and more demonstrative amplification of this physical “wonder of life”, especially the basic explanation in terms of molecular physics, is to be found in the published works of Otto Lehmann.

Growth (*Crescentia*)

The most important living activity of the *rheo-crystals*, one which sets them aside from all other crystals and puts them with the organisms, is their growth, that is, the facility of the individual to make itself bigger, during which it draws in particles similar to itself from the surrounding liquid. In this, the newly arriving molecules order themselves according to the same directional laws (*moletropism*), which already exists in the regular ordering of the ordering forces (*molethyn*) of the attracting individual. While now the *sterro-crystals* usually grow only by apposition, the organic cells grow through intussusception. Both processes can take place in *rheo-crystals*. As Lehmann found, more *rheo-crystals* grow “such that the new arriving molecules, as a consequence of the absorption forces, push themselves between the existing molecules and force them apart,” that is, through a kind of inner take-up, while a normal (*sterro-*) crystal grows by apposition, by the placing of new particles on the surface.

Nourishment

In order to grow, liquid nutritional material must be brought to the rheo-crystal. It can, however, “eat” directly. If two polymorphic modifications of one and the same *rheo-crystal* substance, one sparingly soluble and stable, and the other a more readily soluble and labile form, are mixed together in a liquid and crystallised out together, then the first gradually feeds on the second; the stronger form “gobbles up” the labile form and grows at its expense. Also when two rheo-crystals of the same molecular structure, but of different sizes, come in contact by chance, the larger can then “eat up” the smaller and weaker and ingest it.

Copulation

In many *rheo-crystals* two individuals may flow together as soon as they come in contact with each other; the doubled individual takes on the form of the twin (gamete). This is so for solid, uniaxial, spindle-shaped crystals, as for soft crystals, which as a consequence of stronger surface tension take on the form of spheres (see Fig. 6 and Title plate, Figs. 1, 7, 23 and 24).

Hybridisation

Rheo-crystals which are composed of different substances, but which belong to the same crystal system, can join with each other. They form mixed crystals, which can be treated exactly as inorganic bastards. If the two components are of different colour and the layers alternate in a determined sequence, one can often clearly see the contribution of each parent, and from time to time also in the form.

Fig. 6. Uniaxial spindle crystals of ammonium oleate (a kind of soft-soap) accidentally touching (a) growing together (b) and (d) and finally forming a single spindle.

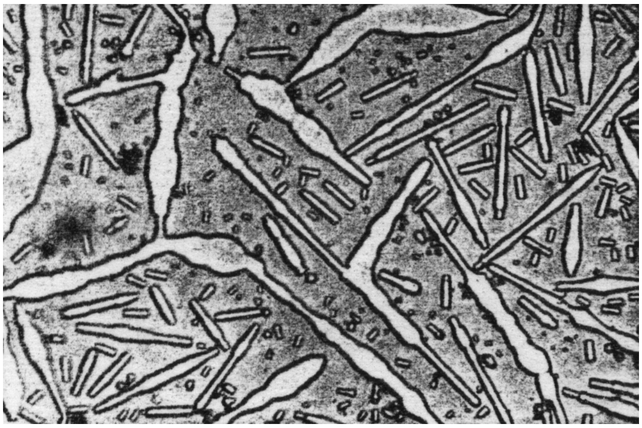


Fig. 7. Uniaxial cylinder crystals of myelin form (“Liquid crystals with sharp-edged planar end faces”, of the ethyl ester of para-azoxybromo cinnamic acid flowing together!) (Photograph by Vorländer).

Differentiation

The inner structural changes, which occur in many *rheo-crystals*, especially in the hybrid mixed crystals, taking place in the originally homogeneous substance and which can be compared directly with the plasma differentiation in true organic cells, are most interesting. On the surfaces they lead to the formation of a membrane and in the centre to the production of a nucleus-like structure.

Membranation

In many *rheo-crystals* the surface seems to be covered over by a thin membrane which is significantly more solid than the inner liquid mass. This skin formation is the consequence of the general surface tension, which enters into the boundary between two materials which meet but do not mix. The raindrops in the air, the oil droplets in diluted alcohol of the same specific gravity etc. owe their sphericity to this surface tension. The first formation of membranes is to be traced back to this purely physical phenomenon; later it becomes, through many kinds of differentiation, a valuable physiological organelle. Walter Hirt, in the second chapter of his “The life of the inorganic world” (1914) has dealt in detail with the general “skin formation in the inorganic world”.

Metabolism

The liquid-crystal state of aggregation of *rheo-crystals* facilitates itself through an exchange of matter (assimilation and dissimilation), just as does the living plasma of organisms. Walter Hirt has laid out in his “Life of the inorganic world” how the phenomenon of breathing—the intake and output of gaseous material—has spread widely in the inorganic world and how it is dependent on temperature. But the intake and output of fluid substances also takes place in the soft and imbibing bodies of the *rheo-crystals* in a way like that in the simplest organisms. This is very clearly shown by colouring them with different dissolved dyes (just as in the staining of real cells).

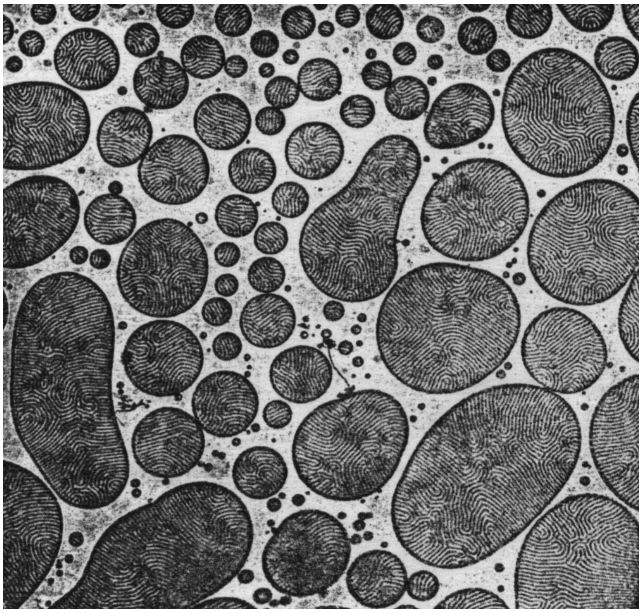


Fig. 8. Liquid mixed-crystals, resulting from the mechanical mixing of two different myelinic substances: Crossing or “bastardisation” of rheo-crystals. Molecular structure strongly laminated.

Poisoning

Very important and evidential (both of their “will” and for their “feeling”) for the “life” of crystals, is the fact that their development is altered by the operation of foreign chemical substances. If ammonium chloride is crystallised out by evaporation from a drop of aqueous solution, characteristic (dendritic) *sterro-crystals* result, which might be compared to fir-trees or to a street of poplars (Fig. 9). If one adds iron chloride to the preparation under the microscope at one side, the ammonium chloride crystals become coloured red-yellow; and their growth is so disturbed that they take up abnormal cross-shapes of four-leafed flowers (Fig. 10). Still more conspicuous is this poisoning in crystals of meconic acid[19], when it is dyed with aniline violet; the more dye is taken up the more the original crystal form is disturbed; there result irregular radial and eventually formless gnarled shapes (Fig. 11).

Nucleation (nucleus formation)

At the centres of many spherical rheo-crystals darker nuclei can be distinguished which are like the homogeneous cell nuclei contained in many of the lower protists. This homogeneous crystal nucleus results from the central densification, through the stronger cohesion of the central molecules. When two such spherical crystal droplets touch and as two water drops or oil drops flow together, the copulated sphere for some time shows two nuclei, and between the two a third dark point of different form. First gradually the round double crystal takes a unitary form and exhibits only one nucleus in the centre. There takes

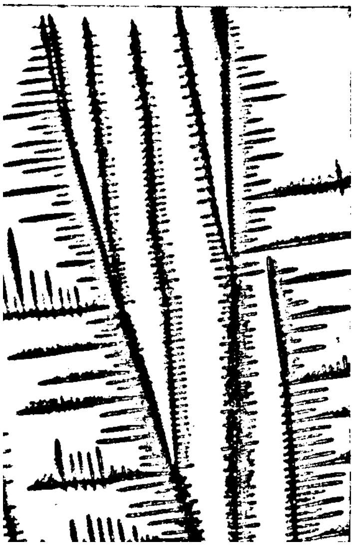


Fig. 9.

Fig. 10.

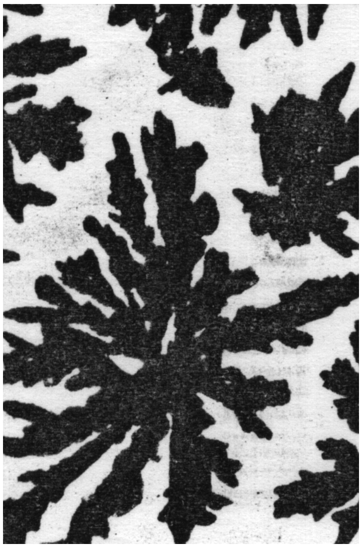


Fig. 11.

Fig. 9. Crystal skeleton of ammonium chloride. Like a row of poplars (“Fir-tree figures”).

Fig. 10. Crystal of ammonium chloride, poisoned by ferric chloride, coloured red-gold, squarish, like a four-leaved flower.

Fig. 11. Poisoned crystal of meconic acid, (from opium) coloured dark violet with aniline, which has grown in knobbly rays.

place here a related direct nuclear formation (without chromosomes) just as in many similarly copulating lower protists (see Figs. 12 and 13 and Title plate, Figs. 7 and 20–24).

Polymorphism

The changes of form of *rheo-crystals* under the influence of different conditions of life—especially of changing temperature and chemical action—are also of great interest and to be compared with the changes of form of many protists. For ammonium oleate, lecithin and related lipids (which also play a substantial role in the plasma of many cells) Lehmann has definitely found out that the liquid crystals are polyhedral, belong to the tetragonal system, and behave in polarised light just as true solid crystals of this system. On the other hand less viscous liquid crystals take up a spherical form and appear isotropic (see the spherical drops of para-azoxy-anisole; Title plate, Figs. 6–28).

Excretion

When finely divided foreign bodies, for example minute Indian ink particles, are present during the crystallisation in the liquid state, they are pushed aside by the molecules of the alkali salts of the fatty acids as they order themselves and carried outwards, so that there results a clear homogeneous *rheo-crystal*. We can compare this phenomenon only with the feeling of the molecules to get themselves clear, and has been called "self-cleaning" by Lehmann, just like the shedding or excretion of organic cells. If an air bubble accidentally finds itself in the mother liquor, the rheo-crystal broadens itself at the surface in the form of sphere-shaped pseudo-isotropic sheet and so forms a bubble-shaped hollow sphero-crystal.

Regeneration

Many crystals, both solid and liquid, possess the faculty of healing damage and of replacing missing parts. This regeneration, which has been long known, signifies an inner correlation of the parts during the "life of the crystal" and delivers a further argument for our *psychomatics*. We must conclude from this that a delicate state of sensitivity of a "feeling for symmetry" animates the molecules and drives them to take up determinate positions and directions in space. The laws of this regeneration are substantially the same in inorganic materials and in organisms and rest on the same principles.

Motion

Among the most conspicuous phenomena of life for the *rheo-crystals* are the lively movements which take place at definite temperatures in the mother liquor. They are connected with significant changes of form and with copulation phenomena. With these social aggregates—coenobia of the simplest kind—the *psychomatic* processes—feeling, excitability, will—are very clearly recognisable and in the *leptonic* laws of their molecular motion are clearly consequential (Figs. 15–22). The double droplets which have coalesced can form rodlets like Bacteria and become extended to long "snake-like bodies". "Just like Bacteria, the rodlets or snakes can creep forwards and backwards, wriggle to and fro and rotate about their axes". The life-like swarm of these nematode-like *rheo-crystals* is like that of infusoria, which throng massively in a water-drop. Their growth follows clearly through intussusception. For many substances, for example, cholesteryl caprinate, vermi-

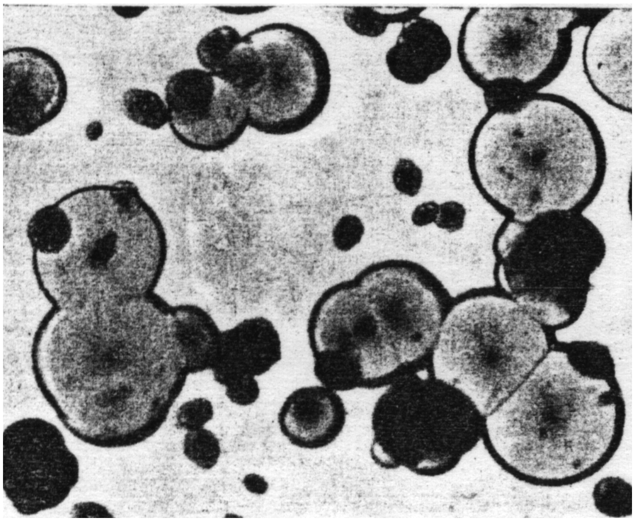


Fig. 12. Spherical crystals of cholesteryl benzoate, sometimes flowing together, of radial feathery construction (like starch grains).

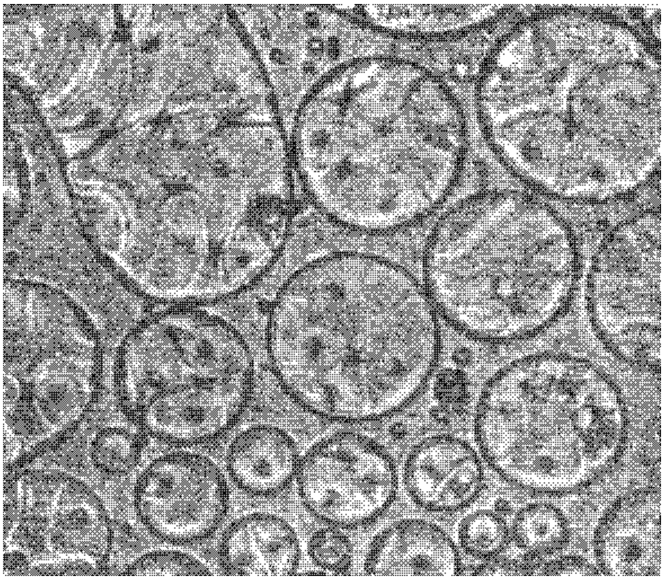


Fig. 13. Copulation of spherulitic crystals containing nuclei. Spherulitic crystals of para-azoxy-phenatol melted in a tube, are as labile as water, enclosing a central nucleus and behave on flowing together like copulating cells.

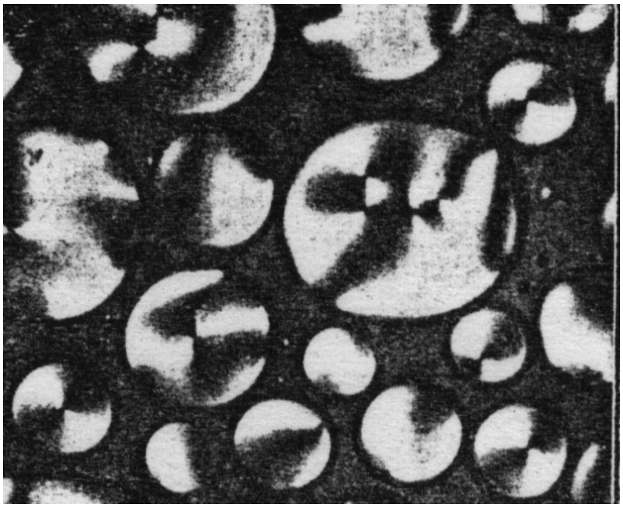


Fig. 14. Dichroism of liquid crystals (of Fig. 13) in polarised light. Inner structure. (See Title plate and explanation. Figs. 9–24 and especially Figs. 10–18 of that plate.)

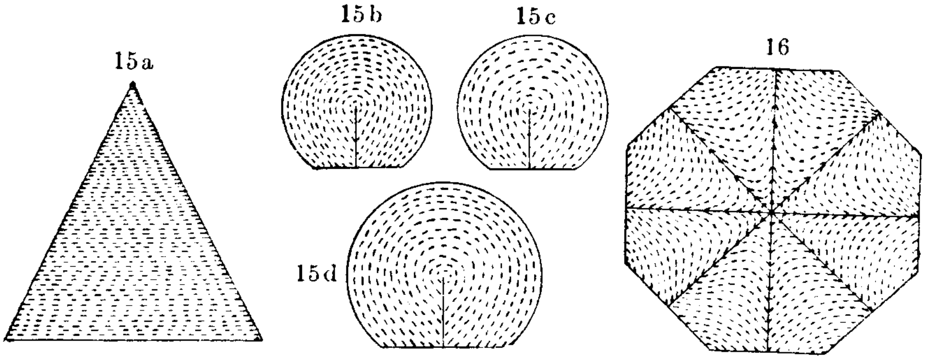
form rheo-crystals in two differing modifications occur, which can transform themselves one into another (Fig. 17).

Feeling (aesthesis)

The unbiassed comparison of the different states of the *rheo-crystals* and of the changes which they undergo in their life activities, especially their critical comparison with the corresponding expressions of life in the lowest organisms (probionts and protists), leads us to the conviction, that the "living substance" of the former is just as endowed with unconscious sensitivity, as is the plasma of the latter. Especially distinctive here is the correspondence with the Radiolaria, the psyche of which we will subsequently look at more closely.

Myelin forms

The most outstanding "phenomena of life" of the *rheo-crystals* are the spontaneous movements which can be observed in the so-called myelin forms. The notable "myelin" was discovered in 1854 by Virchow in the nerve cores of human beings; later it emerged that various carbon compounds with related physical and crystalline properties are widely present in plasma and perhaps play a big role in the organic processes of life. These are in some cases without oxygen (fatty acids and cholesterins) sometimes containing oxygen (lecithin and protagon). The lively moving myelin forms were observed by Lehmann in ammonium oleate fully thirty years ago (Figs. 18–22). These "living" crystals can be obtained artificially very simply if one puts a drop of commercial oleic acid into aqueous ammonia. But compounds of alkalis with fatty acids, as well as various soaps (which have



Figs. 15 and 16. Metamorphosis of liquid crystals at various temperatures (from Vorländers "ethyl ester of para-azoxy-cinnamic acid). The normal form of the "hemimorphic pyramid", (Fig. 15a) loses its points and approaches sphericity. However, a flattening remains at the base from which a streak stretches out towards the centre. (Fig. 15b). Two such spheres, joined in the same orientation flow together to give a single droplet (Fig. 15d). If eight such drops are united an eight-rayed rheocrystal results (Fig. 16). If, however, two components stick together by their bases, they form a twinned or double droplet, without flowing together. The action of the sensitive molecules is expressed very clearly in the properties of their *molythyn.*

Fig. 17. The *molythn* of cholesteryl caprinate. "Worm-like" rheo-crystals in two modifications.

been studied by Otto Bütschli and Georg Quincke in Heidelberg), also show the same properties. They were sometimes interpreted more as purely physical and chemical, than as really physiological or dependent on those "life forces" which, according to our present monistic understanding, as the same in principle. Ambronn[20] describes the myelin movements in the following way: "One spreads some lecithin out on the specimen slide and adds water, and after a short time forms develop which very soon show a clearly doubled contour and develop themselves into the many-formed figures. The points of the outgrowing tubes perform in this an almost continuous rotating motion. Under the microscope one can follow the growth and the structure of these tubes, spheres, etc. for the whole day. If one adds diluted glycerine instead of water, then the growth occurs significantly more slowly." The physical explanation of this lies partly in the conflict between the (external) surface tension and the (internal) self-organising forces of the molecules, the *molethyn.*

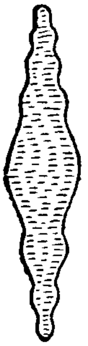


Fig. 22

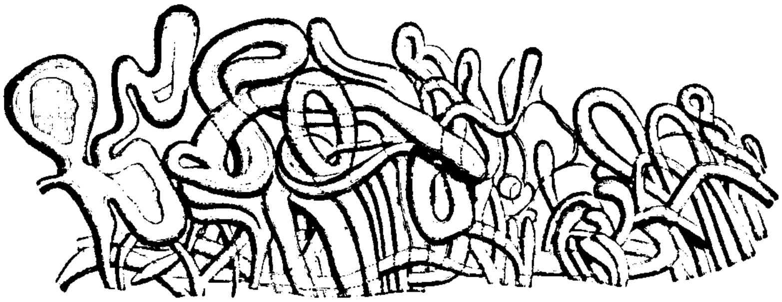


Fig. 18

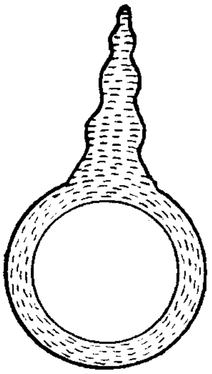


Fig. 20

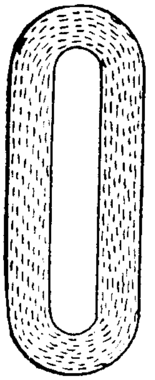


Fig. 21

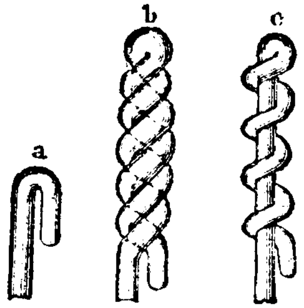


Fig. 19

Figs. 18–22. Myelin forms of ammonium oleate, according to the observations of Otto Lehmann, 1887.

Fig. 18. A group of “living” rheo-crystals, which are continually mobile and continuously alter their shapes.

Fig. 19. A cylindrical rheo-crystal of cylindrical form, in three different states of motion; it bends itself (a) and twists itself spirally about its own axis (b, c).

Fig. 20. A hollow sphaero-crystal which has become rounded.

Fig. 21. This changes itself into a hollow cylinder. Later this goes over to become a uniaxial spindle crystal (Fig. 22). The direction of the molecules is clear from the small streaks in the liquid crystalline skin of the hollow crystal; finally its optic axis is perpendicular to the surface of the fluid.

Hollow sphero-crystals

Among the many notable forms of metabolic myelin crystals which Lehmann observed, first in ammonium oleate and later when heating cholesterine with glycerine and with many other fatty acids of alkalis, special attention should be paid to the bubble formed or “hollow *sphero-crystals*” (see page 261, figures 159–177; compare also Title plate, Figs. 6–22). On cooling down the heated solution, supersaturated droplets form, near which or in which liquid crystals separate. When these round droplets come into contact with the surface and spread out in it, there results a liquid-crystalline coating of the same kind of molecular structure. Since the thickness of this anisotropic membrane and its properties change according to the isotropic liquid content, one observes, on progressive cooling of the solution under the polarising microscope, the remarkable transformations of the hollow sphere crystals and their molecular structure which are shown on our title plate in Figs. 6–24, which are from Lehmann. The similarity, which these “living” hollow balls show in their various stages of formation, to organic cells, is very conspicuous. Not only is the thickness of the outer “membrane” and its relationship to the liquid contents changeable in many ways, but so also is the building up of a thickened “nucleus” at the middle point of this sphere (Title plate, Figs. 6 and 22). If two hollow *sphero*-crystals flow together (as in the copulation of single-cell protists), their two nuclei fuse (Fig. 23). On further growth the stronger *molethyn* (crystalline force of self-organisation) wins in the “struggle for existence among the molecules”, being stronger than the weaker interfacial tension (surface tension). The hollow sphere (Fig. 20) changes itself into a hollow rod or cylinder (Fig. 21). If fresh nourishment is applied, the growing cylinder constricts itself in the middle and breaks by hemitomy into two equal halves. In this, the transformation of molecular structure teaches us that, as is shown diagrammatically in Figs. 8 and 13, we are dealing in reality not with an “artificial cell”, but with a spherical *rheo-crystal*. Nevertheless these physical “metamorphoses” of the “unorganised” rheo-*crystals* and their resemblance to the “organised” cells deserve special notice from the biologists and cytologists. The artificially produced myelin sphere is completely like the natural Chroococcus—*archigony* (the origination) of the probionts!

The life of crystals

If we put together the significant progress, which crystal science has made in the last twelve years, and when we connect this with the rich data of biology (since 1904) then we come to the following important findings:

I. All crystals, the solid crystals as well as the *rheo-crystals*, are living, so long as they grow and develop—so long as the latent forces of formation of their substance (the potential energy) is being converted into actual energy (or “living force”).

II. The molecular movements and the feelings of the crystal substance connected with it, are in principle not to be distinguished from the corresponding “phenomena of life” of the lowest organisms, to which earlier a teleological “life force” was ascribed.

III. All these “Actions of life” (in the widest sense), the inorganic as well as the organic, are to be traced back to the same elementary laws of physics and chemistry, and eventually to the monistic law of substance (Table 8 in the appendix).

IV. From the unbiassed critical comparison of the spherical *rheo-crystals* (myelin spheres) with the simplest probionts (Chroococcus) the traditional artificial wall[21] separating inorganic and organic nature is finally thrown down.

Notes

1. Haeckel's coinage. The usual word today is "crystallography" which covers almost everything concerning crystals.
2. *Haeckel's note*: Gottlob Linek, "Grundriss der Kristallographie für Studierende und zum Selbstunterricht". 3 Aufl., 1913, 274 Seiten.
3. As Haeckel was aware, in 1912 X-ray diffraction from crystals had begun to show the internal structure, but it took time to affect textbook presentations.
4. Haeckel has not properly understood the symmetry of the cubic system.
5. *Haeckel's note*: "Schichtkristalle". Otto Lehmann, 1911. "Die neue Welt der flüssigen Kristalle", S. 124; Schichtkristalle von Tonalaun und Chromalaun.
6. A modern description of this phenomenon can be found in H. Zocher and C. Török, "Crystals of higher order and their relation to other superphases", *Acta Cryst.*, **22,** 751–755 (1967).
7. "Molethyn" is a curious word introduced by Haeckel to denote something like chemical valency. It comes from the Greek "thyno" which means quick, and occurs in the word "tunny-fish" or "tuna".
8. This insight is perhaps realised in the modern discovery of quasi-crystals.
9. *Haeckel's note*: Introduction to C. G. Carus, "Urteile des Knochengerüstes usw.; mitgeteilt von Steiner im Band 114 von Kürschner's "Deutscher National-Literatur" (XI, S. 426).
10. "Elective affinities"—Goethe's favourite expression, used as a book title.
11. "Gestaltungskraft"—what Johannes Kepler designated as the "facultas formatrix".
12. *Haeckel's note*: Scheintod. Vgl. Max Verworn, "Allgemeine Physiologie", 6 Aufl., 1915, S.151. Lebendige und leblose Organismen.
13. A very important contribution of J. D. Bernal was to show that protein crystals in contact with their mother liquor, diffract X-rays and are properly crystalline while on drying, the ordered diffraction disappears.
14. "cytode" is a word of Haeckel's coining. It means (OED) "a non-nucleated, unicellular mass of protoplasm, the lowest form in which life is exhibited".
15. *Haeckel's note*: Stellate sphero-crystals of calcium carbonate, which were originally formed in the mantles of *Ascidia*, can accumulate massively after their deaths on the sea floor and from there pass into the bodies of sponges and other marine creatures. See my monograph on the chalk sponges, 1872, Vol. 1, p. 172.
16. Silica is always amorphous and calcium carbonates are always crystalline as they occur in biology.
17. *Haeckel's note*: An index of the numerous papers published by Otto Lehmann on this topic for the years 1885–1914, is to be found in Frick's "Physikalischer Technik", 7th. Ed., Vol. II, Sec. 2, pp. 2067–2072. His most explanatory exposition is entitled "Flüssige Kristalle sowie Plastizität von Kristallen in allgemeinen; Moleculare Umlagerungen und Aggregat-Zustands-Änderungen" Leipzig (1904). The best general review is given in the lecture, which Lehmann gave in 1906 at the 78 meeting of German scientists in Stuttgart: "Flüssige Kristalle und die Theorien des Lebens" (Leipzig 1906). He has collected in more detail the most significant results of his works in the book: "Die neue Welt der flüssigen Kristalle und deren Bedeutung für Physik, Chemie, Technik und Biologie" (with 246 illustrations) (Leipzig 1911).
18. "tropfbar"—capable of forming drops, presumably from a pipette = "runny" (ed.).
19. *Meconin* is associated with opium.
20. *Haeckel's note*: Ambronn, 1890, in the Berichten der K. S. Gesellschaft der Wissenschaften, Leipzig, S. 42, 425.
21. "Berlin wall?"