THE RESPIRATION OF AN INLAND LAKE

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An inland lake has often been compared to a living being, and this has always seemed to me one of the happiest of the attempts to find resemblances between animate and inanimate objects. Unlike many such comparisons, which turn on a single point of resemblance and whose fitness disappears as soon as the objects are viewed from a different position, the appropriateness of this increases rather than diminishes as our knowledge both of lakes and of living beings is enlarged.

The lake, like the organism, has its birth and its periods of growth, maturity, old age, and death; and this fact is an obvious one, for of all the larger features of the landscape, the lake is the youngest and the most temporary. Its birth lies in the recent past and in no very long space of time its existence must come to an end. In any lake district, lakes may be found in all stages of maturity and decay, and many dead lakes will be seen, —places where lakes once existed which are now extinct. Lakes show not only the cycle of individual existence, but also the rhythm of seasonal activity. The activity of the lake in summer, both physical and vital, contrasts sharply with its torpidity in winter. And the lake resembles the organism not only in its annual recurrence of activity. The comparison may be pushed further and extended to the minor fluctuations of the vigor of vital manifestations which characterize lake and organism alike.

In all these points, and in many others, the lake resembles a living being; but in no respect does it resemble an organism more closely than in the topic on which I am going to speak to you, namely, its respiration. In this comparison, the resemblance is rather in processes and operations than in form. The lake is morphologically a very simple creature, resembling rather a gigantic amoeba than a more highly organized being. Perhaps it would be better to compare the lake, for the purpose of this subject, not with the organism as a whole, but with the special respiratory substance of the animal—the blood.

Like the blood of the higher animals, the lake consists of

an unorganized fluid—the plasma of the blood and the water of the lake—and of numerous organized and actively living parts—cells in the case of blood, and the plants and animals in the lake. As is the case in the animal, the respiratory gases are absorbed and transmitted to the living structures by means of the unorganized fluid. It is my purpose to trace in outline the history of these processes and their result upon the activity of the lake.

The respiration of the lake, like that of the higher animal, may be divided into external and internal respiration. By the former we understand the absorption of certain gases from the air and the return of other gases to it, as well as the processes by which this exchange is effected. We include in it also the methods by which the gases are distributed in the lake and conveyed to and from the surface of the water, which takes them from the atmosphere and gives them back to it. By internal respiration we mean the gaseous exchanges which take place in the lake itself, between its various organisms and the water surrounding them. With these exchanges come the chemical processes by which the character of the gases is altered or new gases manufactured, in the course of the vital activities of the inhabitants of the lake.

The external respiration of the lake closely resembles that of the organism. The lake absorbs oxygen, carbon dioxide, and nitrogen from the atmosphere and returns to it nitrogen, carbon dioxide, and sometimes other gases. The nitrogen absorbed by the lake, like that taken in by an animal, has very little or nothing, to do with the vital processes. In autumn, as the lake cools, larger amounts of nitrogen are absorbed, according to the general law of absorption of gases. As the lake warms during the summer season, the capacity for holding gases in absorption becomes smaller and some of the nitrogen is lost. This process is a purely physical one and has apparently no influence on the life of any of the organisms whose home is in the water.

The relation of the oxygen to life is, however, far different, and the processes of external respiration are of prime importance to the living beings of the lake. Speaking roughly, and in terms of our comparison, we may say that an inland lake is an organism which takes one full inspiration in the fall, and another, less complete, in the early spring; that during the winter it

does not breathe at all and during the summer has only a very shallow and imperfect respiration. As the lake cools in the fall the temperature becomes uniform from top to bottom at a date which will vary from late September to late November or early December, according to the area and the depth of the lake and the consequent temperature of the bottom water, the volume of water to be cooled, and the vigor of the cooling processes. When the temperature has thus become uniform, the water of the lake is readily moved throughout its entire depth by the wind. It is turned over and all parts of it are brought into contact with the atmosphere. As a result, inland lakes, even those whose depth is two hundred feet or more, become almost, or quite, saturated with oxygen at a temperature but little above the freezing point. This quantity amounts to about 10 cc. per liter, or about 1 per cent by volume; nearly twice as much as the water will hold at the highest summer temperature. In this condition as regards oxygen the lake goes into winter quarters, becomes covered with a sheet of ice in our latitudes, and is, therefore, shut off until spring from all further direct connection with the atmosphere. During this period the stock of oxygen is used up to some extent, especially in the water adjacent to the bottom. But as the vital processes of both plants and animals, and also those connected with decay, go on slowly at the low temperature of the water in winter, the amount of oxygen thus consumed is comparatively small, and most lakes contain an abundance for all forms of life at all depths, except perhaps in the strata very close to the bottom. This statement, though generally true, will not hold universally: In some ponds which are shallow and contain a large amount both of living organisms and of decomposing matter, the oxygen beneath the ice may become wholly used up. We all know of lakes, which become so poor in oxygen that if a hole is cut through the ice in late winter, the fish will crowd to it for air so eagerly and in such numbers as to be forced out on the ice. There are on record cases where an unusual exhaustion of the oxygen below the ice of a lake has caused the death of most of the fish. Such cases, however, are not common, and in the great majority of lakes the consumption of oxygen in winter does not go far enough to affect unfavorably their living inhabitants.

Associated with this partial exhaustion of oxygen, there is an increase during winter of the amount of carbon dioxide—the main gaseous product of respiration. This is not present in any observable quantity in the lake at the time of freezing but it increases during the winter and the quantity at the bottom may become very considerable. The amount will be, in general, proportional to the amount of oxygen used up.

In the spring, when the ice has melted, the water of the lake is once more uniform in temperature. It is put into motion once more by the wind and all parts of the water are brought into contact with the air. The carbon dioxide, which has been accumulating during the winter, is discharged and the lake again becomes nearly saturated with oxygen. But, as the temperature in spring is higher than in the autumn, the amount of oxygen taken in is less; and since the temperature of the water continues to rise, the stock of oxygen is being diminished from this cause quite independently of any use made of the gas by the organisms of the lake.

The period of full oxygen saturation in the spring is a very brief one in our climate. The season advances rapidly and the surface water soon acquires a higher temperature than that at the bottom. This warmed water is, of course, lighter than the cooler water below and tends to float upon it. The difference in density thus caused makes it increasingly difficult for the wind to create and maintain a complete circulation of the water. For a time the action of the wind may continue to mix each successive stratum of water with that below it, the mixture extending to the bottom of the lake. But this action is a very different thing from the complete overturning of the water, and while it results in raising the temperature of the lower water, it does not carry freely oxygen to the bottom. Thus, when the surface becomes decidedly warmer than the water below it, the bottom water, though it continues to warm, is withdrawn from direct contact with the air and is therefore at a disadvantage in the matter of gaining a new supply of oxygen.

As the season advances this stratification of water dependent on temperature becomes accentuated, and, in the way of which I spoke last year and need not now repeat, the lake becomes separated into two parts: an upper warm stratum of nearly uniform

temperature, beneath which lies the cold water, consisting of a transition layer—the thermocline—in which the temperature is rapidly falling, and below this the mass of the cold water, whose temperature ordinarily falls rather slowly with the depth until the bottom of the lake is reached. The thickness of the upper layer varies with the size of the lake, from ten or twelve feet to thirty or forty feet. It is present as a definite and permanent layer at a date varying with the area of the lake from late April to the middle of July. It increases in thickness after the cooling of the lake begins but does not change much before that process commences.

This upper layer is subject to the direct action of the wind; is kept in circulation, and may be saturated with oxygen, or nearly so; but the only new supply of oxygen which the lower water can gain must come to it indirectly from the upper stratum. This condition of permanent stratification of the water comes on at the time when the life of the lake and its consequent need for oxygen are rising to the maximum, with the increasing warmth of summer and the development of life. The consumption of oxygen for the purposes of decomposition is also at a maximum. The separation of the lower water from the atmosphere in summer by a thick layer of warm water is therefore a much more serious thing than the separation of the water from the air in winter by ice. In winter the demand for oxygen is at a minimum and the stock contained in the water is at a maximum. In summer both of these conditions are exactly reversed. It is therefore necessary for us to inquire as to the means which the lake has for absorbing oxygen from the air and its means of transporting the gas from the surface to the place where it is to be used, and to note the efficiency of these processes as compared with the call for oxygen in the summer life of the lake.

The absorption and distribution of oxygen constitutes one of the fundamental problems of life for any large and active organism. The difficulty of solving the problem is increased by the fact that no large reserve stock of oxygen can be maintained. In the case of a human being there may be a food supply in the tissues sufficient to sustain life for weeks, even though no new supply is taken in. There is water enough in the body to main-

tain life for days; but if the supply of oxygen is shut off, life can be continued only for a very few minutes on the stock of oxygen contained in the body. So narrow is the space between abundance of oxygen and death from oxygen starvation. In a cold-blooded animal—with which the lake ought to be compared—processes of respiration are slower but the relative situation is not materially different. The result of these conditions is that in any large animal enormous surfaces must be provided for the absorption of oxygen and there must be a perfect mechanism for its distribution. Such respiratory systems exist in a great variety of forms, many of which are extremely complex and efficient. In the case of man the absorbing surface of the lungs is said to amount to about two thousand square feet—an area as great as the combined surface of floor, walls, and ceiling of a room 20 feet square and 15 feet high. The necessity for arrangements for a large absorbing surface increases with the size of the animal, since in a large organism the area of the general surface is far smaller in proportion to its mass than in a small organism of the same shape. In a lake, whose size is enormous as compared with that of any living being, the absorbing surface is very small as compared with its mass; being only the upper surface of the water. The lake is, therefore, at a great disadvantage in the matter of absorbing oxygen as compared with the animal. Still further, all higher animals, both cold-blooded and warm-blooded, contain in their blood some chemical substance which has a special affinity for oxygen and which can rapidly pick up large quantities of it. Such a substance is wholly lacking in the water of the lake, whose respiratory power is correspondingly smaller, both as regards the rapidity with which oxygen can be taken up and the amount which can be absorbed. It is indeed true that water will absorb, according to the general laws of the absorption of gases, about twice as much oxygen as nitrogen under similar conditions. This fact allows the lake to take in a larger stock of oxygen than would otherwise be possible, and that part of the atmosphere which is dissolved in the lake contains about one-third oxygen instead of one-fifth, as is the case outside. But even this amount is very little in comparison to the enormous volumes which a substance like haemoglobin can take up. It is also true that the mass of the water of the lake, in

comparison to the mass of the organisms which draw their oxygen from it, is relatively far greater than the mass of the blood with reference to that of the cells which take their oxygen from it. Yet is it none the less true that the supply of oxygen in most lakes is very small as compared with that of an animal, and the mechanism for renewing it is always very inefficient as compared with the demand for the gas.

The disadvantage of the lake in the matter of respiration appears still more clearly when we consider the means of transporting the oxygen from the region where it is absorbed—the surface—to the deeper parts of the lake, where much of it is to be used. The animal shows a complex and very efficient mechanism for the circulation of the blood; an apparatus whose complexity and efficiency are in large measure determined by the necessity for a rapid distribution of the oxygen and a rapid disposal of the gaseous wastes of the body. In the lake the means of transport are three: diffusion, by which the gas is slowly passed from point to point in the water independently of the currents; currents produced by the wind; and convection currents, produced by the cooling of the surface water to a temperature below that of the water beneath.

Diffusion is a process which operates rapidly when the distances are minute, but whose efficiency decreases greatly as the distances increase. In our lungs, or the gills of a fish, for instance, where the distance between blood and air is measured in thousandths of an inch the process of diffusion goes on with great rapidity. But where, as in the lake, the distances are measured by inches or by feet, or even by scores of feet, the process is practically worthless for the processes of distribution. By diffusion alone oxygen would penetrate the lake only to the depth of a very few feet in a whole season. While diffusion, therefore, plays an active and important part in the exchange of gases between the individual plant and animal and the water immediately surrounding it, it has little or nothing to do with the general circulation of gases within the lake.

During the fall, when the lake is cooling, convection currents aid materially in carrying oxygen down to considerable depths. The surface water, saturated with oxygen, cools, becomes heavier, and sinks, carrying the gas with it. The same

process takes place at night in summer, but ordinarily to very small depths. In general, we may say that during early and midsummer, before the period of general cooling begins, these processes do not extend to greater depths than ten or fifteen feet. At the season, therefore, when vital processes are most active and the need for oxygen is greatest, convection currents afford a minimum of assistance in distributing it. The main reliance, therefore, for the distribution of oxygen is in the third factor, the wind. This, as already said, is very efficient when the lake is uniform in temperature; but during the spring, as the lake warms, it becomes increasingly ineffective and during the summer its action is confined to the upper warmed layer of the lake, and the lower, cooler water is wholly shut off from the direct influence of the wind currents.

These facts show that an inland lake has an extremely inefficient apparatus for absorbing and distributing oxygen and the net result is that in many lakes the amount and character of the higher life which the lake will support are conditioned by the amount of oxygen which the lake contains rather than by the amount of food which it can produce. The oxygen in the lower and cooler water of the lakes cannot be renewed between spring and fall. This amount would be indeed ample to sustain a large amount of animal life in full activity. But its use cannot be confined to the necessities of ordinary life. The processes of decomposition draw upon it much more heavily than does the animal or the ordinary vegetable life. All the plants and animals of the upper water, which die and sink into the deeper strata, the leaves blown into the lake, and the material washed in from the shore, decompose in the cooler water and in the process of decomposition use up a great amount of oxygen. This depletion of the stock of oxygen goes on with a rapidity which varies with the amount of decomposing matter dropping into the lower water; with the temperature of the lower water, which to some extent regulates the rapidity of decomposition; and with the depth of the water, on which depends the quantity of oxygen contained in it. Each of these factors may and does differ in different lakes, but the result is that in a very large proportion of our inland lakes the bottom water loses its stock of oxygen comparatively early in the season and becomes un-

inhabitable for higher animals. This fact excludes from our lakes a good many kinds of animals which they might otherwise support, and very greatly limits the quantity of the higher life which the lake is able to maintain. A lake which loses its bottom oxygen, for example, cannot support a fish like the lake trout, which must retire to the deeper and cooler water during the summer. To such causes may probably be attributed a considerable number of our failures in the planting of fish in our inland lakes. From causes such as these, the whole of the lower water, containing half, or more, of the volume of the lake, may become uninhabitable during the season when life is most abundant; and the quantity of life which the lake supports may be correspondingly limited.

Still further, since the rapidity with which the oxygen is exhausted depends on the amount of material which is deposited in the lower water, those lakes whose upper water contains the greatest quantity of vegetable life, and which can therefore support the greatest amount of animal life, use up the oxygen of the lower water most rapidly. It looks, therefore, as if we were in a somewhat unfavorable situation as regards the possibilities of higher life in the lower water of inland lakes. Those lakes whose food supply is such that they are capable of supporting large quantities of animal life—I may say for our purposes, large numbers of fish—are likely from that very fact to exhaust the stock of oxygen in the lower water, which thus becomes uninhabitable; while those lakes whose lower water is fully habitable are likely to be so poor in organic life that they can support only a limited number of fish. It may be that further study will show that this relation is not so unfavorable as it now appears, but at present we must face the probability that it exists.

A noteworthy exception to this statement should be made in the case of very deep lakes—lakes two hundred or more feet in depth—in which the quantity of the lower water is so great and the consequent amount of dissolved oxygen is so considerable that no ordinary amount of decomposing material can exhaust it or materially reduce it. This is the case, for example, with Green Lake (237 feet in depth) in Wisconsin, and the same statement would doubtless hold for the deep lakes of New York

and similar bodies of water. Such lakes may support an abundant population of fish both in the warmer and the cooler water. If they do not do so, the fault does not lie with the oxygen supply.

Thus we see that if we desire to determine the capacity of a lake for the development of higher life, we must consider not only its capacity for food production but also its respiratory conditions. It may be that an imperfect respiratory mechanism renders a very large share of the bottom of the lake wholly uninhabitable for animal life; that while, for instance, mud-living insect larvae may be found in the mud around the lake to a depth of twenty or thirty feet, they are excluded by the absence of oxygen from the entire bottom of the lake beyond this depth, an area of perhaps many square miles. The supply of food which the lake offers to the higher animals may thus be greatly limited by the lack of oxygen. It may be true also that the greater part of the volume of the water of the lake is uninhabitable for similar reasons, and that a lake whose surface appearance would indicate that it is capable of supporting enormous quantities of fish life may be very considerably restricted in this respect by its respiratory capacity. Each lake should be studied both as to food and oxygen if an intelligent economic use is to be made of its waters; and when this is done, the possibilities of use will often be found to depend on the respiratory mechanism.

I have said nothing on another side of the methods of absorbing and transporting gases in a lake. The same processes which take oxygen from the surface bring waste gases to it and they are as efficient or as inefficient in the latter process as in the former. Processes of absorption and transportation have much to do with the story of the complex relations of carbon dioxide gas in the lake. These matters, however, can better be spoken of under internal respiration. I need only say here that the accumulation of waste gases in the lower water does not seem to affect life unfavorably if there is plenty of oxygen present also. Respiratory inefficiency limits life in a lake because of lack of oxygen rather than because it allows poisonous gases to collect in large quantities.

The subject of internal respiration deals with the changes

of gases within the lake itself and with the manufacture of gases by the organisms which inhabit it. No branch of physiology is more intricate and none less understood than is that of internal respiration. This is true also of the internal respiration of the lake. The gaseous exchanges and the manufacturing operations in the interior of a lake are far more complex than those of any animal. From the water living beings are drawing supplies of gas, each after its kind, and to the water each is contributing gases differing in amount and composition. Animals are withdrawing oxygen from the water and giving carbon dioxide to it. Algae are repeating this process by night and exactly reversing it by day. Fungi and bacteria are using oxygen in the course of their internal vital activities; they are employing far larger quantities in the fermentative processes which they maintain. The numberless chemical changes included under decomposition and fermentation, going on under all sorts of conditions, involving numerous kinds of materials, and operated by various organisms, are adding to the water gases of different kinds and in varying proportions. The upper water, the lower water, and the mud present very dissimilar fields of work to the organisms which inhabit them. It is, therefore, impossible even to attempt a picture of the internal respiration, with the innumerable operations, each adding to or subtracting from the sum of gases in the lake; in an intricate network of processes, consecutive, correlative, and antagonistic; connected by relations which cross and interlock at a thousand points. I shall speak of only a few detached topics.

I have said that the oxygen of the lake is absorbed from the air. This is true so far as the main stock of oxygen is concerned; but a lake has a second source of oxygen which is always considerable and which in certain places and relations may become important. The green plants which inhabit the lake are able to take up carbon dioxide from the water, and under the influence of light they can use it in the manufacture of starch, setting oxygen free in the process. In lakes which contain an abundance of algae, considerable quantities of oxygen may arise from this source and this manufactured oxygen may play an important part in the vital history of the lake.

Consider the effect of the addition of this power of the algae

to the numerous factors which are affecting the supply of oxygen in the upper water of the lake in summer. If the oxygen of this region is studied, it rarely happens that the quantity found is the amount which would be theoretically expected, according to the laws of the absorption of gases by water at different temperatures. It is sometimes largely in excess of the theoretical amount, and sometimes is considerably deficient. The fact is that the amount of oxygen in the upper water of the lake is the result of very numerous and variable forces. The lake may or may not be absorbing oxygen from the air. If saturated, it will give off oxygen to the air as the water warms, or will take it in as it cools. Both of these processes go on somewhat slowly, as the oxygen is not given off or absorbed as rapidly as the rate of cooling and warming varies. Into the water the green plants are discharging oxygen during the hours when the light is sufficiently strong; from the water both plants and animals are taking oxygen to assist their vital operations; and the process of decomposition is aiding to exhaust the stock of oxygen. Thus the amount present at any given moment will depend on the relative value of these forces; some of them positive; others negative; and all varying not only from day to day but from hour to hour. Nor do these factors exhaust the list. The wind has something to do here. During a calm period the oxygen content of the upper water may differ from that of a stormy period. The vital condition of the successive crops of algae, as they come and go, may determine for the time, the predominance of the manufacture of starch, with accompanying liberation of oxygen, or decomposition, with partial exhaustion of oxygen. Thus the ability of the green plant to set free oxygen into the upper water may be of great value in maintaining the supply of the lake.

This power may be far more important in the lower water. If the transparency of the water and the thickness of the warm layer are such that a good deal of light can penetrate to the colder water, algae will be able to manufacture starch in the upper part of this stratum. Thus in the region which is practically cut off from access to the atmosphere, large amounts of oxygen may be set free. There may be enough not only to serve the ordinary needs of the stratum, but the water may be satur-

ated or even over-saturated with the gas. I gave several instances of this process in my address last year and need not repeat them at this time. I repeat the diagram of Elkhart Lake

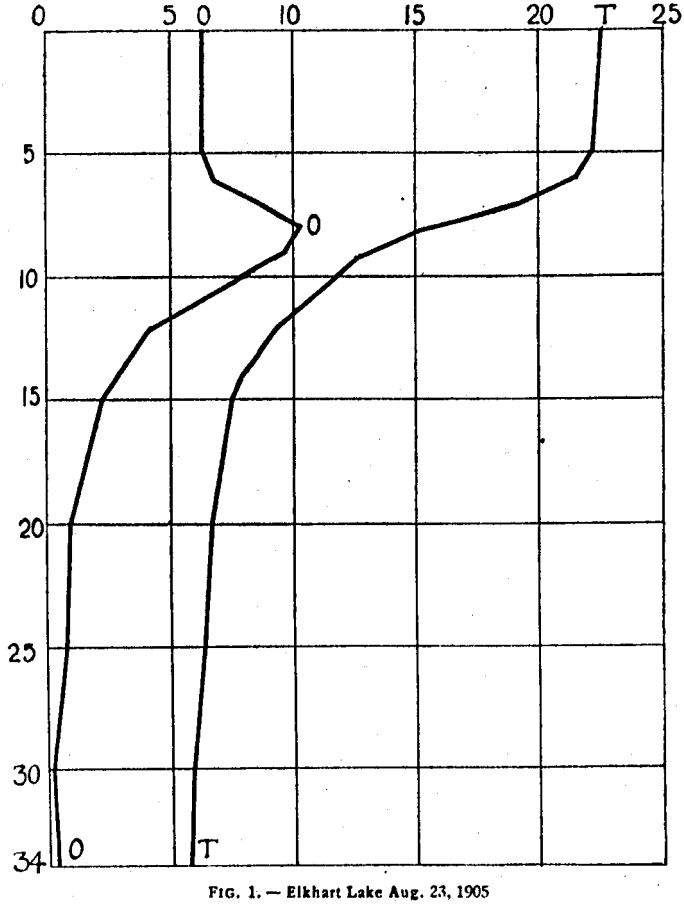

FIG. 1. — Elkhart Lake Aug. 23, 1905

This diagram represents the condition of Elkhart Lake with respect to temperature and oxygen. The vertical spaces represent meters of depth. The horizontal spaces represent two things: (1) degrees centigrade, as indicated by the temperature line (T—T); and (2) cubic centimeters of oxygen per liter, as represented by the oxygen line (O—O); or the oxygen is indicated as parts per thousand, by volume. It is easily seen that the temperature of the water begins to fall rapidly at about 6 m. and that the oxygen begins to rise rapidly at that depth, reaching a maximum of more than 10 cc. at 8 m., and decreasing from that depth. A very important addition is made to the oxygen stock of the lake by this manufactured gas.

from that paper, which shows clearly the position and amount of this manufactured oxygen, and the addition which it makes to the thickness of that part of the lake that has abundance of oxygen. Lakes whose habitable portion would otherwise be only twelve to twenty feet in thickness may have this depth doubled by the presence of the manufactured oxygen. The plants in this undisturbed cooler water find a peculiarly favorable situation for growth. They obtain for their food the products of decomposition, which is taking place rapidly in the lower water; and not infrequently a far larger amount of organic life may be found in these strata than in any other portion of the lake. This process is necessarily limited to lakes whose upper warm layer is thin, and is confined to the upper part of the cold water, since only there can the light have sufficient intensity to carry on the operation. But even as thus restricted, it is of great value to some lakes.

I have said little hitherto of the carbon dioxide—a gas whose importance is quite equal to that of oxygen—and now can only sketch a part of its complex story. This gas plays many roles in the respiration of the lake. It is at once the waste product of the tissue activity of plant and animal, the product or by-product of decomposition, and the indispensable food of green plants. The lake may obtain the gas from the air, and to some extent does so. Carbon dioxide exists in the atmosphere in very small amount—about four parts in 10,000. Minute as this quantity is, the land plants are able to secure from it ample supplies of carbon. The movement of the air is so free and such enormous quantities pass over the surface of the plants, that they readily pick up the gas in large amounts. But the situation of the algae and other plants of the lake is very different, as they must secure their carbon dioxide through the intermedium of the water. This readily absorbs large quantities of the gas. But the percentage existing in the air is so small, the absorbing surface of the lake is so restricted, and the means of transport are so poor that the lake is quite unable to take from the air enough carbon dioxide to maintain a vigorous growth of plants. The lake is forced to depend on its own resources to a large degree for this plant food. Fortunately, these resources are considerable. Great amounts of carbon dioxide are manu-

factured in the lake as the result of decomposition and these may be utilized as food by the green plants. Thus there is kept up in the lake a sort of internal circulation of carbon dioxide; the stock of the circulating medium being increased and replenished by additions from the outside. The activities of animals and the processes of decomposition liberate the gas, which is taken up and manufactured by the plants into organic substances; and these in turn serve as food and as material for new decomposition; while from the air the water may be absorbing new supplies of carbon dioxide to make good the losses of this process. Thus under normal conditions, the lake would return little or no carbon dioxide to the atmosphere, but would utilize within itself all that it manufactured or absorbed, at least until the plant life became so abundant as to be limited by other causes than that of food supply.

If this were all, the story would be quite simple and quite to the advantage of the lake. But it is by no means all the story; on the other hand, so far from being forced to solve problems associated with an oversupply of carbon dioxide, the lake has to encounter many difficulties in securing an adequate supply of that gas, and is able to meet them only very partially and imperfectly. Since the plants are able to utilize carbon dioxide in the manufacture of starch only during the hours of sunlight, considerable quantities may escape into the atmosphere during the night. But this is not the only disadvantage as regards the supply of carbon dioxide, with which the plants of the upper water have to contend. By no means all, or even the greater part of the organic matter which they manufacture decomposes in the upper, warmer stratum of the lake. As the plants and animals die, they sink into the lower and cooler water before any great part of the decomposition has been completed. The carbon dioxide which is there produced is discharged into this bottom water. It cannot be used there by plants on account of lack of light; and the same imperfections of transportation which prevent the access of oxygen to the cooler water in summer make it impossible to transport the carbon dioxide produced there to the upper stratum, where it can be utilized. In certain lakes, indeed, a small portion of this gas may be used in the cooler water, as I indicated above, but, in general, the upper water, as a result of

this process, is growing poorer during the summer in the materials on which plants feed, both gaseous and other. These are for the time locked up in the lower water and so withdrawn from the circulation of life. In the autumn, as the lake cools and the thickness of the circulating stratum increases, these matters become available so far as they lie in the upper part of the cooler water, and when the lake has become uniform in temperature to the bottom, and the water is turned over by the wind, the whole of this accumulated stock is available for the purposes of plant growth. This may be one of the reasons for the abundant growth of algae, which takes place in the autumn. But while the non-gaseous products of decomposition may be wholly utilized in the lake, the carbon dioxide is hardly likely to find full use. When it once becomes distributed through the water and new portions of the water are being continually exposed to the air, considerable quantities must escape during the hours when plants are unable to avail themselves of it.

Thus the rudimentary character of the circulatory apparatus of the lake forms an insuperable obstacle to the best utilization of its food supply. It is therefore easy to see why life is relatively so abundant in large and shallow lakes, in which the circulating methods have a maximum efficiency. The fact that they are shallow permits a larger growth of life, since not only is the water available but plants in large quantities may grow from the bottom. But of even more importance than this relation is the fact that since the entire mass of water is kept in circulation by the wind, all of the products of decomposition are immediately available for use and the life cycles of the plants may go on as rapidly as their rhythm of growth will permit. The carbon dioxide and other products of decomposition, instead of being locked up in the deeper water and set free only during that season which is less favorable for growth, are utilized immediately and are employed over and over again through the warmer season as the cycles of life and death of the individual plants recur. It is plain that lakes whose margin is wide and shallow, though the middle may be deep, must stand next to the shallow lake in efficiency of means of transportation. Much growth takes place in shallow waters, much decomposition goes on there, and little of the organic matter sinks into the deep

water, to be withdrawn from circulation. Least favorably situated is the deep and steep-sided lake, whose cold depths are continually swallowing almost all of the products of the summer's growth, and give them back for use, only late in the autumn when the season for active life is passing away.

Some lakes may find aid from another source in the task of securing carbon dioxide. Most natural waters contain a certain amount of calcium and magnesium salts in solution, and, for the greater part, these exist in the form of bicarbonates. Lakes whose water is hard contain a considerable amount of these bicarbonates and soft-water lakes have little or none. In hard-water lakes it is found that during the growing season, when algae are active, the upper water contains no free carbon dioxide, but is, on the contrary, alkaline to indicators like phenolphthalein. This alkalinity comes from the fact that one molecule of carbon dioxide has been withdrawn from part of the bicarbonates converting them into carbonates. It appears that the algae are able to effect this reduction and that they can obtain their supply of carbon from the carbon dioxide of the bicarbonates dissolved in the water. This fact introduces a wholly new feature into the story of the food supply of the plants. It provides a chemical carrier for the carbon dioxide, which may carry this gas somewhat as the haemoglobin carries oxygen in the blood. All carbon dioxide set free in this alkaline water as the result of decomposition or other processes, will be taken up immediately by the carbonates. Thus if plants are not at hand to utilize the carbon dioxide at once, it is not lost but kept until it is needed. So in the night, the lake is able to retain all the carbon dioxide set free and which the plants do not use at that time.

Such alkaline water has also a great advantage in absorbing carbon dioxide from the air. It presents for absorption, not merely the relatively weak and slow powers of the water for dissolving the gas, but the eager and vigorous powers of chemical affinity. And until these alkaline carbonates are saturated, no free carbon dioxide will appear in the water to diminish the rapidity of absorption from the air. Thus hard-water lakes have an advantage over soft-water lakes in the matter of securing plant food, and in fact the population of soft-water lakes is smaller than that of lakes of the other type.

It is worth while to devote a few words to gaseous products of decomposition other than carbon dioxide. So long as the bottom water contains an abundance of oxygen no other gas than carbon dioxide is produced in appreciable quantities. But as the oxygen becomes greatly reduced or wholly disappears, decomposition continues in new forms, and under these conditions of anaerobic fermentation other gases may be developed in considerable amount. It is apparently true that carbon monoxide may be present in the lower water of lakes in appreciable quantities, and it is certain that marsh gas is developed in large volumes in lakes where the amount of fermentable material is great and where the oxygen disappears from the lower water early in the season. These gases first appear near the bottom, where decomposition is going on most actively and where oxygen first disappears. In many lakes they are found only in small quantities and close to the bottom, but in proportion as the amount of decomposable matter increases, they are found at considerable distances from the bottom, and in certain lakes all of the water below the thermocline may contain marsh gas in appreciable quantities, often becoming very great as the bottom is approached. These gases do not seem to have any very definite unfavorable effect on the life of the lake. Diffusion is so slow that they do not reach the upper water and experiments indicate that their presence in the lower water adds little, or nothing, to the unfavorable conditions brought about by the absence of oxygen.

It should be noted that these processes involve a loss of meterial for plant food. Carbon dioxide, produced by aerobic decomposition, is available for plant food in the lake, or, if not there, then elsewhere as part of the general stock of that gas in the atmosphere. But marsh gas has no such relation to plants and all substances converted into it are lost to the cycle of life. Its production means just so much reduction of the food supply of the lake. The same may be said of the carbonized, peat-like substances produced from the partial decomposition of plants under water. So long as these remain under water, they are practically withdrawn from the food supply. Against all these influences which tend to diminish the stock of food for its inhabitants, the lake is contending, but with imperfect means and only partial success.

I have thus hastily and imperfectly sketched the respiration of an inland lake, not because the story is known with any fullness or completeness, but partly because our present knowledge, imperfect though it is, shows that the subject is one of great scientific interest; partly also because many practical hints regarding the utilization of lakes in fish culture can come from our knowledge of respiratory conditions. We are accustomed to think of the food producing capacity of the lake as the factor which determines the kind and amount of the crop of fish which it can produce. It is a somewhat new thought to me, and I have no doubt that it is equally new to many of you that the respiratory capacity of the lake may have even greater influence in this matter than has the capacity for the production of food. Yet it is plain that such is the case and that a knowledge of the respiratory conditions of the lakes in which our fish are to be planted is necessary if the best results are to be reached.