SCIENCE

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THE SO-CALLED "SAP" OF TREES AND ITS MOVEMENTS.[1]

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THE subject which I have chosen to present to you this evening is not chosen so much on account of the information which I am able to impart as for the purpose of correcting a great deal of misinformation which is widely prevalent. Many false ideas as to the nature and movements of what is popularly known as the sap of trees are extant, and in a large number of cases these ideas are founded upon mistaken notions of the physiology of plants. Our own knowledge about many of these matters is yet exceedingly imperfect, and it is for that reason that many of my statements will of necessity be negative. The subject also is one which must have considerable interest for those who are so intimately engaged in cultivating fruit and shade trees as are the members of this society; and I take it that no fact in regard to the life and mode of working of the plants with which we are so constantly dealing will be entirely without interest.

What is Meant by "Sap?"

It will be necessary for us at the outset to gain some accurate idea, if possible, of what is meant by the word "sap." If we think for a moment of its various uses, we shall see that it is a word which designates not a fluid of definite composition, but one under which is included a great variety of watery solutions. The sugar-maker begins even before the snows have left the ground to collect from wounds in the trunk of the maple-trees a sweetish liquid which he calls "sap." After a considerable time the proportion of sugar which this liquid contains diminishes very greatly, and he then abandons his work because, as he says, the "sap" has become too poor. The man who has postponed pruning his grape-vines or trees to too late in the season finds that from the cut surfaces a watery substance is trickling which he calls "sap." But the sugar-maker will be unable to obtain either sugar or syrup from this fluid, which is, however, called by the same name as that from which he manufactures his sweets. When a boy, who is making a whistle, hammers the bark of the twig in the spring, he finds it easy to separate the bark, because, as he says, the surface of the wood is then slippery with "sap." The sap of the boy is widely different from the sap of the pruner and the sap of the sugar-maker.

Again, what we do not call sap may furnish us with some illustrations of the diversity of meanings of this term. We do not ordinarily speak of the "sap" of the apple, or of the "sap" of the grape, or of the "sap" of the orange, but call the fluids which these fruits contain "juice." And yet they are not more different in their composition from those fluids which we do call sap, than the three examples already mentioned are different from each other. We might therefore, in all reason, apply this word sap to the juices of fruits.

We popularly distinguish the older hard internal wood of the tree under the name of "heart wood," from the younger, softer, and lighter-colored external wood, which we call the "sap wood." To the fluids which saturate the sap wood we are constantly in the habit of applying the word "sap," but I have never heard it applied to the exactly similar fluids which saturate the heart wood. As far as the composition of these fluids is concerned, there is no reason why that in the heart wood should not equally well be designated as sap.

What then are we to understand by the word "sap?" Evidently not a substance of any definite composition; but the word signifies only in the most general way the various watery fluids which are found in the plant. There is no reason indeed why these solutions should not be called *water*, for in many cases they are almost as pure as the water which we drink. In the chemist's sense, the water which we draw from our wells is a watery solution of various substances, and yet we do not designate it commonly by any other term than simply "water." In a similar manner, it is quite proper for us, and perhaps it would conduce to clearness of ideas, to designate the watery solutions in plants simply by the term "water," understanding it in its popular and not in its strictly chemical sense.

Movements of Water in Trees.

Let us turn now to the consideration of the movements which the water in trees exhibits. I shall confine my remarks to trees simply for the reason that they present the greatest variety of water movement, and at the same time furnish the greatest difficulties in the explanation of these movements. If, therefore, we understand the movement of water in trees, we shall be able readily to transfer these ideas to the movement of water in the smaller plants, although the statements applicable to the trees are not always applicable to the smaller plants, because of their greater simplicity; however, the greater includes the less.

The Evaporation Stream.

In the first place, there is need of a very considerable amount of water to supply the constant evaporation which is going on from the leaves of trees. Immense areas of delicate tissue are exposed to the dry air, and oftentimes to the hot sun, in the form of foliage, and from this foliage there is going off at such times large quantities of water in the form of vapor. The water needed to supply this evaporation must come from the soil, because it is not possible for the leaves to take in any water, not even when they are wet by the rains or by the dews. The water enters, not at the base of the trunk where the large roots are found, but only at the extremities of the finest rootlets. At these points the rootlets are clothed with a "nap" or "pile" of fine hairs. These root-hairs must not be confounded with the fine branches of the root, for it is only the finest branches which are covered with the close-set hairs. Consequently, it is only the youngest and most delicate parts of the root which allow the entrance of the water. But the water escapes from the leaves, and from the point of entrance to the point of exit is a far cry for the coursing droplets. How does it pass through this long space?

It is just here that our knowledge is most defective. We know a number of things that are true in regard to it, and we know a number of things which are not true in regard to it.

We know that it moves in the sap wood of the tree, and neither in the bark or in the heart wood. Many of you must have made observations which are sufficient to establish this point. You have, for instance, observed that the bark of trees might be peeled off for a considerable distance, and that the leaves would still retain their green color and their freshness. In many cases, indeed, the mere removal of the bark from the tree is not sufficient to bring about its death until several months, and in some trees not until several years, after the injury. Death, however, is inevitable sooner or later; but the fact that the leaves remain fresh for so long a time is evidence that the supply of water is not interfered with. Death ensues from a totally different cause, namely, from the starvation of the roots in a way which will be explained later.

Again, you must have observed that it is quite possible to have the entire heart wood of the tree removed, as is often done by decay

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and yet to have the leaves remain fresh and green for an indefinite time. In fact, the rotting-out of the heart wood scarcely interferes with the vitality of the tree, except as it renders it mechanically weaker, and consequently more liable to be overthrown by storms. If any further proof were needed, it is perfectly possible to show experimentally that the sap wood alone is engaged in the transfer of the water required for evaporation by cutting into it. A saw-cut which passes through the sap wood, but leaves the heart wood intact, brings about within a very short time the withering of the leaves. In some trees, indeed, a cut which severs only the outer youngest layers of the sap wood will produce the same effect, since in such trees *only* the youngest layers of the wood carry the water. By experiments on twigs it can be demonstrated that withering will occur even if the bark is almost completely uninjured.

We know the water to supply evaporation moves chiefly in the cavities of the elements of the wood. The wood of the tree is composed of a large number of *fibres*, that is, elongated cells pointed at both ends, and of *ducts*, that is, tubes of great length formed by the breaking together of rows of cells placed end to end. You can get an idea of the manner in which these ducts are formed by imagining a series of round pasteboard boxes piled one on top of another, after which the top and bottom of each is removed, so that, instead of a series of separate chambers, we have now a long tube. The fibres may be likened to a series of lead pencils, sharpened at each end, and placed in contact with each other, the points of the lower ones overlapping the next ones above and fitting in between them. In my illustration the cavity of the fibre would be represented by the lead, and it would be more accurate if we could conceive of the cavity as not extending entirely through the pencil, but stopping short of the point. Minute pits extend from the cavity of one of these fibres to the other, and the walls also of the long ducts are also marked by larger thin spots. It is in the cavities of these ducts and fibres that the water chiefly travels.

We do not know what part is taken in this ascent of the water by those peculiar elements of the wood which you know by the name of silver grain or the pith rays. You will remember these as the shining plates of tissue which extend from the centre of the wood toward the circumference. They are particularly prominent in the oak and show most when it is split "with the grain." It is probable that these cells have a great deal to do with the movement of water, but their exact *rôle* is not fully agreed upon.

We are in almost total ignorance at the present time as to the force by which the water is elevated through so many feet. There are trees in the gullies of Victoria, Australia, whose height exceeds 470 feet, and we must invoke some force which is able to raise water from the level of the soil to the level of the highest leaf. A year ago we thought we had a hypothesis which would account for this movement, but later researches have brought to light some facts which are at present totally irreconcilable with what was a most charming, and, at that time, a most satisfactory explanation, and we shall be obliged to abandon it unless the wine of the new knowledge can be held by the old bottles of theory.

At the time when our knowledge of capillarity was greatly extended by the celebrated researches of Jamin, it was thought that we had knowledge of a force adequate to account for the raising of water to these great heights. The fibres and ducts which I have described to you seemed to answer very perfectly the requirements of capillary attraction, and it was thought that this force, by reason of which water rises through narrow spaces, was the one sought. But the rise of water in capillary spaces is proportioned to the size of the opening; the smaller the opening, the higher will it rise. With the decrease of the calibre of the tubes, however, the friction increases enormously, and only small quantities will be able to be moved on account of the diminished size of the tubes. It was quickly seen that, in order to account for a rise of even a hundred feet, the tubes of the wood must be vastly smaller than they really are.

When it was found that the air in a plant is under a less pressure than that outside the plant, it was thought that the force had been discovered, and that atmospheric pressure furnished the explanation. Negative pressure, however, on the interior never reaches zero, and consequently cannot account for a rise of more than 33 feet.

Again, what was called root-pressure was invoked to explain the phenomena. It is found that water is absorbed at certain times so rapidly by the roots that it exists in the plant under considerable pressure, and it has been claimed that root-pressure, combined with the other forces already known, was adequate to account for the rise of water. But this, too, has failed us.

It is perhaps the greatest weakness of the last theory (that of Godlewski), which we have just had to abandon temporarily at least, that it depended for its explanation upon the indefinite and illusive "vitality" of certain portions of the plant. Godlewski's brilliant hypothesis, which ascribes to the activity of the living cells of the medullary rays the function of receiving from lower levels the water and passing it on to higher tissues through rhythmic variations in their osmotic power, due possibly to respiratory changes, may yet hold the clue which we are seeking. But when Strasburger jacketed a young tree for a distance of 35 feet, and kept it surrounded by hot water until all of the living cells in the tree trunk were unquestionably killed, and when under these circumstances the water-supply to the leaves was not interfered with, so that they remained green and fresh, we were obliged to conclude that the lifting of the water is not dependent upon the life of the tissues directly, but that it is evidently carried on by a physical process yet to be explained.

Before passing from this topic of the movement of water which supplies evaporation, I must allude to a very common and widespread idea,—at least I judge it to be widespread, because it is so frequently propounded by my students,—that "the sap goes down in winter and up in the spring." Just where the sap is supposed to go in winter is not exactly clear; since, if the roots are absorbing water in the fall when the evaporation is diminished, they are likely to have quite as much water as they can hold already. The conception, apparently, is that all of the water lodged in the trunk and spreading branches goes downward into these roots. It needs, however, only the most casual examination of trees in winter to discover that at this time they are almost saturated with water. The twigs of the hickory tree, for example, will be frozen on a cold day in winter, so that they are as brittle almost as glass, and one can snap off a twig half an inch in diameter as though it were an icicle. The same twig, when not frozen, on a mild day will be so tough that there will be no possibility of breaking it.

Again, if one cuts off a branch from a tree in winter and brings it into a warm room, he will quickly discover that water is oozing from the cut end, showing that the twigs are almost saturated with it. As a matter of fact, the water in trees increases from mid-summer or early fall to the beginning of growth in early spring. There is thus no necessity for any "going up" of the sap in spring until the leaves are expanded and the water with which the tree is already saturated begins to be evaporated from the foliage.

Bleeding.

A second movement of water in trees is that which occurs in the so-called "bleeding." The bleeding of trees occurs at different times of the year, either before growth has begun at all, or just as it is beginning. In the two cases the cause is quite different. We find a good example of both sorts of bleeding in the gathering of the sap by the sugar-maker. This gathering begins at the time when the ground is still frozen and the roots are almost or quite unable to absorb any water, but at a time when the air is warmed through the middle of the day by the increased heat of the sun. At first the expulsion of water from wounds made in the trunk is due to the expansion by heat of the air inside the smaller branches and twigs of the tree. This sets up at once a pressure upon the water, and this pressure is transmitted to all parts of the tree. The water with which the tree is filled is thereby forced out as soon as an opening is made for its escape. Later in the season, however, the roots begin their work of absorption, and there is then set up the so-called *root-pressure*, by reason of which the water is forced out at the same openings.

The latter sort of bleeding is necessarily delayed until growth is about to begin, and is checked as soon as the foliage is sufficiently expanded to begin evaporation.

A bleeding similar to the last takes place at the hood-like tips of grass leaves, where the skin is nearly always ruptured. The little drops of water which accumulate here are commonly mistaken for dew, but are merely droplets exuded from the interior of the leaf, because the falling temperature of the air toward evening has diminished the evaporation from the leaves, while the roots in the warm soil are still absorbing water, and consequently producing an internal pressure. The movement of water in these cases of bleeding, it will be seen, is necessarily toward the point of exit, which may be above or below the point at which the pressure arises.

Secretion of Nectar.

A third sort of movement of water is that which takes place in the nectaries of flowers and leaves. The flowers of our common linden, for example, secrete a considerable quantity of sweet fluid, which is sometimes miscalled "honey," but is properly known as nectar. Honey, by the way, is nectar after it has been digested by the bees. At certain points in the flower there are groups of cells whose special business it is to withdraw water from the parts below, and filter it through their outer walls, after having added to it the materials which make it sweet. The movement of water in this case is extremely limited.

The Transfer of Food.

The last movement of water of which I shall speak is of those solutions which contain the food of the plant. These materials are not those absorbed from the soil, or gathered directly from the air, but they are the substances which have been manufactured by the leaves out of the materials obtained from the soil and from the air. Since these foods are put together in the leaves, necessarily the movement of water containing them in solution must be in a different direction from that which supplies the evaporation. The materials thus manufactured in the leaves must be carried either to those parts which are growing or to those places in which they are to be stored for future use. It is manifest at the first glance, therefore, that the direction of the movement must be in general *inwards* from the leaves, and, since the roots require for their nutrition a considerable amount of these substances, there must be a very decided *downward* movement to supply them.

Now it is plain that these solutions of food must keep out of the way of those portions of the water which are chiefly to supply the evaporation from the leaves. We have seen that the latter travel in the sap wood. The food currents, however, travel almost exclusively in the inner parts of the bark. You will therefore understand why stripping off the bark, or even cutting it, ensures the death of the tree eventually, even though the leaves remain long unwithered, since the roots depend upon the food formed by the leaves, they perish when severed from their base of supplies.

The movement of the evaporation stream is relatively rapid. The movement of this food current is relatively slow. We do know something of the mode of movement of these food currents. They are apparently brought about through the process known as diffusion, or osmosis, and are therefore necessarily slow. The cause of the movement is practically the same as that for the movement of oil in the lamp-wick, although it is by no means by the same method. The oil in the lamp-wick travels upward because at the top it is being destroyed *as oil* by reason of the heat of the flame. So the direction and existence of the current of water carrying food is because the various substances dissolved in the water are being altered at the place of growth or storage into new materials. The commonest of these food substances is sugar, and at the growing point of the stem, for example, the sugar is being constantly destroyed as sugar and is being converted into cellulose or protoplasm or some other material. So long as that alteration is going on, just so long will the sugar particles move toward that point.

But I must not impose further upon your patience. I have tried to sketch very briefly, and only in outline, the different movements which the water in the plant is undergoing. I have said nothing of the extreme variety of materials which may be found in this water in different plants, or even the variety found in the same plant at different times, but have endeavored merely to show you that there is going on constantly in the living tree a series of molecular and mass movements, of which too few people have any conception. To our imperfect knowledge let me hope that some of you may contribute facts which shall enable us some day to explain the many things which are now obscure.

NOTE ON THE SEA-URCHIN SKELETONS.

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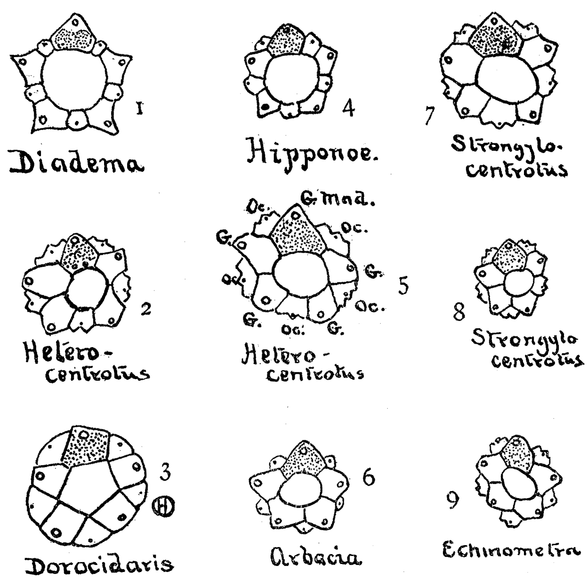
IN looking through the drawings of students in the freshman class of the aboral ring in *Strongylocentrotus droebachiensis* from Portland, Maine, I came upon one which I at first supposed to be erroneous, but which, on comparison with the specimen, proved the specimen to be exceptional. The usual arrangement of the genital and ocular plates in this species is shown in Fig. 7 of our cut. The five genital plates and two of the oculars border upon the anal ring, the three remaining oculars being shut out by



the contiguity of the enlarged genitals. The arrangement found by exception is figured at 8. It consists in the exclusion of four oculars from the aboral ring, so that only one gets a share in forming the border. I seized the occasion to look into the cases of about fifty specimens which happened to be on hand in the laboratory, and found that the case of Fig. 8 occurred twice in that series and that all others were like Fig. 7, which is normal, and which I have observed in many more than fifty different specimens at different times. It is interesting to note that in Fig. 122 of Agassiz's "Seaside Studies," page 103, a drawing of a specimen of this species is given, in which three ocular plates border the aboral ring, and in which the plates are thus quite symmetrical. This must be of very exceptional occurrence, for I have never met it in the many specimens I have seen. I should be very glad to know if it has been at all generally observed.

In connection with the case of Strongylocentrotus, it is interesting to examine the aboral ring of other regular echinoids. In *Diadema* (Fig. 1) the ring is perfectly regular, with five genitals and five oculars of equal size; in *Arbacia* (Fig. 6) it is equally regular, but with five large genitals, which form a ring about the aboral area, and exclude from it wholly the five small genitals. In *Dorocidaris* (Fig. 3) the ring is nearly regular, four oculars barely reaching the ring, the fifth being shut out. In *Hipponoe* (Fig. 4) the case is nearly as in *Diadema*, one ocular, however, not reaching the ring. In *Echinometra* (Fig. 9), a very elongate urchin, but not elongate in the plane of the madreporic plate, the five oculars do not any of them reach the ring and the