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Title: Liquid Drops and Globules, Their Formation and Movements

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Release date: November 5, 2011 [EBook #37939]

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LIQUID DROPS AND GLOBULES

Their Formation and Movements

THREE LECTURES DELIVERED
TO POPULAR AUDIENCES

BY

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ASSOCIATE OF THE ROYAL COLLEGE OF SCIENCE, IRELAND; FELLOW OF THE INSTITUTE
OF CHEMISTRY; FELLOW OF THE PHYSICAL SOCIETY, ETC.; LECTURER
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London
E. & F. N. SPON, LIMITED, 57 HAYMARKET

NEW YORK
SPON & CHAMBERLAIN, 123 LIBERTY STREET

1914

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PREFACE

The object of the present little volume is to reproduce in connected form, an account of the many interesting phenomena associated with liquid drops and globules. Much of the matter relates to experiments devised by the author during the past four years, descriptions of which have appeared in the *Proceedings of the Physical Society*; in the columns of *Nature* and *Knowledge*; and elsewhere. The exhibition of these experiments at the conversazioni of the Royal Society and the Royal Institution, and in the author's lectures, has evoked such interest as to suggest the present publication. It may be added that all the experiments described may be repeated by any intelligent reader at a trifling cost, no special manipulative skill being required.

The context maintains the form of the lectures delivered on this subject by the author at various places, and the method of presentation is such as may be followed by those who have not received a training in this branch of science. It is hoped, in addition, that the book may prove of some service to teachers of science and others interested in the properties of liquids.

A number of the illustrations used have appeared in the pages of *Knowledge* in connexion with the author's articles, and are here reproduced by courtesy of the Editor. Other drawings have been provided by Mr. W. Narbeth, to whom the author expresses his thanks.

CHAS. R. DARLING.

City and Guilds Technical College,
Finsbury, 1914.

[1]

LIQUID DROPS AND GLOBULES

LECTURE I

Introduction.—In choosing a subject for a scientific discourse, it would be difficult to find anything more familiar than a drop of liquid. It might even appear, at first sight, that such a subject in itself would be quite inadequate to furnish sufficient material for extended observation. We shall find, however, that the closer study of a drop of liquid brings into view many interesting phenomena, and provides problems of great profundity. A drop of liquid is one of the commonest things in nature; yet it is one of the most wonderful.

Apart from the liquids associated with animal or vegetable life, water and petroleum are the only two which are found in abundance on the earth; and it is highly probable that petroleum has been derived from the remains of vegetable life. Many liquids are fabricated by living organisms, such as turpentine, alcohol, olive oil, castor oil, and all the numerous vegetable oils with which we are all familiar. But in addition to these, there are many liquids produced in the laboratory of the chemist, many of which are of great importance; for example, nitric acid, sulphuric acid, and [2] aniline. The progress of chemical science has greatly enlarged the number of liquids available, and in our experiments we shall frequently utilize these products of the chemist's skill, for they often possess properties not usually associated with the commoner liquids.

General Properties of Liquids.—No scientific study can be pursued to advantage unless the underlying principles be understood; and hence it will be necessary, in the beginning, to refer to certain properties possessed by all liquids, whatever their origin. The most prominent characteristic of a liquid is *mobility*, or freedom of movement of its parts. It is owing to this property that a liquid, when placed in a vessel, flows in all directions until it reaches the sides; and it is this same freedom of movement which enables water, gathering on the hills, to flow under the pull of gravitation into the lowlands, and finally to the sea. If we drop a small quantity of a strongly-coloured fluid—such as ink—into a large volume of water, and stir the mixture for a short time, the colour is evenly distributed throughout the whole mass of water, because the freedom of movement of the particles enables the different portions to intermingle readily. This property of mobility distinguishes a liquid from a solid; for a solid maintains its own shape, and its separate parts cannot be made to mix freely. Mobility, however, is not possessed in equal degree by all liquids. Petrol, for example, flows more freely than water, which in turn is more mobile than glycerine or treacle. Sometimes a substance exhibits properties intermediate between those of a solid and a liquid, as, for instance, butter in hot weather. We shall not be [3] concerned, however, with these border-line substances, but shall confine our attention to well-defined liquids.

There is another feature, however, common to all liquids, which has a most important bearing on our subject. Every liquid is capable of forming a boundary surface of its own; and this surface has the properties of a stretched, elastic membrane. Herein a liquid differs from a gas or vapour, either of which always completely fills the containing vessel. You cannot have a bottle half full of a vapour or gas only; if one-half of that already present be withdrawn, the remaining half immediately expands and distributes itself evenly throughout the bottle, which is thus always filled. But a liquid may be poured to any height in a vessel, because it forms its own boundary at the top. Let us now take a dish containing the commonest of all liquids, and in many ways the most remarkable—water—and examine some of the properties of the upper surface.

Properties of the Surface Skin of Water.—Here is a flat piece of thin sheet silver, which, volume for volume, is 10½ times as heavy as water, in which it might therefore be expected to sink if placed upon the surface. I lower it gently, by means of a piece of cotton, until it just reaches the top, and then let go the cotton. Instead of sinking, the piece of silver floats on the surface; and moreover, a certain amount of pressure may be applied to it without causing it to fall to the bottom of the water. By alternately applying and relaxing the pressure we are able, within small limits, to make the sheet of silver bob up and down as if it were a piece of cork. If we [4] look closely, we notice that the water beneath the silver is at a lower level than the rest of the surface, the dimple thus formed being visible at the edge of the floating sheet (Fig. 1). If now I apply a greater pressure, the piece of silver breaks through the surface and sinks rapidly to the bottom of the vessel. Or, if instead I place a thick piece of silver, such as a shilling, on the surface of the water, we find that this will not float, but sinks immediately. All these results are in agreement with the supposition that the surface layer of water possesses the properties of a very thin elastic sheet. If we could obtain an extremely fine sheet of stretched rubber, which would merely form a depression under the weight of the thin piece of silver, but would break under the application of a further pressure or the weight of a heavier sheet, the condition of the water surface would then be realized. We may note in passing that a sheet of metal resting on the surface of water is a phenomenon quite distinct from the floating of an iron ship, or hollow metal vessel, which sinks until it has displaced an amount of water equal in weight to itself.

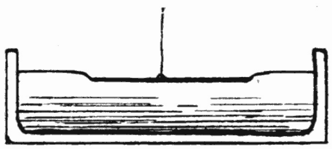


Fig. 1.—Silver sheet floating on water.

We can now understand why a water-beetle is able to run across the surface of a pond, without [5] wetting its legs or running any risk of sinking. Each of its legs produces a dimple in the surface, but the pressure on any one leg is not sufficient to break through the skin. We can imitate this by bringing the point of a lead pencil gently to the surface of water, when a dimple is produced, but the skin is not actually penetrated. On removing the pencil, the dimple immediately disappears, just as the depression caused by pushing the finger into a stretched sheet of indiarubber becomes straight immediately the finger is removed.

Elastic Skin of other Liquids—Minimum Thermometer.—The possession of an elastic skin at the surface is not confined to water, but is common to all liquids. The strength of the skin varies with different liquids, most of which are inferior to water in this respect. The surface of petroleum, for example, is ruptured by a weight which a water surface can readily sustain. But wherever we have a free liquid surface, we shall always find this elastic layer at the boundary, and I will now show, by the aid of lantern projection, an example in which the presence of this layer is utilized. On the screen is shown the stem of a minimum thermometer—that is, a thermometer intended to indicate the lowest temperature reached during a given period. The liquid used in this instrument is alcohol, and you will observe that the termination of the column is curved (Fig. 2). In contact with the end of the column is a thin piece of coloured glass, with rounded ends, which fits loosely in the stem, and serves as an index. When I warm the bulb of the [6] thermometer, you notice that the end of the column moves forward, but the index, round which the alcohol can flow freely, does not change its position. On inclining the stem, the index slides to the end of the column, but its rounded end does not penetrate the elastic skin at the surface. I now pour cold water over the bulb, which causes the alcohol to contract, and consequently the end of the column moves towards the bulb. In doing so, it encounters the opposition of the index, which endeavours to penetrate the surface; but we see that the elastic skin, although somewhat flattened, is not pierced, but is strong enough to push the index in front of it. And so the index is carried towards the bulb, and its position indicates the lowest point attained by the end of the column—that is, the minimum temperature. Obviously, a thermometer of this kind must be mounted horizontally, to prevent the index falling by its own weight.

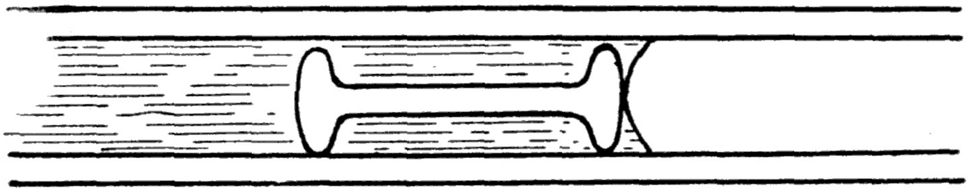


Fig. 2.—Column and index of minimum thermometer.

Boundary Surface of two Liquids.—So far we have been considering surfaces bounded by air, or—in the case of the alcohol thermometer—by vapour. It is possible, however, for the surface of one liquid to be bounded by a second liquid, provided the two do not mix. We may, for example, pour petroleum on to water, when the top of the water will be in contact with the floating oil. If [7] now we lower our piece of silver foil through the petroleum, and allow it to reach the surface of the water, we find that the elastic skin is still capable of sustaining the weight; and thus we see that the elastic layer is present at the junction of the two liquids. What is true of water and oil in this respect also holds good for the boundary or interface of any two liquids which do not mix. Evidently, if the two liquids intermingled, there would be no definite boundary between them; and this would be the case with water and alcohol, for example.

Area of Stretched Surface.—We will not at present discuss the nature of the forces which give rise to this remarkable property of a liquid surface, but will consider one of the effects. The tendency, as in the case of all stretched membranes, will be to reduce the area of the surface to a minimum. If we take a disc of stretched indiarubber and place a weight upon it, we cause a depression which increases the area of the surface. But on removing the weight, the disc immediately flattens out, and the surface is restored to its original smallest dimension. Now, in practice, the surface of a liquid is frequently prevented from attaining the smallest possible area, owing to the contrary action of superior forces; but the tendency is always manifest, and when the opposing forces are absent or balanced the surface always possesses the minimum size. A simple experiment will serve to illustrate this point. I dip a glass rod into treacle or “golden syrup,” and withdraw it with a small quantity of the syrup adhering to the end. I then hold the rod with the smeared end downwards, and the syrup falls from it slowly in the form of a long, [8] tapered column. When the column has become very thin, however, owing to the diminished supply of syrup from the rod, we notice that it breaks across, and the upper portion then shrinks upwards and remains attached to the rod in the form of a small drop (Fig. 3). So long as the column was thick, the tendency of the surface layer to reduce its area to the smallest dimensions was overpowered by gravity; but when the column became thin, and consequently less in weight, the elastic force of the outer surface was strong enough to overcome gravitation, and the column was therefore lifted, its area of surface growing less and less as it rose, until the smallest area possible under the conditions was attained.

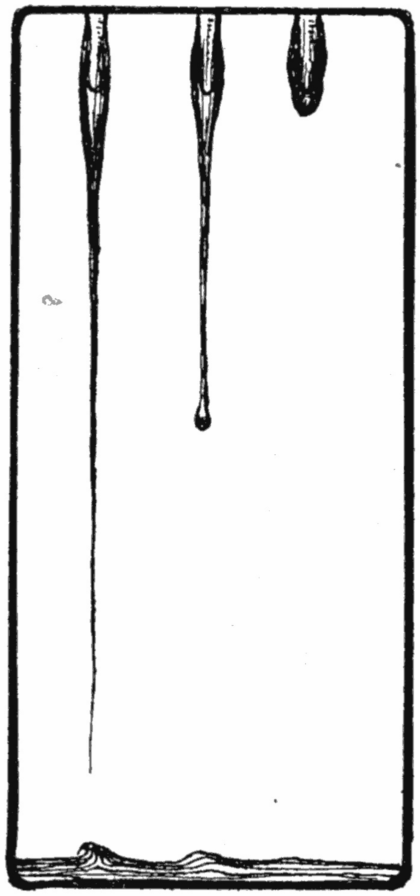


Fig. 3.—Thread of golden syrup rising and forming a drop.

Shape of Detached Masses of Liquid.—Let us now pay a little attention to the small drop of syrup which remains hanging from the rod. It is in contact with the glass at the top part only, and the lower portion is only prevented from falling by the elastic skin around it, which sustains the weight. We may compare it to a bladder full of liquid, in which case also the weight is borne by the containing skin. Now suppose we could separate the drop of syrup entirely from the rod; what shape would it take? We know that its surface, if not prevented by outside forces from doing so, would become of minimum area. Assuming such extraneous forces to be absent or counterbalanced, what would then be the shape of the drop? It would be an exact sphere. For a sphere has a less surface-area in proportion to its volume than any other shape; and hence a free drop of liquid, if its outline were determined solely by its elastic skin, would be spherical. A numerical example will serve to illustrate this property of a sphere. Supposing we construct three closed vessels, each to contain 1 cubic foot, the first being a cube, the second a cylinder of length equal to its diameter, and the third a sphere. The areas of the surfaces would then be:—

Cube	6 square feet.
Cylinder	5·86 ,, ,,
Sphere	4·9 ,, ,,

And whatever shape we make the vessel, it will always be found that the spherical form possesses the least surface.

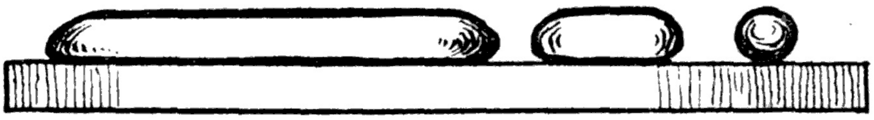


Fig. 4.—Drops of different sizes resting on flat plate.

[10] Now let us examine some of the shapes which drops actually assume. I take a glass plate covered with a thin layer of grease, which prevents adhesion of water to the glass, and form upon it drops of water of various sizes by the aid of a pipette. You see them projected on the screen (Fig. 4). The larger drops are flattened above and below, but possess rounded sides and resemble a teacake in shape. Those of intermediate size are more globular, but still show signs of flattening; whilst the very small ones, so far as the eye can judge, are spherical. Evidently, the shape depends upon the size; and this calls for some explanation. If we take a balloon of indiarubber filled with water, and rest it on a table, the weight of the enclosed water will naturally tend to stretch the balloon sideways, and so to flatten it. A smaller balloon, made of rubber of the same strength, will not be stretched so much, as the weight of the enclosed water would be less; and if the balloon were very small, but still had walls of the same strength, the weight of the enclosed water would be incompetent to produce any visible distortion. It is evident, however, that so long as it is under the influence of gravitation, even the smallest drop cannot be truly spherical, but will be slightly flattened. The tendency of drops to become spherical, however, is always present.

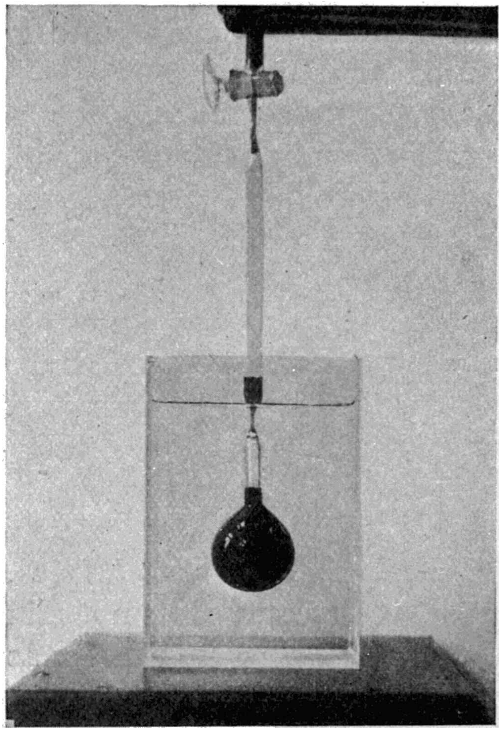


Fig. 5.—Formation of a sphere of orthotoluidine.

[11] **Production of True Spheres of Liquids.**—Now it is quite possible to produce true spheres of liquid, even of large size, if we cancel the effect of gravity; and we may obtain a hint as to how this may be accomplished by considering the case of a soap-bubble, which, when floating in air, is spherical in shape. Such a bubble is merely a skin of liquid enclosing air; but being surrounded by air of the same density, there is no tendency for the bubble to distort, nor would it fall to the ground were it not for the weight of the extremely thin skin. The downward pull of gravity on the air inside the bubble is balanced by the buoyancy of the outside air; and hence the skin, unhampered by any extraneous force, assumes and retains the spherical form. And similarly, if we can arrange to surround a drop of liquid by a medium of the same density, it will in turn become a sphere. Evidently the medium used must not mix with the liquid composing the drop, as it would then be impossible to establish a boundary surface between the two. Plateau, many years ago, produced liquid spheres in this manner. He prepared a mixture of alcohol and water exactly equal in density to olive oil, and discharged the oil into the mixture, the buoyancy of which exactly counteracted the effect of gravity on the oil, and hence spheres were formed. The preparation of an alcohol-water mixture of exactly correct density is a tedious process, and we are now able to dispense with it and form true spheres in a more convenient way. There is a

liquid known as *orthotoluidine*, which possesses a beautiful red colour, does not mix with water, and which has exactly the same density as water when the temperature of both is 75° F. or 24° C. At this temperature, therefore, if orthotoluidine be run into water, spheres should be formed; and there is no reason why we should not be able to make one as large as a cricket-ball, or even larger. I take a flat-sided vessel for this experiment, in order that the appearance of the drop will not be distorted as it would be in a beaker, and pour into it water at 75° F. until it is about two-[12] thirds full. I now take a pipette containing a 3 per cent. solution of common salt, and discharge it at the bottom of the water. Being heavier, the salt solution will remain below the water, and will serve as a resting-place for the drop. The orthotoluidine is contained in a vessel provided with a tap and wide stem, which is now inserted in the water so that the end of the stem is about 1 inch above the top of the salty layer. I now open the tap so as to allow the orthotoluidine to flow out [13] gradually; and we then see the ball of liquid growing at the end of the stem (Fig. 5). By using a graduated vessel, we can read off the quantity of orthotoluidine which runs out, and thus measure the volume of the sphere formed. When the lower part reaches the layer of salt solution, we raise the delivery tube gently, and repeat this as needed during the growth of the sphere. We have now run out 100 cubic centimetres, or about one-sixth of a pint, and our sphere consequently has a diameter of 5¾ centimetres, or 2¼ inches. To set it free in the water we lift [14] the delivery tube rapidly—and there is the sphere floating in the water (Fig. 6). We could have made it as much larger as we pleased, but the present sphere will serve all our requirements.

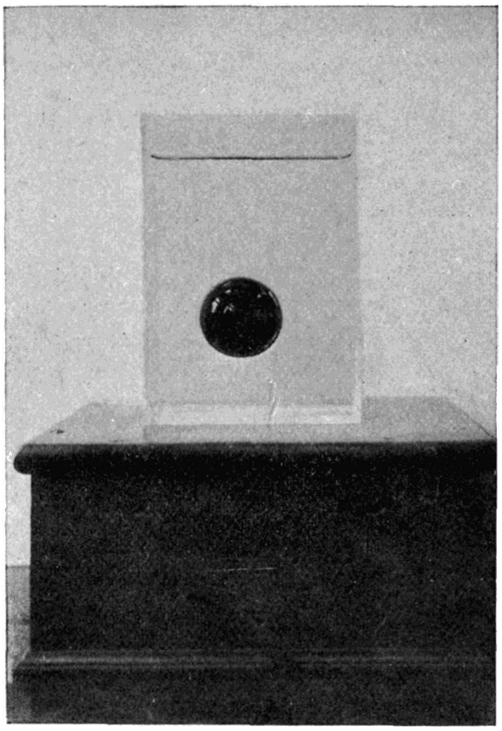


Fig. 6.—The detached sphere floating under water.

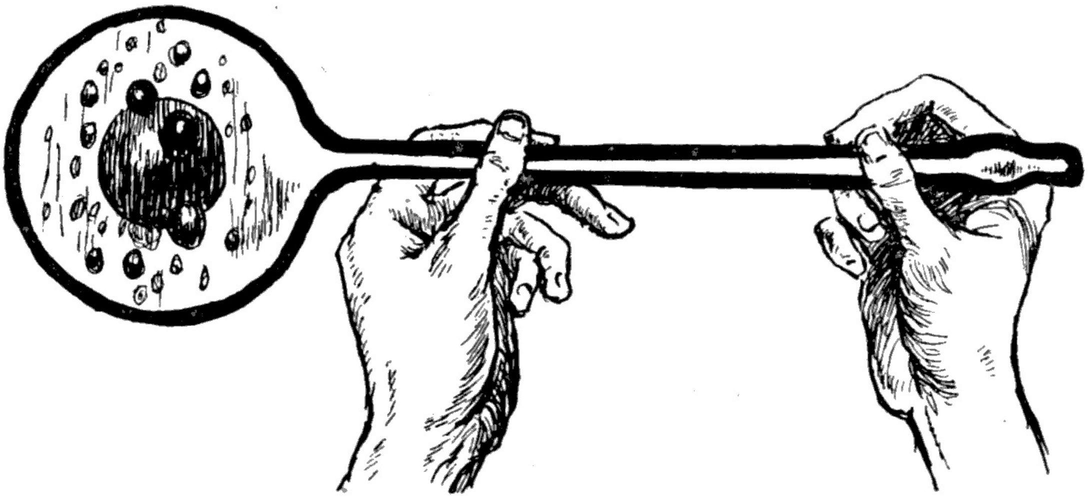
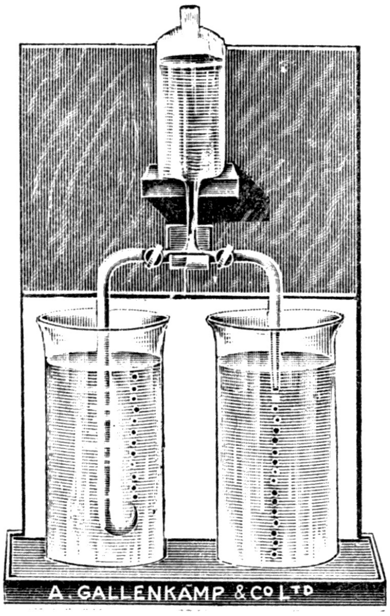


Fig. 7.—The Centrifugoscope.

The Centrifugoscope.—I have here a toy, which we may suitably call the centrifugoscope, which shows in a simple way the formation of spheres of liquid in a medium of practically equal density. It consists of a large glass bulb attached to a stem, about three-quarters full of water, the remaining quarter being occupied by orthotoluidine. This liquid, being slightly denser than water at the temperature of the room, rests on the bottom of the bulb. When I hold the stem horizontally, and rotate it—suddenly at first, and steadily afterwards—a number of fragments are detached from the orthotoluidine, which immediately become spherical, and rotate near the outer side of the bulb. The main mass of the red liquid rises to the centre of the bulb, and rotates on its axis (Fig. 7), and we thus get an imitation of the solar system, with the planets of various sizes [15] revolving round the central mass; and even the asteroids are represented by the numerous tiny spheres which are always torn off from the main body of liquid along with the larger ones. When the rotation ceases, the detached spheres sink, and after a short time join the parent mass of orthotoluidine. We can therefore take this simple apparatus at any time, and use it to show that a mass of liquid, possessing a free surface all round, and unaffected by gravity, automatically becomes a sphere. After all, this is only what we should expect of an elastic skin filled with a free-flowing medium.

Effect of Temperature on Sphere of Orthotoluidine.—I will now return to the large sphere formed under water in the flat-sided vessel, and direct your attention to an experiment which teaches an important lesson. By placing a little ice on the top of the water, we are enabled to cool the contents of the vessel, and we soon notice that the red-coloured sphere becomes flattened on the top and below, and sinks a short distance into the saline layer. Evidently the cooling action, which has affected both liquids, has caused the orthotoluidine to become denser than water. I now surround the vessel with warm water, and allow the contents gradually to attain a temperature higher than 75° F. You observe that the flattened drop changes in shape until it is again spherical; and as the heating is continued elongates in a vertical direction, and then rises to the surface, being now less dense than water. So sensitive are these temperature effects that a difference of 1 degree on either side of 75° F. causes a perceptible departure from the spherical [16] shape in the case of a large drop. It therefore follows that orthotoluidine may be either heavier or lighter than water, according to temperature, and this fact admits of a simple explanation. Orthotoluidine expands more than water on heating, and contracts more on cooling. The effect of expansion is to decrease the density, and of contraction to increase it; hence the reason why warm air rises through cold air, and vice versa. Now if orthotoluidine and water, which are equal in density at 75° F., expanded or contracted equally on heating above or cooling below this temperature, their densities would always be identical. But inasmuch as orthotoluidine increases in volume to a greater extent than water on heating, and shrinks more on cooling, it becomes lighter than water when both are hotter than 75° F., and heavier when both are colder. We call the temperature when both are equal in density the *equi-density temperature*. Here are some figures which show how the densities of these two liquids diverge from a common value on heating or cooling, and which establish the conclusions we have drawn:—

Temperature.		**Density.**	
Deg. F.	**Deg. C.**	**Water.**	**Orthotoluidine.**
50	10	0·9997	1·009
59	15	0·9991	1·005
68	20	0·9982	1·001
Equal: 75	24	0·9973	0·997
86	30	0·9957	0·992
95	35	0·9940	0·988
104	40	0·9923	0·983



[17] *Fig. 8.—Aniline drops falling through cold water and ascending through hot water.*

Other Examples of Equi-Density.—There are many other liquids which, like orthotoluidine, may be heavier or lighter than water, according to temperature, and I now wish to bring to your notice the remarkable liquid *aniline*, which falls under this head. Aniline is an oily liquid, which, unless specially purified, has a deep red colour. It forms the basis of the beautiful and varied colouring materials known as the aniline dyes, which we owe to the skill of the chemist. The equi-density temperature of water and aniline is 147° F. or 64° C.; that is, aniline will sink in water if both be colder than 147° F., and rise to the surface if this temperature be exceeded. We may [18] illustrate this fact by a simple but striking experiment. Here are two tall beakers side by side, and above them a cistern containing aniline (Fig. 8). The stem of the cistern communicates with the two branches of a horizontal tube, the termination of one branch being near the top of one of the beakers, whilst the other branch is prolonged to the bottom of the second beaker, and is curved upwards at the end. Both branches are provided with taps to regulate the flow of liquid, and to commence with are full of aniline. Cold water is poured into the beaker containing the shorter branch until the end is submerged; and water nearly boiling is placed in the second beaker to an equal height. I now open the taps, so that the aniline may flow gradually into each beaker; and you notice that the drops of aniline sink through the cold water and rise through the hot. We have thus the same liquid descending and ascending simultaneously in water, the only difference being that the water is cold on the one side and hot on the other. Prolonging the delivery-tube to the bottom of the beaker containing the hot water enables the rising drops to be observed throughout the length of the column of water; and in addition enables the cold aniline from the cistern to be warmed up on its way to the outlet, so that by the time it escapes its temperature is practically the same as that of the water. If this temperature exceed 147° F., the drops will rise. We might, in this experiment, have used orthotoluidine instead of aniline; or, indeed, any other liquid equal in density to water at some temperature intermediate between those of the hot and cold water—always provided that the liquid chosen did not mix with water. Amongst such other [19] liquids may be mentioned *anisol*; *butyl benzoate*; and *aceto-acctic ether*; but none of these possess the fine colour of aniline or its chemical relative orthotoluidine, and in addition are more costly liquids. Besides these are a number of other liquids rarer still, practically only known to the chemist, which behave in the same way. These liquids are all carbon compounds, and more or less oily in character. There is a simple rule which may be used to predict whether any organic liquid will be both lighter and heavier than water, according to temperature. Here it is: If the density of the liquid at 32° F. or 0° C. be not greater than 1·12, the liquid will become less dense than water below 212° F. or 100° C., at which temperature water boils. This rule is derived from a knowledge of the extent to which the expansion of organic liquids in general exceeds that of water. I have considered it necessary to enter at some length into this subject of equi-density, as much that will follow involves a knowledge of this physical relation between liquids.

Aniline Films or Skins.—We have previously concluded, largely from circumstantial evidence, that a liquid drop is encased in a skin or what is equivalent to a skin, and I propose now to show by experiments with aniline how we can construct a drop, commencing with a skin of liquid. Here is some aniline in a vessel, covered by water. I lower into the aniline a circular frame of wire, which I then raise slowly into the overlying water; and you observe that a film of aniline remains stretched across the frame. By lifting the frame up and down in the water the skin is stretched, [20] forming a drop which is constricted near the frame (Fig. 9). On lifting the wire more suddenly, the skin of aniline closes in completely at the narrow part, and a sphere of water, encased in an aniline skin, then falls through the water in the beaker, and comes to rest on the aniline below—into which, however, it soon merges. You were previously asked to regard a drop of liquid as being similar to a filled soap-bubble; and this experiment realizes the terms of the definition. And it requires only a little imagination to picture a drop surrounded by its own skin instead of that of another liquid. It is easy to make one of these enclosed water-drops by imitating the blowing of a soap-bubble—using, however, water instead of air. In order to do this I take a piece of glass [21] tubing, open at both ends, and pass it down the vessel, until it reaches the aniline. Water, in the meantime, has entered the tube, to the same height as that at which it stands in the vessel. On raising the tube gently, a skin of aniline adheres to the end; and as we raise it still further, the water in the tube, sinking so as to remain at the level in the vessel, expands the skin into a sphere (Fig. 9)—the equivalent of a filled soap-bubble. On withdrawing the tube gradually, the composite sphere is left hanging from the surface of the water.

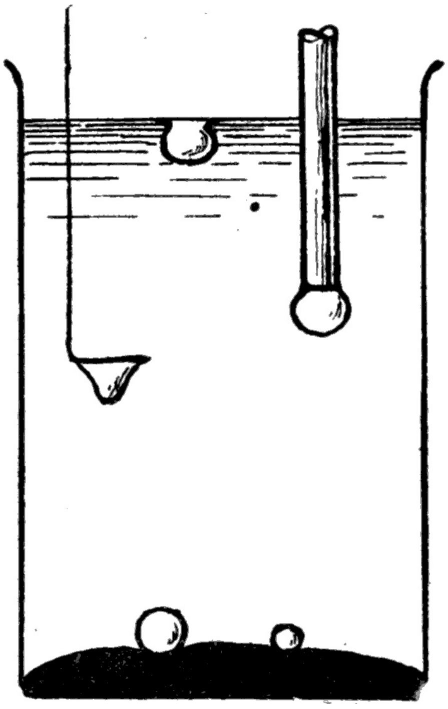


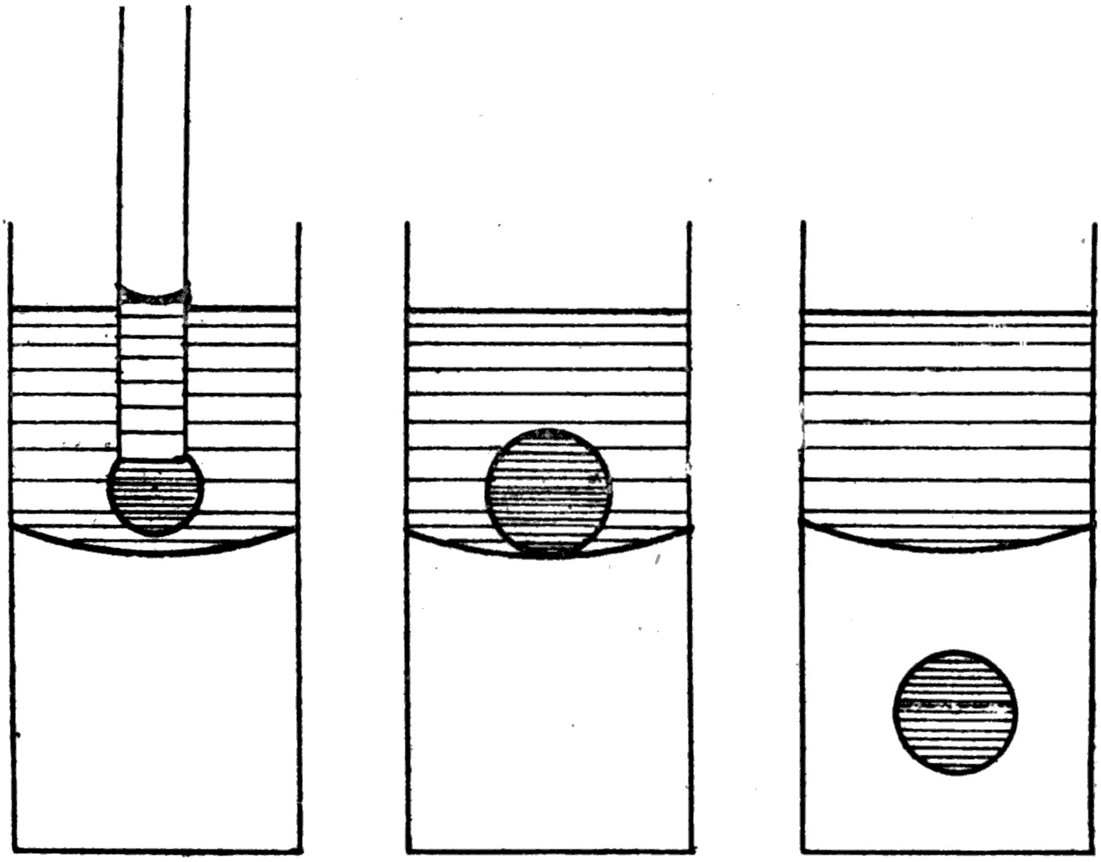
Fig. 9.—Aniline skins enveloping water.

Surface Tension.—Before proceeding further, it will be advisable to introduce and explain the term “surface tension.” We frequently use it, without attaching to it any numerical value, to express the fact that the free surface of a liquid is subjected to stretching forces, or is in a state of tension; and thus we say that certain phenomena are “due to surface tension.” But the physicist does not content himself with merely observing occurrences; he tries also to measure, in definite units, the quantities involved in the phenomena. And hence surface tension is defined as the force tending to pull apart the two portions of the surface on either side of a line 1 centimetre in length. That is, we imagine a line 1 centimetre long on the surface of the liquid, dividing the surface into two portions on opposite sides of the line, and we call the force tending to pull these two portions away from each other the surface tension. Experiments show that this force, in the case of cold water, is equal to about 75 dynes, or nearly $^{8}/_{100}$ of a gramme. If we choose a line 1 inch long on the surface of water, the surface tension is represented by about [22] 3 $^{1}/_{6}$ grains. It is always necessary to specify the length when assigning a value to the surface tension; and unless otherwise stated a length of 1 centimetre is implied. The values for different liquids vary considerably; and it is also necessary to note that the figure for a given liquid depends upon the nature of the medium by which it is bounded—whether, for example, the surface is in contact with air or another liquid. The following table gives the values for several liquids when the surfaces are in contact with air:—

Liquid.	Tension at 15° C. (59° F.), dynes per cm.
Water	75
Aniline	43
Olive Oil	32
Chloroform	27
Alcohol	25

When one liquid is bounded by another, the *interfacial* tension, as it is called, is generally less than when in contact with air. Thus the value for water and olive oil is about 21 dynes per centimetre at 15° C.

We are now in a position to speak of surface tension *quantitatively*, and shall frequently find it necessary to do so in order to explain matters which will come under our notice later.



Figs. 10, 11 and 12.—The Diving Drop. Three stages.

The "Diving" Drop.—In order to illustrate the tension at the boundary surface of two liquids, I now show an experiment in which a drop is forcibly projected downwards by the operation of this tension. I pour some water into a narrow glass vessel, and float upon it a liquid called *dimethyl-aniline*, so as to form a layer about 1 inch in depth. A glass tube, open at both ends, is now passed down the floating liquid into the water, and then raised gradually, with the result that a skin of water adheres to the end, and is inflated by the upper liquid, forming a sphere on the end of the tube ([Fig. 10](#)). On withdrawing the tube from the upper surface, the sphere is detached and falls to the boundary surface, where it rests for a few seconds, and is then suddenly shot downwards into the water (Figs. 11 and 12). It then rises to the interface; breaks through, and mingles with the floating liquid, thereby losing its identity. Why should the drop, which is less dense than [24] water, dive below in this manner? The explanation is that the drop (which consists of a skin of water filled with dimethyl-aniline), after resting for a time on the joining surface, loses the under part of its skin, which merges into the water below. The shape of the boundary of the two liquids is thereby altered, the sides now being continuous with the skin forming the upper part of the drop. This is an unstable shape; and accordingly the boundary surface flattens to its normal condition, and with such force as to cause the drop beneath it to dive into the water, although the liquid is lighter than water and tends to float. The result is the same as that which would occur if a marble were pressed on to a stretched disc of rubber, and then released, when it would be projected upwards owing to the straightening of the disc. I now repeat the experiment, using paraffin oil instead of dimethyl-aniline; but in this case the drop is only projected to a small depth, and the effect is not so marked. The experiment furnishes conclusive evidence of the existence of the interfacial tension.

Formation of Falling Drops of Liquid.—We will now direct our attention to one of the most beautiful of natural phenomena—the growth and partition of a drop of liquid. Let us observe, by the aid of the lantern, this process in the case of water, falling in drops from the end of a glass tube. The flow of water is controlled by a tap, and you observe that the drop on the end gradually grows in size, then becomes narrower near the end of the tube, and breaks across at this narrow [25] part, the separated drop falling to the ground. Another drop then grows and breaks away; but the process is so rapid that the details cannot be observed. None of you saw, for example, that each large drop after severance was followed by a small droplet, formed from the narrowed portion from which the main drop parted. But the small, secondary drop is always present, and is called, in honour of its discoverer, Plateau's spherule. Nor did any of you observe that the large drop, immediately after separation, became flattened at the top, nor were you able to notice the changing shape of the narrow portion. To show all these things it will be necessary to modify the experimental conditions.

Mr. H. G. Wells, in one of his short stories, describes the wonderful effects of a dose of a peculiarly potent drug, called by him the “Accelerator.” While its influence lasted, all the perceptions were speeded up to a remarkable degree, so that occurrences which normally appeared to be rapid seemed absurdly slow. A cyclist, for example, although travelling at his best pace, scarcely appeared to be making any movement; and a falling body looked as if it were stationary. Now if we could come into possession of some of this marvellous compound, and take the prescribed quantity, we should then be able to examine all that happens when a drop forms and falls at our leisure. But it is not necessary to resort to such means as this to render the process visible to the eye. We could, for example, take a number of photographs succeeding each other by very minute intervals of time—a kind of moving picture—from which the details might be gleaned by examining the individual photographs. This procedure, however, would be [26] troublesome; and evidently the simplest plan, if it could be accomplished, would be to draw out the time taken by a drop in forming and falling. And our previous experiments indicate how this may be done, as we shall see when we have considered the forces at work on the escaping liquid.

A liquid issuing from a tube is pulled downwards by the force of gravitation, and therefore is always tending to fall. At first, when the drop is small, the action of gravity is overcome by the surface tension of the liquid; but as the drop grows in size and increases in weight, a point arrives at which the surface tension is overpowered. Then commences the formation of a neck, which grows narrower under the stretching force exerted by the weight of the drop, until rupture takes place. Now if we wish to make the process more gradual, it will be necessary to reduce the effect of gravity, as we cannot increase the surface tension. We have already seen how this may be done in connexion with liquid spheres—indeed, we were able to cancel the influence of gravity entirely, by surrounding the working liquid by a second liquid of exactly equal density. We require now, however, to allow the downward pull of the drop ultimately to overcome the surface tension, and we must therefore form the drop in a less dense liquid. If this surrounding liquid be only slightly less dense, we should be able to produce a very large drop; and if we make its growth slow we may observe the whole process of formation and separation with the unaided eye.

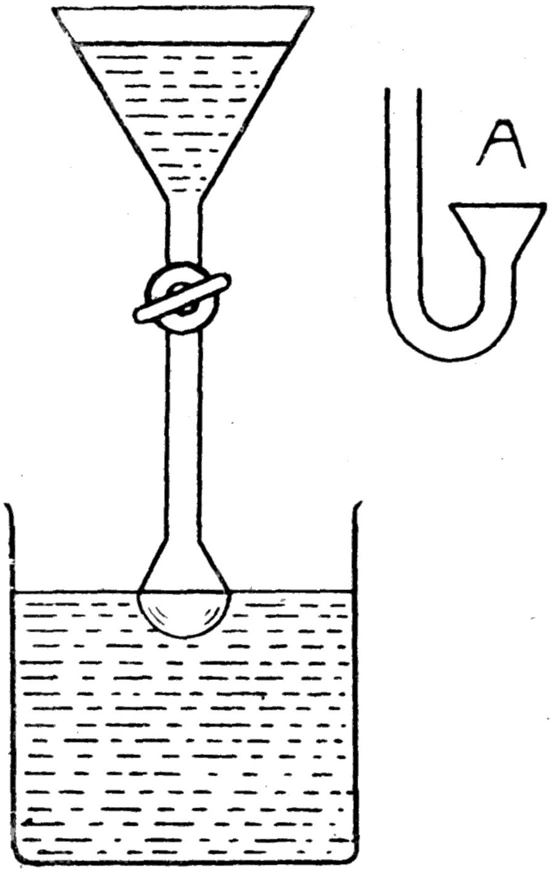


Fig. 13.—Apparatus for forming ascending or descending drops of liquids.

Now it so happens that we have to hand two liquids which, without any preparation, fulfil our [27] requirements. Orthotoluidine, at temperatures below 75° F. or 24° C., is denser than water of equal temperature. At 75° F. their densities are identical; and as the ordinary temperature of a room lies between 60° and 70° F., water, under the prevailing conditions, will be slightly the less dense of the two, and will therefore form a suitable medium in which to form a large drop of orthotoluidine. I therefore run this red-coloured liquid into water from a funnel controlled by a tap (Fig. 13), and in order to make a large drop the end of the stem is widened to a diameter of [28] 1½ inches. It is best, when starting, to place the end of the stem in contact with the surface of the water, as the first quantity of orthotoluidine which runs down then spreads over the surface and attaches itself to the rim of the widened end of the stem. The tap is regulated so that the liquid flows out slowly, and we may now watch the formation of the drop. At first it is nearly hemispherical in shape; gradually, as you see, it becomes more elongated; now the part near the top commences to narrow, forming a neck, which, under the growing weight of the lower portion, is stretched until it breaks, setting the large drop free (Figs. 14 to 18). And then follows the droplet; very small by comparison with the big drop, but plainly visible (Figs. 19 and 20). The graceful outline of the drop at all stages of the formation must appeal to all who possess an eye for beauty in form; free-flowing curves that no artist could surpass, changing continuously until the process is complete.

Slow as was the formation of this drop, it was still too rapid to enable you to trace the origin of the droplet. It came, as it always does come, from the drawn-out neck. When the large drop is severed, the mass of liquid clinging to the delivery-tube shrinks upwards, as the downward pull upon it is now relieved. The result of this shrinkage—which, as usual, reduces the area of surface to the minimum possible—is to cut off the elongated neck, at its upper part, thus leaving free a spindle-shaped column of liquid. This column immediately contracts, owing to its surface tension, until its surface is a minimum—that is, it becomes practically a sphere; and this constitutes the [29] droplet. In a later experiment, in which the formation is slower still, and the liquid more viscous, the origin of the droplet will be plainly seen, and the correctness of the description verified. The recoil due to the liberation of the stretching force after rupture of the neck was visible on the top of the large drop, and also on the bottom of the portion of liquid which remained attached to the tube, both of which were momentarily flattened (Figs. 19 and 20) before assuming their final rounded shape. This is exactly what we should expect to happen if a filled skin of indiarubber were stretched until it gave way at the narrowest part.

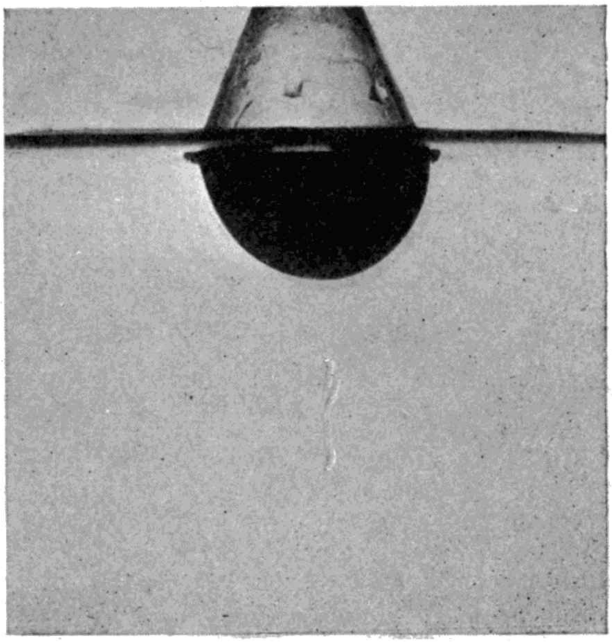


Fig. 14.

As a variation on the two liquids just used, I now take the yellow liquid *nitrobenzene*, and run it into nitric acid (or other suitable medium) of specific gravity 1·2, and you observe the same sequence of events as in the previous experiment, even to the details. Very rapid photography shows that the breaking away of a drop of water from the end of a tube in air is in all respects identical with what we have just seen on a large scale.

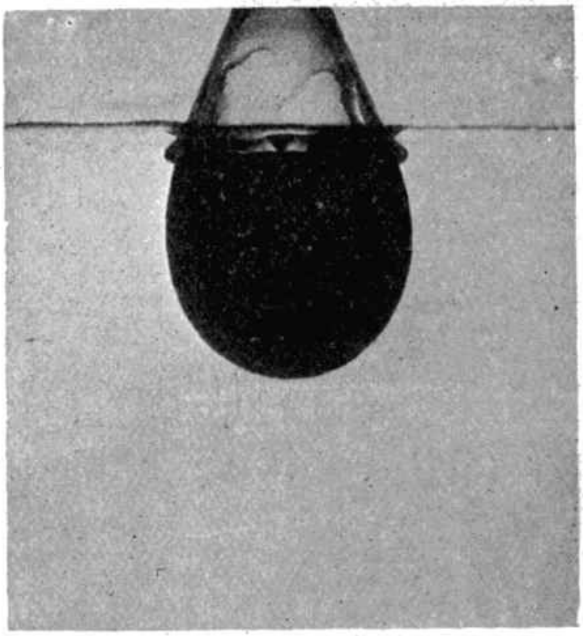


FIG. 15.

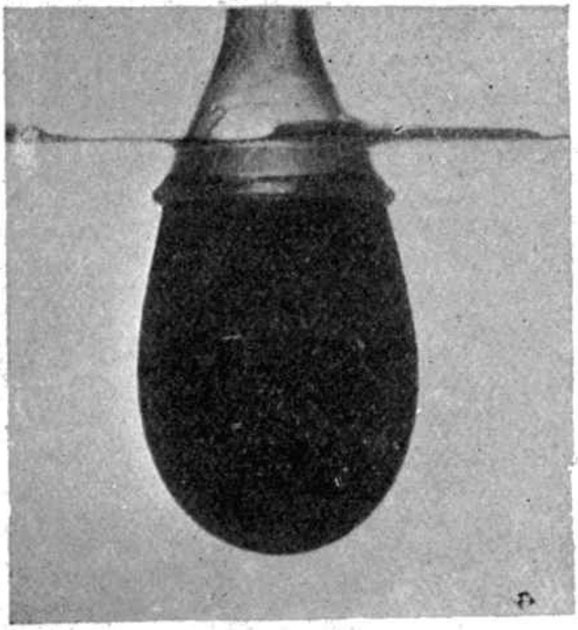


FIG. 16.

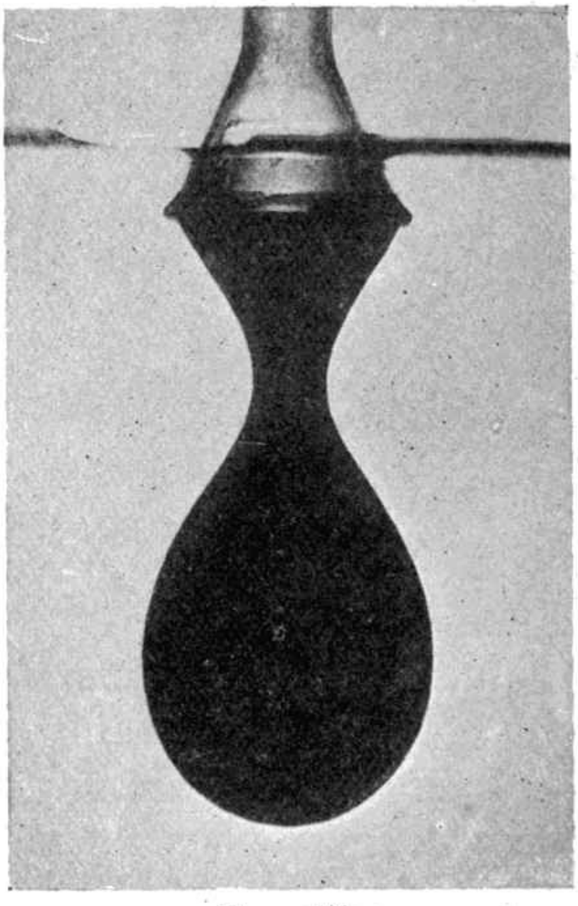


FIG. 17.

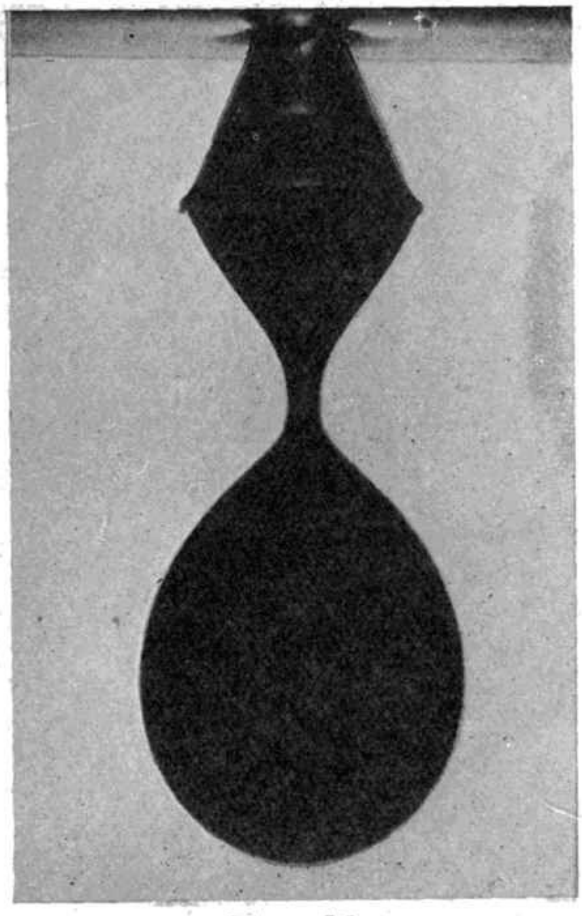


FIG. 18.

Figs. 14 to 20.—Formation of a drop of orthotoluidine, showing the droplet. Seven stages.

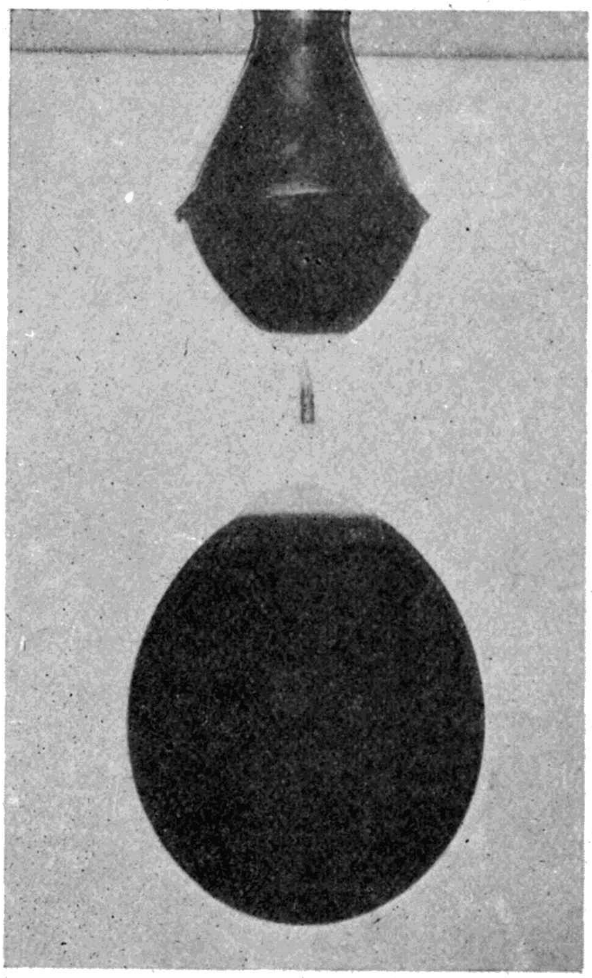


FIG. 19.

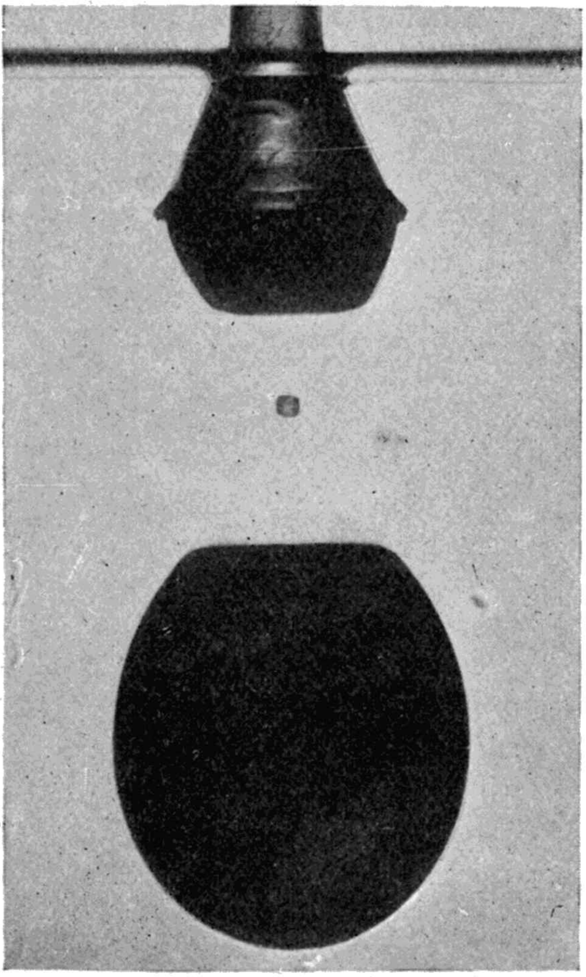


FIG. 20.

Ascending or Inverted Drops.—If we discharge orthotoluidine into water when both are hotter than 75° F., the former liquid will rise, as its density is now less than that of water. If, therefore, I take a funnel with the stem bent into a parallel branch, so as to discharge upwards (A, Fig. 13) and raise the temperature of both liquids above 75° F., we see that the drop gradually grows towards the top of the water, finally breaking away and giving rise to the droplet. Everything, in fact, was the same as in the case of a falling drop, except that the direction was reversed. A slight rise in temperature has thus turned the whole process topsy-turvy, but the action is really the same in both cases. When, on heating, the water acquired the greater density, its buoyancy overcame the pull of gravitation on the orthotoluidine, and accordingly the drop was pushed upwards, the result being the same as when it was pulled downwards. An inverted drop may always be obtained by discharging a light liquid into a heavier one, e.g. olive oil into water, or water into any of the liquids mentioned on p. 19, below the equi-density temperature.

[33]

LECTURE II

Automatic Aniline Drops.—In the foregoing experiments the drop was enlarged until it broke away by feeding it with liquid; but it is possible to arrange that the formation shall be quite automatic. The experiment, as we shall see, is extremely simple, and yet it contains an element of surprise. Into a beaker containing water nearly boiling I pour a considerable quantity of aniline, which at first breaks up into a large number of drops. After a short time, however, all the aniline floats to the surface, having been warmed by contact with the water to a temperature higher than that of equi-density (147° F., or 64° C.)—which is exactly what we should expect to happen. There it remains for a brief period in the form of a large mass with the lower portion curved in outline. Soon, however, we observe the centre of the mass sinking in the water, and taking on the now familiar outline of a falling drop. Gradually, it narrows at the neck and breaks away; but as aniline is a viscous liquid, the neck in this case is long and therefore easily seen. The large drop breaks away and falls to the bottom of the beaker, its upper surface rising and falling for some [34] time owing to the recoil of its skin after separation, finally becoming permanently convex. Immediately after the large drop has parted, the upper mass shrinks upwards, spreading out further on the surface of the water, with the result that the long neck is severed at the top, its own weight assisting the breakage. Now follows the resolution of the detached neck into two or more spheres, usually a large and a small (Fig. 22). And now, to those who view the experiment [35] for the first time, comes the surprise. The large drop, which was more or less flattened when it came to rest at the bottom of the beaker, becomes more and more rounded, and finally spherical. Then, unaided, it rises to the top and mingles itself with the aniline which remained on the surface. After a brief interval a second drop falls, imitating the performance of the first one; and, [36] like its predecessor, rises to the surface, after remaining for a short time at the bottom of the vessel. And so long as we keep the temperature a few degrees above that of equi-density, the process of partition and reunion goes on indefinitely. The action is automatic and continuous, and the large size of the drop and of the neck, and the slowness of the procedure, enables us to follow with ease every stage in the formation of a parting drop.

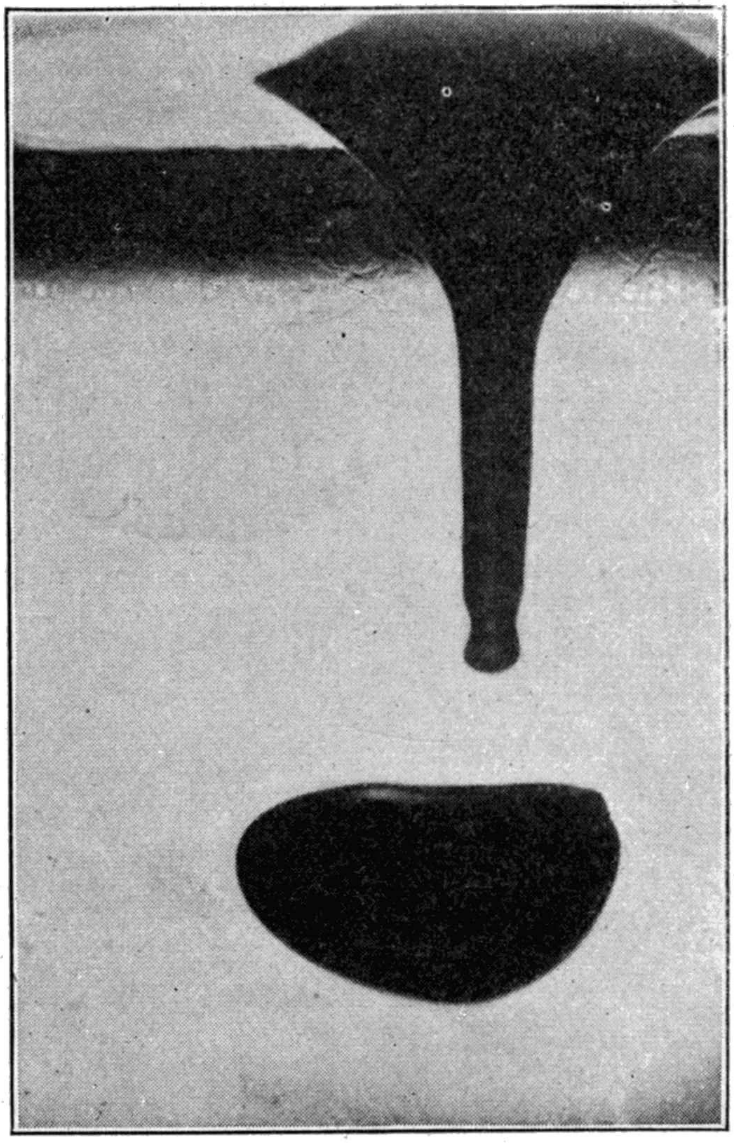


Fig. 21.

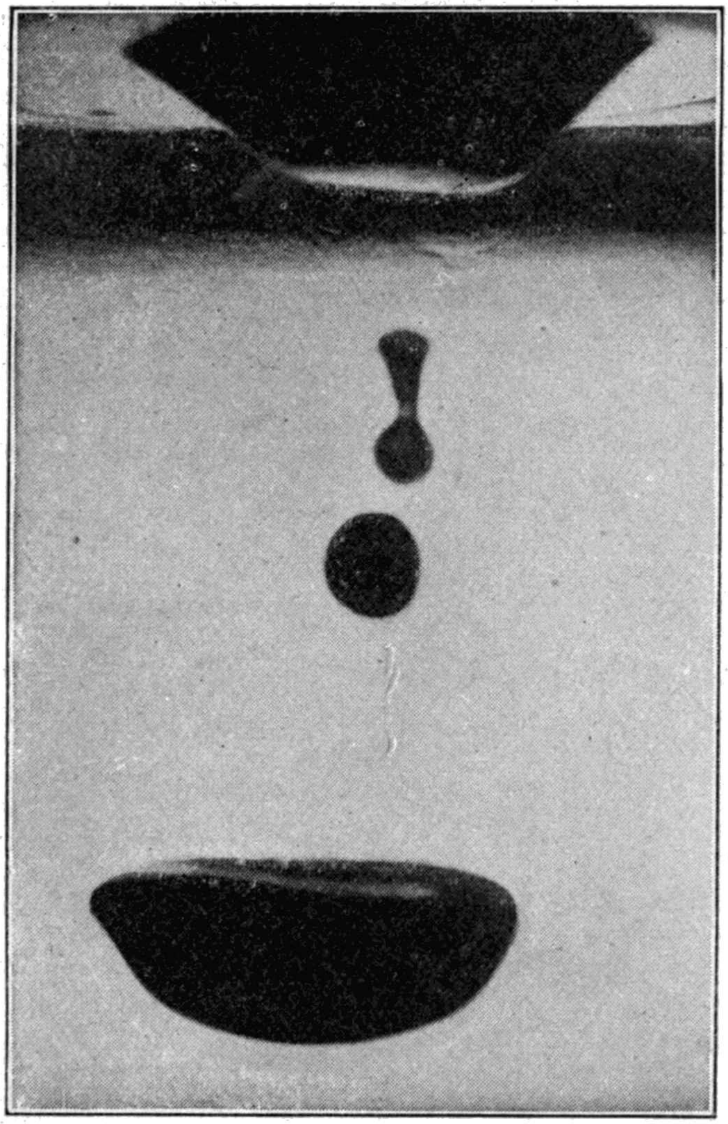


FIG. 22.

FIGS. 21 and 22.—Automatically formed aniline drops, showing the formation of droplets from the neck.

And now as to the explanation of this curious performance. When the aniline reaches the surface, and spreads out, it cools by contact with the air more rapidly than the water below. As it cools, its density increases, and soon becomes greater than that of the water, in which it then attempts to sink. The forces of surface tension prevent the whole of the aniline from falling—the water surface can sustain a certain weight of the liquid—but the surplus weight cannot be held, and therefore breaks away. But when the detached drop reaches the bottom of the vessel, it is warmed up again; and when its temperature rises above that of equi-density it floats up to the top. And so the cycle of operations becomes continuous, owing to cooling taking place at the top and heating at the bottom.

Perpetual motion, you might suggest. Nothing of the kind. Perpetual motion means the continuous performance of work without any supply of energy; it does not mean merely continuous movement. A steam-engine works so long as it is provided with steam, and an electric motor so long as it is fed with electricity; but both stop when the supply of energy is withdrawn. So with our aniline drop, which derives its energy from the heat of the water, and which comes to rest immediately the temperature falls below 147° F. or 64° C. But in order that the process of separation and reunion may continue, the cooling at the top is quite as necessary as the heating at the bottom. Our aniline drop is in essence a heat-engine—although it does no external work—and like all heat-engines possesses a source from which heat is derived, and a sink into which heat at a lower temperature is rejected. We might, with certain stipulations, work out an indicator diagram for our liquid engine, but that would be straying too far from our present subject.

Automatic Drops of other Liquids.—Liquids which possess a low equi-density temperature with water do not form automatic drops like aniline, as the rate of cooling at the surface is too slow, and hence the floating mass of liquid does not attain a density in excess of that of the water beneath. Aceto-acetic ether, however, behaves like aniline, if the temperature of the water be maintained at about 170° F. (77° C.), but as this liquid is fairly soluble in hot water further quantities must be added during the progress of the experiment. Results equal to those obtained with aniline, however, may be secured by using nitrobenzene in nitric acid of specific gravity 1·2 at 59° F. (15° C.), the acid being heated to 185° F. (85° C.); and here you see the yellow drop performing its alternate ascents and descents exactly as in the case of aniline and water. Other examples might be given; but we may take it as a general rule that when the equi-density [38] temperature of the liquid and medium is above 125° F. (52° C.), the phenomenon of the automatic drop may usually be observed when the temperature is raised by 30° F. (17° C.), above this point.

Liquid Jets.—So far we have been observing the formation of single drops, growing slowly at the end of a tube, or breaking away from a large mass of the floating liquid. If, however, we accelerate the speed at which the liquid escapes, the drop has no time to form at the outlet, and a jet is then formed. We are all familiar with a jet of water escaping from a tap; it consists of an unbroken column of the liquid up to a certain distance, depending upon the pressure, but the lower part is broken up into a large number of drops, which break away from the column at a definite distance from the tap. There are many remarkable features about jets which I do not intend to discuss here, as it is only intended to consider the manner in which the drops at the end are formed. To observe this procedure, it is necessary again to resort to our method of slowing down the rate of formation, by allowing the liquid to flow into a medium only slightly inferior in density. For this purpose, orthotoluidine falling into water at the ordinary room temperature is eminently satisfactory; and we see on the screen the projection of a pipe, with its end under water, placed so that a jet of orthotoluidine may be discharged vertically downwards from a stoppered funnel. I open the tap slightly at first, and we then merely form a single drop at the end. Now it is opened more widely, and you observe that the drop breaks away some distance [39] below the outlet, being rapidly succeeded by another and another (Fig. 23). On still further opening the tap the drops form at a still greater distance from the end of the pipe, and succeed each other more rapidly, so that quite a number appear in view at any given moment (Figs. 24 [40] and 25). Notice how the drop is distorted by breaking away from the stream of liquid, and how it gradually recovers its spherical shape during its fall through the water. Finally, I increase the discharge to such an extent that the formation of the terminal drops is so rapid as to be no longer visible to the eye, but appears like the turmoil observed at the end of a jet of water escaping into air.

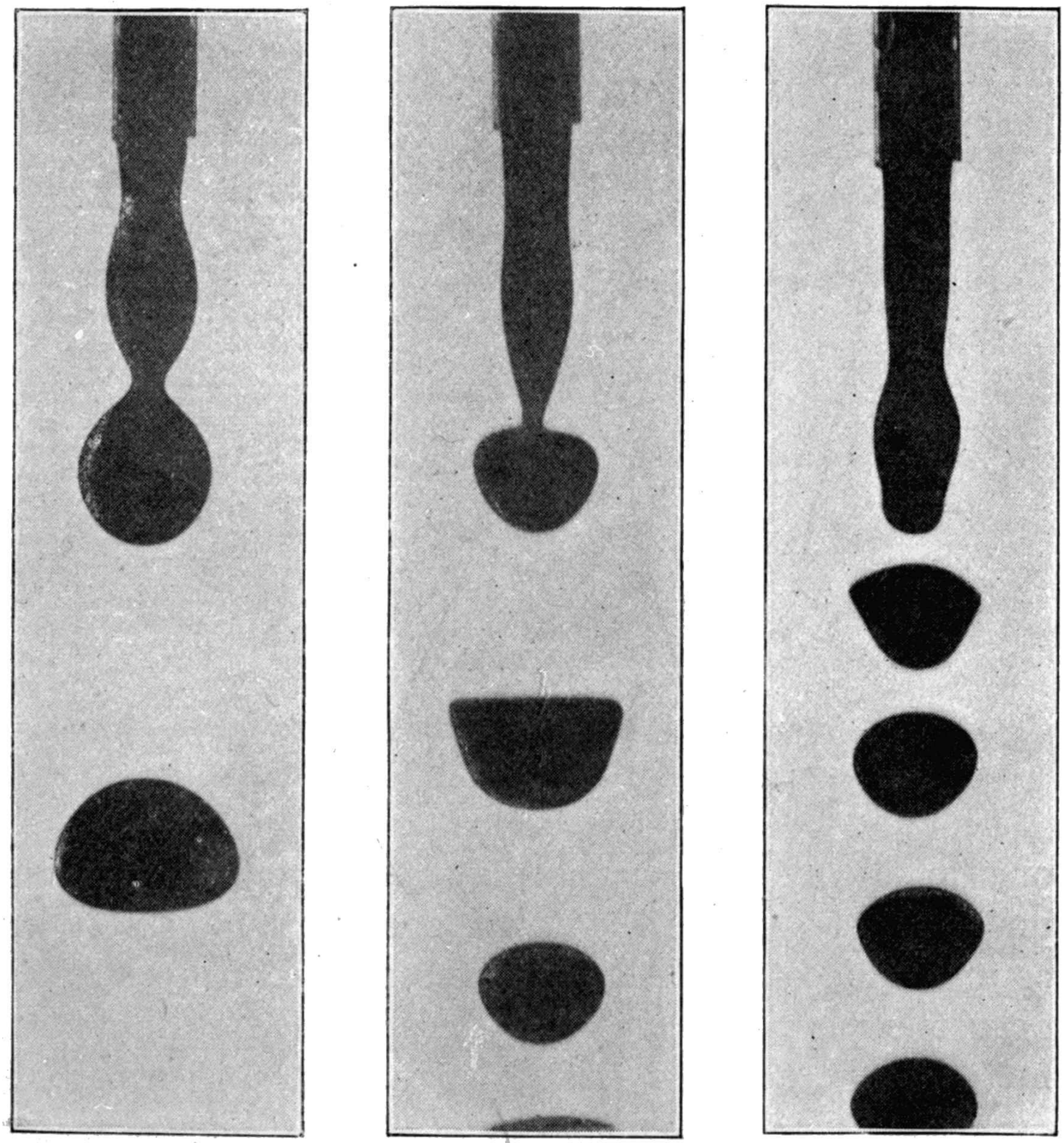


FIG. 23. FIG. 24. FIG. 25.

Figs. 23, 24, 25.—Jets of Orthotoluidine, discharged under water.

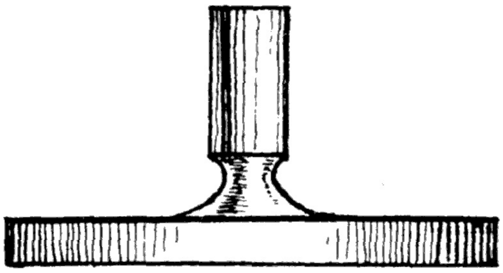


Fig. 26.—Water stretched between a tube and a plate.

Liquid Columns.—A simple experiment will suffice to illustrate what is meant by a liquid column. Here is a drop of water hanging from the end of a glass tube. I place it in the lantern and obtain a magnified image on the screen, and then bring up a flat plate of glass until it just touches the suspended drop. As soon as contact is established, the water spreads outwards over the plate, causing the drop to contract in diameter at or near its middle part, so that its outline resembles that of a capstan (Fig. 26). The end of the glass tube is now connected to the plate by a column of water of curved outline, which is quite stable if undisturbed. If, however, I gradually raise the tube, or lower the plate, the narrow part of the column becomes still narrower, and [41] finally breaks across. In the same way we may produce columns of other liquids; those obtained with viscous liquids such as glycerine being capable of stretching to a greater extent than water, but showing the same general characteristics. A liquid column, then, is in reality a supported drop, and the severance effected by lowering the support is similar to that which occurs when a pendent drop breaks away owing to its weight.

In our previous experiments we have seen that in order to produce large drops of a given liquid, the surroundings should be of nearly the same density, so as largely to diminish the effective weight of the suspended mass. We might therefore expect that large columns of liquid could be produced under similar conditions; and our conjecture is correct. We may, for example, use the apparatus by means of which large drops of orthotoluidine were formed (Fig. 13), using a shallow layer of water, so that the lower end of the drop would come into contact with the bottom of the vessel before the breaking stage was reached, and thus produce, on a large scale, the same result as that we have just achieved by allowing a hanging drop of water to touch a glass plate. This method, however, restricts the diameter of the top of the column to that of the delivery tube, and in this respect the shape is strained. The remedy for this is to hang the drop from the surface of the water, when a degree of freedom is conferred upon the upper part, which enables the column to assume a greater variety of shapes. In order to show how this may be accomplished, I pour a small quantity of water into the rounded end of a wide test-tube, which is now seen [42] projected on the screen, and then pour gently down the side a quantity of *ethyl benzoate*, a liquid slightly denser than water. You observe that the liquid spreads out on the surface of the water, forming a hanging drop which at first is nearly hemispherical in shape; but as I continue to add the liquid the drop grows in size downwards, and finally reaches the bottom of the tube. There is our liquid column (Fig. 27), which has formed itself in its own way, free from the restriction imposed by a delivery tube. Notice the graceful curved outline, produced by a beautiful balance between the forces of surface tension and gravitation; and notice also how the outline may be varied by the gradual addition of water, which causes the upper surface to rise, and thus stretches the column (Fig. 28). The middle becomes more and more narrow (Fig. 29), and finally breaks across, leaving a portion of the former column hanging from the surface, and the remainder, in rounded form (Fig. 30), at the bottom of the tube. And, as usual, the partition was accompanied by the formation of a small droplet.

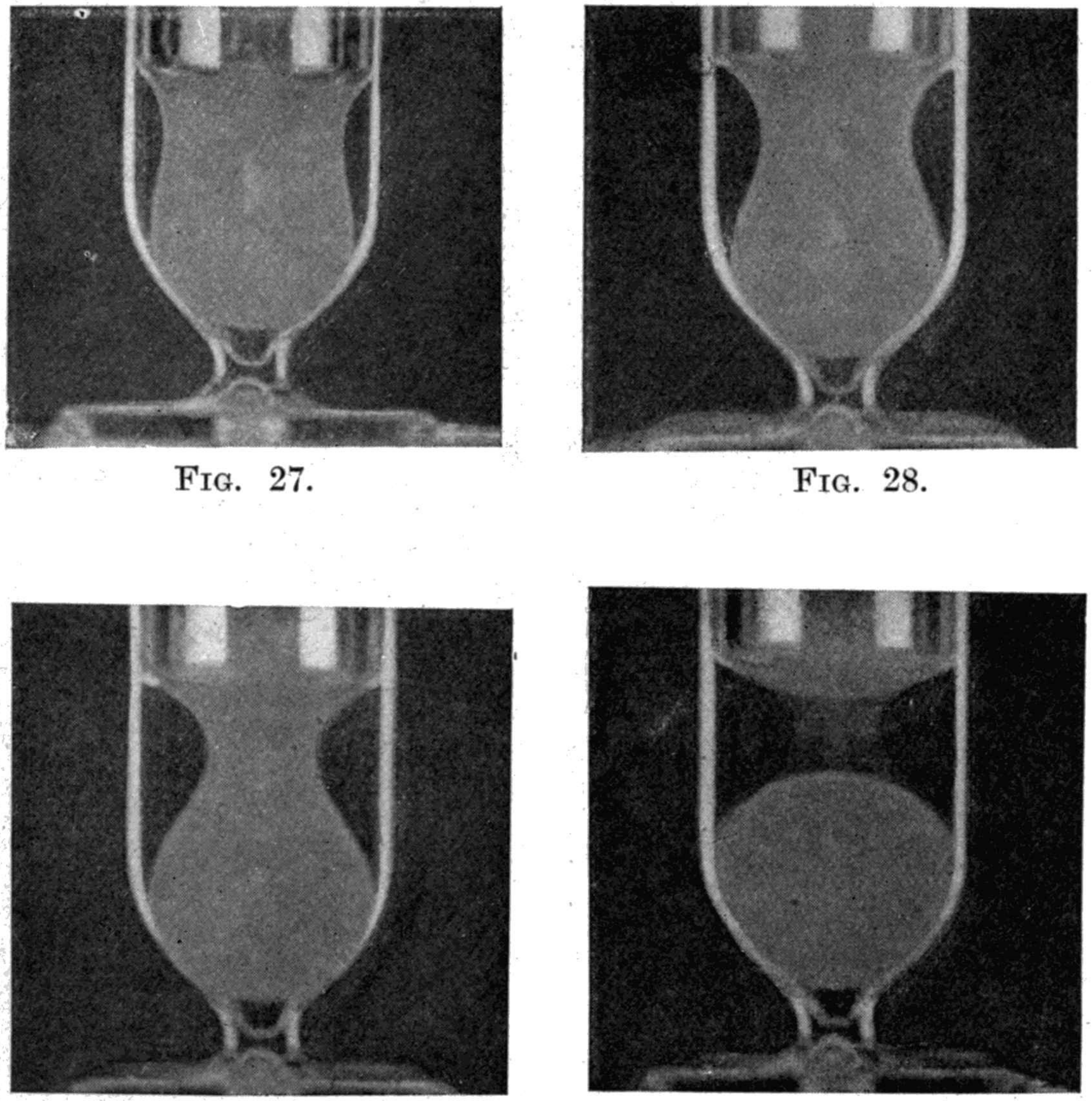


Fig. 27. Fig. 28.

Fig. 29. Fig. 30.

Figs. 27, 28, 29, 30.—A liquid column stretched upwards until broken by addition of water. Four stages.

It is possible, by using other liquids, and different diameters of vessels, to produce columns of a
large variety of outlines. Some liquids spread over a greater area on the surface of water than
others, and therefore produce columns with wider tops. Here we see a column of orthotoluidine,
which has a top diameter of 2 inches; and here again, in contrast, is a column of aceto-acetic
ether, the surface diameter of which is only ½ inch (Fig. 31). Other liquids, such as aniline, give
an intermediate result. The lower diameter is determined by the width of the vessel; and hence
[43] we are able to produce an almost endless number of shapes. It is interesting to note how workers
in glass and pottery have unconsciously imitated these shapes; and I have here a variety of
articles which simulate the outlines of one or other of the liquid columns you have just seen. It is
[44] possible that designers in these branches of industry might obtain useful ideas from a study of
liquid columns, which present an almost limitless field for the practical observation of curved
forms.

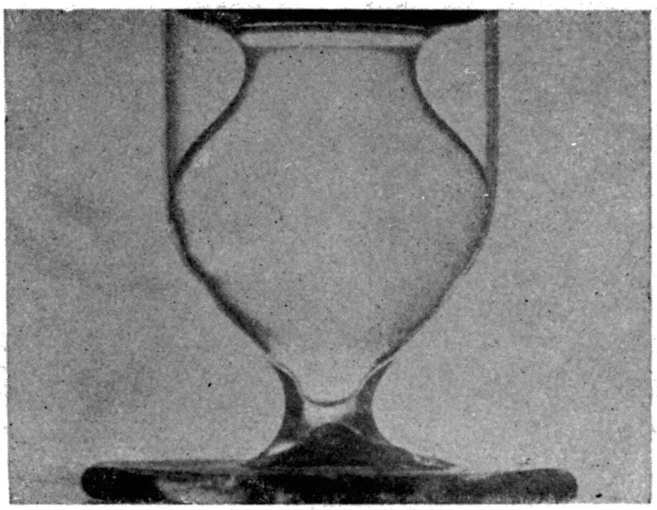


Fig. 31.—A column of aceto-acetic ether in water.

Communicating Drops.—There is a well-known experiment, which some of you may have seen, in which two soap-bubbles are blown on separate tubes, and are then placed in communication internally. If the bubbles are exactly equal in size, no alteration takes place in either; but if unequal, the smaller bubble shrinks, and forces the air in its interior into the larger one, which therefore increases in size. Finally, the small bubble is resolved into a slightly-curved skin which covers the end of the tube on which it was originally blown. It is evident from this experiment that the pressure per unit area exerted by the surface of a bubble on the air inside is greater in a small than in a large bubble. The internal pressure may be proved to vary inversely as the radius of the bubble; thus by halving the radius we double the pressure due to the elastic surface, and so on. The reciprocal of the radius of a sphere is called its *curvature*, and we may therefore state that the pressure exerted by the walls of the bubble on the interior vary directly as the curvature.

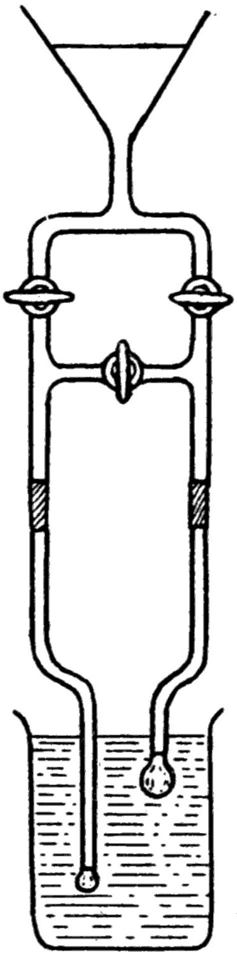


Fig. 32.—Apparatus for communicating drops, with extensions

of unequal length attached.

We have already seen that a drop of liquid possesses an elastic surface, and is practically the same thing as a soap-bubble filled with liquid instead of air. We might therefore expect the same results if two suspended drops of liquid were placed in communication as those observed in the case of soap-bubbles. And our reasoning is correct, as we may now demonstrate. The apparatus consists (Fig. 32) of two parallel tubes, each provided with a tap, and communicating with a cross-branch at the top, which contains a reservoir to hold the liquid used. About half-way down the parallel tubes a cross-piece, provided with a tap, is placed. We commence by filling the whole of the system with the liquid under trial, and the parallel tubes equal in length. Drops are then formed at the ends of each vertical tube by opening the taps on these in turn, and closing after suitable drops have been formed. Then, by opening the tap on the horizontal cross-piece, we [46] place the drops in communication and watch the result.

I have chosen orthotoluidine as the liquid, and by placing the ends of the vertical tubes under water—which at the temperature of the room is slightly less dense than orthotoluidine—I am able to form much larger drops than would be possible in air. You now see a small and a large drop projected on the screen; and I now open the cross-tap, so that they may communicate. Notice how the little drop shrinks until it forms merely a slightly-curved prominence at the end of its tube. It attains a position of rest when the curvature of this prominence is equal to that of the now enlarged drop which has swallowed up the contents of the smaller one. So far the result is identical with that obtained with soap-bubbles; but we can extend the experiment in such a way as to reverse the process, and make the little drop absorb the big one. In order to do this I fasten an extension to one of the tubes, and form a small drop deep down in the water, and a larger one on the unextended branch near the top. When I open the communicating top, the system becomes a kind of siphon, the orthotoluidine tending to flow out of the end of the longer tube. The tendency of the large drop to siphon over is opposed by the superior pressure exerted by the skin of the smaller drop; but the former now prevails, and the big drop gradually shrinks and the little one is observed to grow larger. It is possible by regulating the depth at which the smaller drop is placed, to balance the two tendencies, so that the superior pressure due to the lesser [47] drop is equalled by the extra downward pressure due to the greater length of the column of which it forms the terminus. Both pressures are numerically very small, but are still of sufficient magnitude to cause a flow of liquid in one or other direction when not exactly in equilibrium. In the case of communicating soap-bubbles, containing air and surrounded by air, locating the small bubble at a lower level would not reverse the direction of flow, which we succeeded in accomplishing with liquid drops formed in a medium of slightly inferior density.

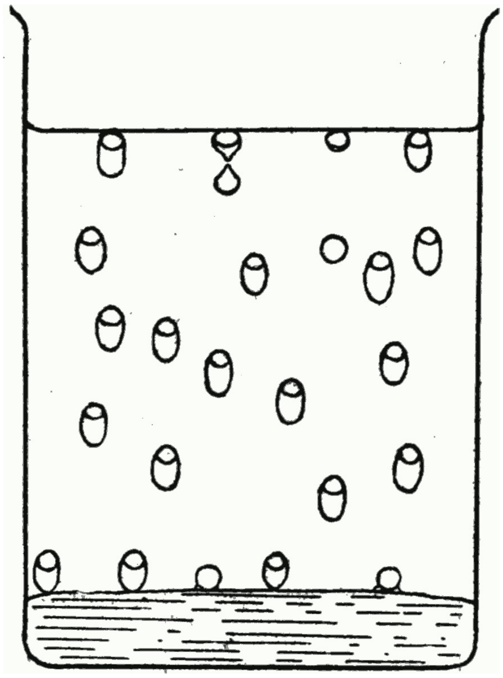


Fig. 33.—*Combined drops of vapour and liquid.*

Combined Vapour and Liquid Drops.—All liquids when heated give off vapour, the amount increasing as the temperature rises. The vapour formed in the lower part of the vessel in which the liquid is heated rises in the form of bubbles, which may condense again if the upper part of the liquid be cold. When the liquid becomes hot throughout, however, the vapour bubbles reach the surface and break, allowing the contents to escape into the air above. Everyone who has watched a liquid boiling will be familiar with this process, but it should be remembered that a liquid may give off large quantities of vapour without actually boiling. A dish of cold water, if exposed to the air, will gradually evaporate away; whilst other liquids, such as petrol and alcohol, will disappear rapidly under the same circumstances—and hence are called “volatile” liquids.

The formation of vapour and its subsequent escape at the surface of the liquid, enable us to produce a very novel kind of drop; if, instead of allowing the bubbles to escape into air, we cause [48] them to enter a second liquid. Here, for example, is a coloured layer of chloroform[1] at the bottom of a beaker, with a column of water above. I project the image of the beaker on the screen, and then heat it below. The chloroform vapour escapes in bubbles; but notice that each bubble carries with it a quantity of liquid, torn off, as it were, at the moment of separation. The vapour bubbles and their liquid appendages vary in size, but some of them, you observe, have an average density about equal to that of the water, and float about like weighted balloons. Some rise nearly to the surface, where the water is coldest; and then the vapour partially condenses, with the result that its lifting power is diminished, and hence the drops sink into the lower part of the beaker. But the water is warmer in this region, and consequently the vapour bubble increases in size and lifting power until again able to lift its load to the surface. So the composite drops go up and down, until finally they reach the surface, when the vapour passes into the air, and the suspended liquid falls back to the mass at the bottom of the beaker. Notice that the drop of liquid attached to each bubble is elongated vertically. This is because chloroform is a much denser liquid than water (Fig. 33). There is a practical lesson to be drawn from this experiment. Whenever a bubble of vapour breaks through the surface of a liquid, it tends to carry with it some of the liquid, which is dragged mechanically into the space above. In our experiment the space [49] was occupied by water, which enabled the bubble to detach a much greater weight than would be possible if the surface of escape had been covered by air, which is far less buoyant than water. But even when the bubbles escape into air, tiny quantities of liquid are detached; so that steam from boiling water, for example, is never entirely free from liquid. All users of steam are well acquainted with this fact.

Condensation of Drops from Vapour,—Mists, Fogs and Raindrops.—The atmosphere is the great laboratory for the manufacture of drops. It is continually receiving water in the form of vapour from the surface of the sea, from lakes, from running water, and even from snow and ice. [50] All this vapour is ultimately turned into drops, and returned again to the surface, and to this never-ceasing exchange all the phenomena connected with the precipitation of moisture are due. The atmosphere is only capable of holding a certain quantity of water in the form of vapour, and the lower the temperature the less the capacity for invisible moisture. When fully charged, the atmosphere is said to be “saturated”—a condition realized on the small scale by air in a corked bottle containing some water, which evaporates until the air can hold no more. The maximum weight of vapour that can be held by 1 cubic metre of air at different temperatures is shown in the table:—

Temperature.		**Weight of water vapour (grammes) required to saturate 1 cubic metre.**
Deg. C.	**Deg. F.**	
0	32	4·8
5	41	6·8
10	50	9·3
15	59	12·7
20	68	17·1
25	77	22·8

30	86	30·0
35	95	39·2
40	104	50·6

It will be seen from the table that air on a warm day in summer, with a temperature of 77° F., can hold nearly five times as much moisture as air at the freezing point, or 32° F. The amount [51] actually present, however, is usually below the maximum, and is recorded for meteorological purposes as a percentage of the maximum. Thus if the “relative humidity” at 77° F. were 70 per cent., it would imply that the weight of moisture in 1 cubic metre was 70 per cent. of 22·8 grammes; that is, nearly 16 grammes. If 1 cubic metre of air at 77° F., containing 16 grammes of moisture, were cooled to 50° F., a quantity of water equal to (16-9·3) = 6·7 grammes would separate out, as the maximum content at the lower temperature is 9·3 grammes. Precipitation would commence at 66° F., at which temperature 1 cubic metre is saturated by 16 grammes. And similarly for all states of the atmosphere with respect to moisture, cooling to a sufficient extent causes deposition of water to commence immediately below the saturation temperature, and the colder the air becomes afterwards the greater the amount which settles out. The temperature at which deposition commences is called the “dew point.”

Whenever atmospheric moisture assumes the liquid form, drops are invariably formed. These may vary in size, from the tiny spheres which form a mist to the large raindrops which accompany a thunderstorm. But in every instance it is necessary that the air shall be cooled below its saturation point before the separation can commence; and keeping this fact in mind we can now proceed to demonstrate the production of mists and fogs. Here is a large flask containing some water, fitted with a cork through which is passed a glass tube provided with a tap. I pump some air into it with a bicycle pump, and then close the tap. As excess of water is [52] present, the enclosed air will be saturated. Now a compressed gas, on expanding into the atmosphere, does work, and is therefore cooled; and consequently if I open the tap the air in the flask will be cooled, and as it was already saturated the result of cooling will be to cause some of the moisture to liquefy. Accordingly, when I open the tap, the interior of the flask immediately becomes filled with mist. If we examine the mist in a strong light by the aid of a magnifying glass, we observe that it consists of myriads of tiny spheres of water, which float in the air, and only subside very gradually, owing to the friction between their surfaces and the surrounding air preventing a rapid fall. The smaller the sphere, the greater the area of surface in proportion to mass, and therefore the slower its fall. And so in nature, the mists are formed by the cooling of the atmosphere by contact with the surface, until, after the saturation point is reached, the surplus moisture settles out in the form of tiny spheres, which float near the surface, and are dissipated when the sun warms up the ground and the misty air, and thus enables the water again to be held as vapour.

Fogs, like mists, are composed of small spheres of water condensed from the atmosphere by cooling; but in these unwelcome visitors the region of cooling extends to a higher level, and the lowering of temperature is due to other causes than contact with the cold surface of the earth. In our populous cities, the density of the fogs is accentuated by the presence of large quantities of solid particles in the atmosphere, which arise from the smoke from coal fires, and the abrasion of [53] the roads by traffic. We can make a city fog in our flask. I blow in some tobacco smoke, and then pump in air as before. You will notice that the smoke, which is now disseminated through the air in the flask, is scarcely visible; but now, on opening the tap, the interior becomes much darker than was the case in our previous experiment. We have produced a genuine yellow fog, that is, a dense mist coloured by smoke. When we have learned how to abolish smoke, and how to prevent dust arising from the streets, our worst fogs will be reduced to dense mists, such as are now met with on the sea or on land remote from large centres of habitation.

There is one feature common to the spheres which compose a mist or fog, or indeed to any kind of drop resulting from the condensation of moisture in the atmosphere. As shown by the deeply interesting researches of Aitken and others, each separate sphere forms round a core or nucleus, which is usually a small speck of dust, and hence an atmosphere charged with solid particles lends itself to the formation of dense fogs immediately the temperature falls below the dew-point. But dust particles are not indispensable to the production of condensed spheres, for it has been shown that the extremely small bodies we call “ions,” which are electrically charged atoms, can act as centres round which the water will collect; and much atmospheric condensation at high elevations is probably due to the aid of ions.[2] Near the surface, however, where dust is ever present, [54] condensation round the innumerable specks or motes is the rule. Here, for example, is a jet of steam escaping into air, forming a white cloud composed of a multitude of small spheres of condensed water. If now I allow the steam to enter a large flask containing air from which the dust has been removed by filtration through cotton wool, no cloud is formed in the interior, but instead condensation takes place at the end of the jet, from which large drops fall, and on the cold sides of the flask. The cloud we see in dusty air is entirely absent, and the effect of solid particles in the process of condensation is thus shown in a striking manner. Clouds are masses of thick mist floating at varying heights in the atmosphere. On sinking into a warmer layer of dry air the particles of which clouds are composed will evaporate and vanish from sight. If the condensation continue, however, the spheres will grow in size until the friction of the atmosphere is unable to arrest their fall; and then we have rain. And whether the precipitation be very gentle, and composed of small drops falling slowly, as in a “Scotch mist,” or in the form of rapid-falling large drops such as accompany a thunderstorm, the processes at work are identical. Every particle of a mist or cloud, and every raindrop, is formed round a nucleus, and owes its spherical shape to the tension at the surface.

Liquid Clouds in Liquid Media.—Just as the excess of moisture is precipitated from saturated air when the temperature falls, so is the excess of one liquid dissolved in another thrown down by cooling below the saturation temperature. Moreover, a liquid when precipitated in a second [55] liquid appears in the form of myriads of small spheres, which have the appearance of a dense cloud. Here is some boiling water to which an excess of aniline has been added, so that the water has dissolved as much aniline as it can hold. Aniline dissolves more freely in hot water than in cold, so that if I remove the flame, and allow the beaker to cool, the surplus of dissolved aniline will settle out. Cooling takes place most rapidly at the surface, and you observe white streaks falling from the top into the interior, where they are warmed up and disappear. Soon, however, the cooling spreads throughout; and now the streaks become permanent, and the water becomes opaque, owing to the thick white cloud of precipitated aniline. The absence of the red colour characteristic of aniline is due to the extremely fine state of division assumed in the process. If left for some hours, the white cloud sinks through the water to the bottom of the beaker, where the small particles coalesce and form large drops, leaving the overlying water quite transparent. The process is quite analogous to the precipitation of moisture from the atmosphere in the form of small spheres, which, if undisturbed, would gradually sink to the ground and leave the air clear.

Overheated Drops.—The temperature at which a liquid boils, under normal conditions, depends only upon the pressure on its surface. Thus water boiling in air, when the pressure is 76 centimetres or 29·92 inches of mercury, corresponding to 14·7 pounds per square inch, possesses a temperature of 100° C. or 212° F. At higher elevations, where the pressure is less, the boiling point is lower; thus Tyndall observed that on the summit of the Finsteraarhorn (14,000 feet) [56] water boiled at 86° C. or 187° F. Conversely, under increased pressure, the boiling point rises; so that at a pressure of 35 pounds per square inch water does not boil until the temperature reaches 125° C. or 257° F. There are certain abnormal conditions, however, under which the boiling point of a liquid may be raised considerably without any increase in the pressure at the surface; and it is then said to be “over-heated.” Dufour showed that when drops of water are floating in another liquid of the same density, they may become greatly overheated, and if very small in size may attain a temperature of 150° C. or 302° F., or even higher, before bursting into steam. In order to provide a medium in which water drops would float at these temperatures, Dufour made a mixture of linseed oil and oil of cloves, which possessed the necessary equi-density temperature with water. To demonstrate this curious phenomenon, I take a mixture of 4 volumes of ethyl benzoate and 1 volume of aniline, which at 125° C. or 257° F. is exactly equal in density to water at the same temperature. I add to the mixture two or three cubic centimetres of freshly-boiled water, the temperature being maintained at 125° C. by surrounding the vessel with glycerine heated by a flame. At first the water sinks, but on attaining the temperature of the mixture it breaks up with some violence, forming spheres of various sizes which remain suspended in the mixture. Any portion of the water which has reached the surface boils vigorously, and escapes in the form of steam; and some of the larger spheres may be observed to be giving off steam, which

[57] rises to the surface. Most of the spheres, however, remain perfectly tranquil, in spite of the fact that the water of which they are composed is many degrees above its normal boiling point. If I penetrate one of these spheres with a wire, you notice that it breaks up immediately, with a rapid generation of steam. A complete explanation of this abnormal condition of water is difficult to follow, as a number of factors are involved. One of the contributory causes—though possibly a minor one—is the opposition offered to the liberation of steam by the tension at the surface of the spheres.

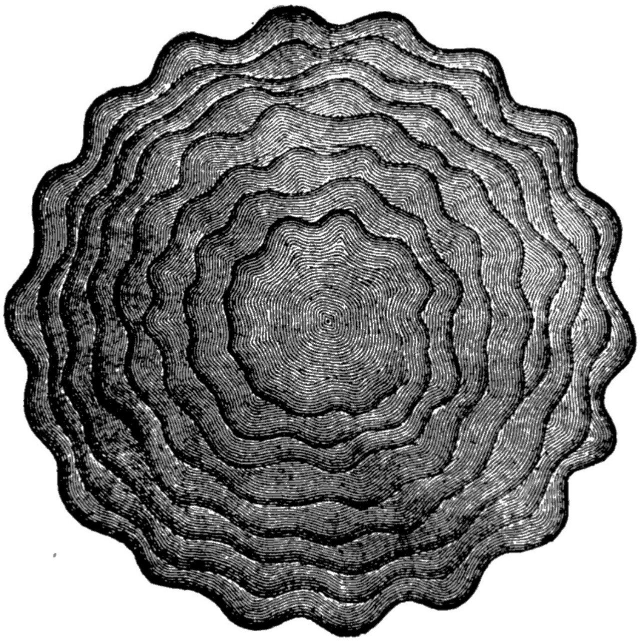


Fig. 34.—Spheroid of water on a hot plate.

Floating Drops on Hot Surfaces.—If a liquid be allowed to fall in small quantity on to a very hot solid, it does not spread out over the surface, but forms into drops which run about and gradually evaporate. By careful procedure, we may form a very large, flattened drop on a hot surface, and on investigation we shall notice some remarkable facts. I take a plate of aluminium, with a dimple in the centre, and make it very hot by means of a burner. You see the upper surface of this plate projected on the screen. I now allow water to fall on the plate drop by drop, and you hear a hissing noise produced when each drop strikes the plate. The separate drops gather together in the depression at the centre of the plate, forming a very large flattened globule. You might have expected the water to boil vigorously, but no signs of ebullition are visible; and what is more remarkable, the temperature of the drop, in spite of its surroundings, is actually less than the ordinary boiling point. Notice now how the drop has commenced to rotate, and has been set into vibration, causing the edges to become scalloped (Fig. 34). The drop, although not actually [58] boiling, is giving off vapour rapidly, and therefore gradually diminishes in size. And now I want to prove that the drop is not really touching the plate, but floating above it. To do this I make an electric circuit containing a cell and galvanometer, and connect one terminal to the plate and place the other in the drop. No movement is shown on the galvanometer, as would be the case if the drop touched the plate and thus completed the electric circuit. And at close range we can actually see a gap between the drop and the plate, so that the evidence is conclusive. If now I remove the flame—leaving the electric circuit intact—and allow the plate to cool, we notice after a time that the globule flattens out suddenly and touches the plate, as shown by the deflection of [59] the galvanometer; and simultaneously a large cloud of steam arises, due to the rapid boiling which occurs immediately contact is made.

What we have seen in the case of water is shown by most liquids when presented to a surface possessing a temperature much higher than the boiling point of the liquid. A liquid held up in this manner above a hot surface is said to be in the *spheroidal state*, to distinguish it from the flat state usually assumed by spreading when contact occurs between the liquid and the surface. It is doubtful whether any satisfactory explanation of the spheroidal state has ever been given. Evidently, the layer of vapour between the plate and the drop must exert a considerable upward pressure in order to sustain the drop, but the exact origin of this pressure is difficult to trace.

[60]

LECTURE III

Spreading of Oil on the Surface of Water.—If a small drop of oil be placed on the surface of water it will be observed to spread immediately until it forms a thin layer covering the surface. If a further addition of the oil be made, globules will be formed, which, as you now see upon the screen, remain floating on the surface. The spreading of the oil in all directions from the place on which the small quantity of oil was dropped is due to the superior surface tension of water, which pulls the oil outwards. The surface tension of the oil opposes that of the water, and would prevent the drop from spreading were it not overcome by a greater force. The result is the same as would be observed if the centre or any other part of a stretched rubber disc were weakened; the weak part would be stretched in all directions, and the rest of the disc would shrink towards the sides. When the oil has spread out, however, and contaminated, as it were, the surface of the water, the surface tension is reduced, and is not sufficiently strong to stretch out a further quantity of oil, which, if added, remains in the form of a floating globule.

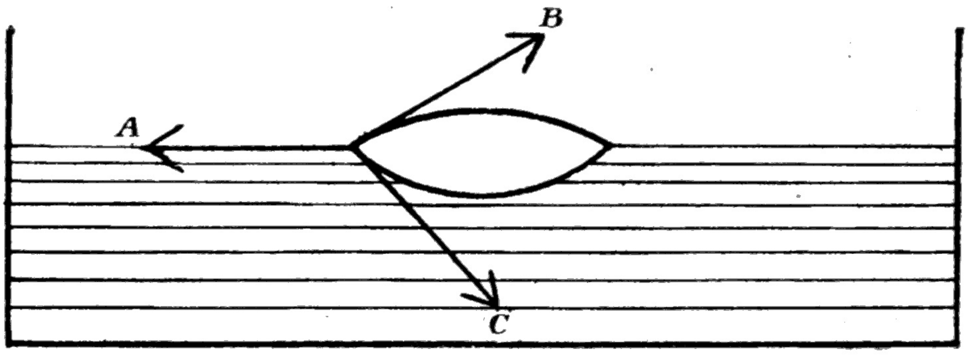


Fig. 35.—Forces acting on a floating globule.

Let us study the forces at work on the floating globule a little more closely. Its upper surface is in [61] contact with air, and the surface tension tends, as usual, to reduce the area to a minimum. The top of the globule is not flat, but curved (Fig. 35), and its surface meets that of the water at an angle; and the counter-pull exerted against the stretching-pull of the water surface is not horizontal, but inclined in the direction of the angle of contact, as shown by the line B. The under part of the globule is also curved, and meets the water surface from below at an angle; and here also is exerted a pull in opposition to that of the water surface, different in magnitude to the force at the upper surface, but also directed at the angle of contact as shown by the line C. This tension at the joining surface of two liquids is called the “interfacial” tension, to distinguish it from that of a surface in contact with air. Acting against these two tensions is that of the water, which is directed horizontally along the surface, as shown by the line A. The lines A, B, and C indicate the forces acting at a single point; but the same forces are at work at every point round the circle of contact of the globule and the surface of the water. And therefore the tendency on [62] the part of the water tension is to cause the globule to spread out in all directions, whereas the other two tensions tend to prevent any enlargement of its surface. The result depends upon the magnitudes and directions of the conflicting forces. We can imagine a kind of tug-of-war taking place, in which one contestant, A, is opposed to two others, B and C, all pulling in the directions indicated in Fig. 35. Although A is single-handed, he has the advantage of a straight pull, whereas B and C can only exert their strength at an angle, and the larger the angle the more they are handicapped. If A be more powerful than B and C, the globule will spread; but the result of the spreading is to diminish the angles at which the pulls of B and C are inclined to the surface, and hence their effective opposition to A will be increased. Moreover, the spreading of the liquid diminishes the surface tension of the water—that is, weakens A—and hence it becomes possible for B and C to prevail and draw back the surface of the globule which A had previously stretched. If, in spite of these disabilities, A should still be the stronger, the globule will be stretched until it covers the whole surface; whereas if B and C overcome A, the globule will shrink, increasing the angles at which B and C operate, and therefore reducing their effective pulls, until their combined strength is equal to that of A, when the globule will remain at rest. Bearing these facts in mind, we can understand why a small drop of oil placed on a clean water surface spreads across; for in this case A is stronger than B and C combined. But when the surface of the water is covered with a layer of oil, A is weakened, and can no longer overcome the opposing pulls of B [63] and C. Hence a further drop of oil poured on to the surface remains in the form of a globule.

Movements due to Solubility.—When small fragments of camphor are placed on the surface of water some remarkable movements are seen.[3] The bits of camphor move about with great rapidity over the surface, and generally, in addition, show a rapid rotary motion. The explanation usually given is that the camphor dissolves in the water at the points of contact forming a solution which possesses a less surface tension than pure water. This solution is in consequence stretched by the tension of the rest of the surface, and the camphor floating on its solution is therefore made to move in the direction of the line along which the stretching force happens to be the greatest. But the camphor continues to dissolve wherever it goes, and is therefore continuously pulled about as a result of this interplay of tensions. Touching the surface with a wire which has been dipped in oil immediately arrests the movements, owing to the tension of the water being diminished to such an extent by the skin of oil that it is no longer competent to stretch the part on which the camphor floats. No doubt this explanation is correct so far as it goes, but it is highly probable that when the floating substance dissolves, other forces are called into action in addition to the tensions.

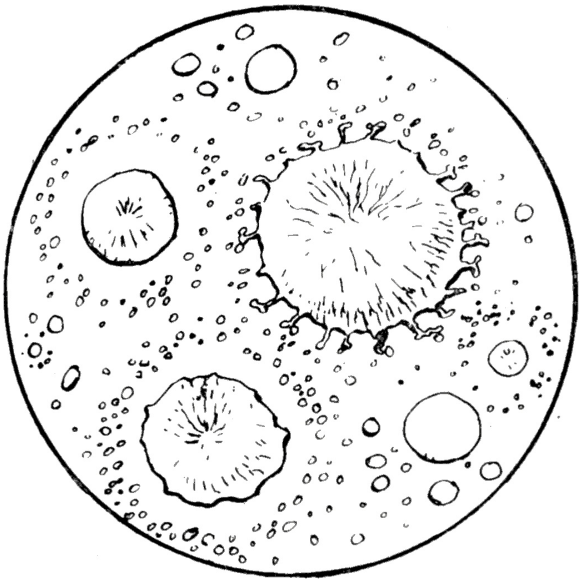


Fig. 36.—Aniline globules on a water surface.

Movements of Aniline Globules on a Water Surface.—If we allow a small quantity of aniline to run on to the surface of water, it forms itself into a number of floating globules. I now project [64] on the screen a water surface on which a little aniline has been poured, and we are thus enabled to watch the movements which occur. All the globules appear to be twitching or shuddering; and if you observe closely you will notice the surface of each globule stretching and recoiling alternately. The recoil is accompanied by the projection of tiny globules from the rim, which becomes scalloped when the globule is stretched. The small globules thrown off appear to be formed from the protuberances at the edge (Fig. 36), and after leaving the main globule they spread out over the surface, or dissolve. This process continues for a long time, gradually diminishing in vigour, until small stationary globules are left floating on the surface, which is now [65] covered with a skin of aniline. This action is in striking contrast to the tranquil formation of floating globules of oil, and calls for some special comment.

Let us recall again the three forces at work at the edge of a floating globule (Fig. 35). The surface tension of the water, acting horizontally, tends to stretch the globule, and is successful momentarily in overcoming the opposing tensions, each of which pulls at an angle to the surface. Enlargement of the upper surface of the globule, however, reduces the angles at which the tensions B and C act, and in consequence their effective strength is increased. The spreading of the aniline over the water surface diminishes the pull A, which B and C combined now overcome, and hence the surface of the globule shrinks again. For some unexplained reason both the stretching and recoil of the globule occur suddenly, there being an interval of repose between each, and these jerky movements result in small portions of the rim being detached, each of which forms a separate small globule. The aniline which spreads over the surface of the water dissolves, and the water tension A, which had been enfeebled by the presence of the aniline skin, recovers its former strength, and again stretches the globule; and so the whole process is repeated. When the surface of the water becomes permanently covered with a skin, which occurs when the top layer is saturated with aniline, the globule remains at rest, and has such a shape that the tensions B and C act at angles which enable them just to balance the weakened pull of A. Why the edge of the globule becomes indented during the movements, and why these movements [66] are spasmodic instead of gradual, has not been clearly made out. It is interesting to recall that a spheroid of liquid on a hot plate also possesses a scalloped edge, and it may be that the two phenomena have something in common.

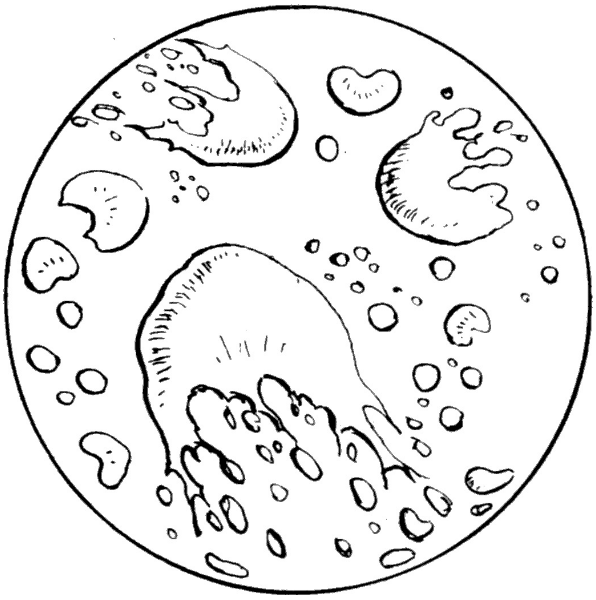


Fig. 37.—Orthotoluidine globules on a water surface.

Movements of Orthotoluidine and Xylidine 1-3-4 on a Water Surface.—We will now observe, by the aid of the lantern, movements of globules more striking, and certainly more puzzling, than those of aniline. I place on the surface of the water a quantity of a special sample of orthotoluidine, and you see that immediately a number of globules are formed which are endowed with remarkable activity. They become indented at one side, and then dart across the surface at a great speed, usually breaking into two as a result of the violent action (Fig. 37). Then [67] follows a short period of rest, when suddenly, as if in response to a signal, all the larger globules again become indented, forming shapes like kidneys, and again shoot across the surface, breaking up into smaller globules. Notice that the very small globules remain at rest; it is only those above a certain size that display this remarkable activity. A film of the liquid forms on the water, and the action gradually becomes more intermittent, ceasing altogether when a skin is well established, and the large globules have sub-divided into very small ones. My sample of orthotoluidine is somewhat unique, as other specimens of the liquid, obtained from the same and other sources, do not show the same lively characteristics. As in the case of camphor, touching the surface with a drop of oil arrests the movements immediately. The organic liquid *xylidine* 1-3-4, however, exhibits the same movements, as you now see on the screen; and, if anything, is even more active than the orthotoluidine previously shown. It may be added that occasional samples of aniline show similar movements, but of less intensity.

Now if I am asked to explain these extraordinary movements, I am bound to confess my inability to do so at present. Why should the globules become indented on one side only? The two tensions acting at the edge in opposition to the water tension are at work all round the globule, and it is not easy to see why they should prevail to such a marked degree at one spot only. The movement across the surface, if we followed our previous explanations, would be due to the superior pull of the water tension behind the globule, opposite the indented part; although to look at it would [68] seem as if some single force produced the indentation and pushed the globule along bodily. Are there local weaknesses in the tension of the water, and, if so, why should such weak spots form simultaneously near each globule, causing each to move at the same moment? Any explanation we may give as to the origin of the cavity in the side of the globule does not suffice to account for the intermittent character of the movement, and its simultaneous occurrence over the whole surface. We must therefore leave the problem at present, and trust to future investigation to provide a solution.

FIG. 38.—Resolution of a floating skin into globules.

Production of Globules from Films.—When a film of oil spreads over a water surface it sometimes remains as such indefinitely. Certain other liquids, however, form films which after a [69] short interval break up into globules, and the process of transition is at once striking and beautiful. In order to show it, I project a water surface on the screen, and pour on to it a very small quantity of *dimethyl-aniline*—an oily liquid related to but distinct from ordinary aniline. It spreads out into a film of irregular outline, which floats quietly for a short time. Soon, however, indentations are formed at the edges, which penetrate the film, and from the sides of the indentations branches spread which in turn become branched; and shortly the whole film becomes ramified, resembling a mass of coral, or, to use a more homely illustration, a jig-saw puzzle (Fig. 38). The various branches join in numerous places, cutting off small islands from the film; and immediately each island becomes circular in outline—and the resolution into globules is complete. We have witnessed one of the beauty-sights of Nature.

The same method of globule formation is shown by nitro-benzol and *quinoline*, and as the action is more gradual in the case of the latter substance, I show it in order that we may study the process in greater detail. Notice the formation of the indentations and their subsequent branching; and also that holes form in the skin from which branchings also proceed. In this instance the film is broken up in sections, but the action continues until nothing but globules remain on the surface.[4]

It is not easy to see why the canals of water penetrate the film and split it up into small sections,

[70] nor why entry takes place at certain points on the edge in preference to others. Some orderly interplay of forces, not yet properly understood, gives rise to the action; and a satisfactory explanation has yet to be given.

Network formed from a Film.—A further example of the breaking up of a film is furnished by certain oils derived from coal-tar, the result in this case being the formation of a network or cellular structure. I place on the surface of water in a glass dish a small quantity of tar-oil, and project it on the screen. It spreads out at first into a thin film, which, by reflected light, shows a gorgeous display of colours. After a short time, little holes make an appearance in the film, and these holes gradually increase in size until the whole of the film is honeycombed (Fig. 39), the oil having been heaped up into the walls which divide the separate compartments. Here again the accepted views on surface tension do not appear competent to explain the action. It appears to be [71] the case that most films on the surface of water show this tendency to perforation, which may be due to inequalities in the thickness of the film, or in the distribution of the strain to which it is subjected.[5]

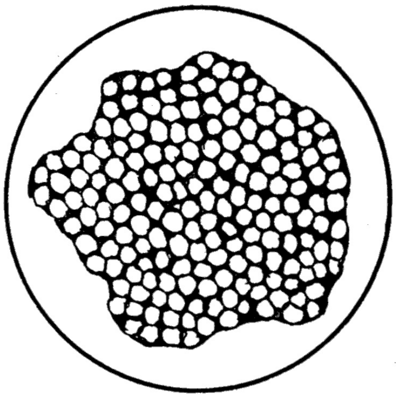


Fig. 39.—Network formed from a film of tar-oil on the surface of water.

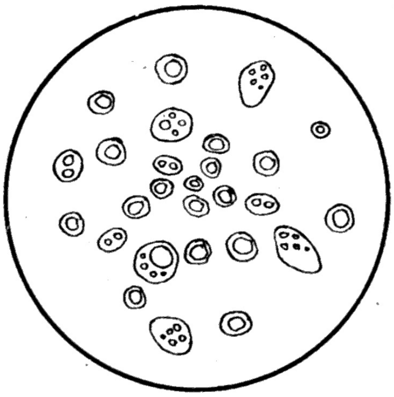


Fig. 40.—Quinoline rings and perforated plates.

Quinoline Rings.—Reference has already been made to the breaking-up of a quinoline film into globules. But if we examine the surface about half an hour after the formation of these globules, we find that each has been perforated in the centre, forming a ring or annulus (Fig. 40). Some of the larger globules have undergone perforation in several places, forming honeycombed plates. These rings and plates, which you now see projected on the screen, remain unchanged, and apparently represent the final stage of equilibrium under the action of the various forces. Quinoline, so far as observations have been made, appears to be unique in respect to the formation of stable rings from globules.

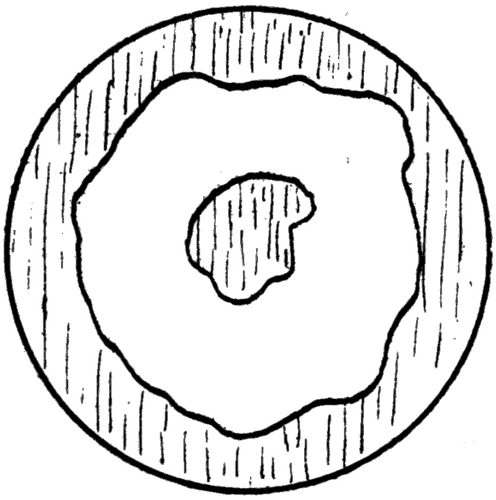


Fig. 41.—The expanding globule.

[72] **Expanding Globules.**—I now wish to show, by an experiment, how sensitive a floating globule is to disturbances in the existing tensions, which maintain it at rest. On the screen is projected a globule of dimethyl-aniline, floating tranquilly on the surface of water. I now allow a small drop of quinoline to fall upon it, and immediately it spreads out over the surface, forming a hole in its centre (Fig. 41), after which it gradually resumes its former shape. Sometimes the action is so violent that the globule is split up into several portions, which, however, join together again after a short time. In order to explain this action, we must again refer to the three tensions operating on the globule (Fig. 35). When in equilibrium, A is balanced by the joint pull of B and C; and hence if either of the latter be weakened, A will predominate and stretch the globule. In our experiment it is the interfacial tension, C, which has been diminished in strength, as we may now [73] prove by a second experiment. In this instance I float on the water surface a globule of lubricating oil, with which quinoline does not readily mix, and which does not act so immediately as dimethyl-aniline. On allowing the drop of quinoline to fall into it, no action is observed until the drop has rested on the junction of the oil and water for a short time; but when it has penetrated the interface the oil globule suddenly spreads over the water surface, and with such violence as to detach several portions from the main globule. Merely touching the upper surface of the oil with a rod moistened with quinoline has no effect, and hence the result is due to the weakening of the interfacial tension. A similar effect is obtained when quinoline is dropped into a globule of aniline, and may be obtained with various other liquids.

Attraction between Floating Globules.—The "Devouring" Globule. When globules of different liquids are floating on the same water surface, a tendency to coalesce is sometimes noticed, but is by no means general. I will show one example which possesses striking features, showing as it does the remarkable results which may be brought about by surface forces. First of all, we form a number of active orthotoluidine globules on the surface of a dish of water, which you see wriggling about in their characteristic fashion. After their activity has subsided somewhat, I float on to the surface a large globule of dimethyl-aniline. Attraction of some kind is at once apparent, for the nearest globule of orthotoluidine immediately approaches the intruder. And now comes the process of absorption. The large globule of dimethyl-aniline develops a [74] protuberance in the direction of its victim (Figs. 42 and 43), and the small globule of orthotoluidine coalesces with this "feeler," which then shrinks back into the large globule, conveying with it the entangled orthotoluidine. This, however, by no means satisfies the devouring globule, as a second victim is at once appropriated in the same manner; and you will notice a nibbling process at work round the edges continuously, which is due to the absorption of the smaller globules of orthotoluidine. The action continues until the whole of the surface has been cleared of orthotoluidine, after which the large globule floats tranquilly in the centre of the [75] vessel, apparently resting after its heavy meal. The interaction of the forces which gives rise to this phenomenon is difficult to fathom; there are no doubt several tensions, constantly changing in magnitude, which in the result cause the liquids of the large and small globules to intermingle. Separate globules of a single liquid sometimes unite in this manner, but this is not common, it being more usual for the scattered units to remain apart.

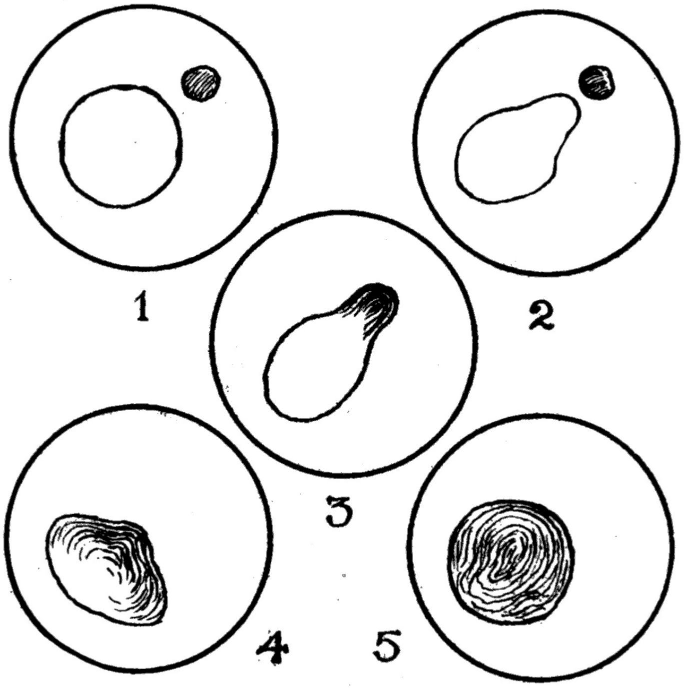


Fig. 42.—The "devouring" globule. Five stages.

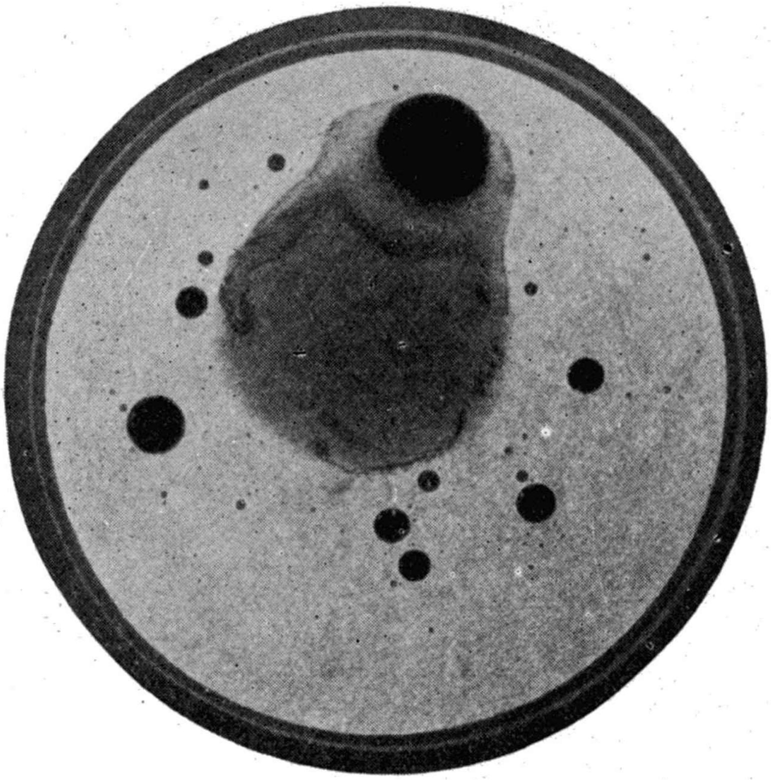


Fig. 43.—Photograph of one globule absorbing another.

Analogies of Surface Tension Phenomena with Life.—When we watch the movements of globules on the surface of water, the resemblance to the antics of the lower forms of life immediately occurs to our minds. Now I do not intend here to intrude any opinion on the much-discussed subject of the Origin of Life, but merely to point out that certain phenomena, usually supposed to be associated only with living things, may result from the interplay of surface tensions. In our experiments we have witnessed expansive and contractile motion (aniline globules on water); movement of translation, of a very vigorous kind (xylidine and orthotoluidine globules); incorporation of external matter, or feeding (dimethyl-aniline absorbing orthotoluidine)—we are getting quite familiar with these long names now—, splitting up of masses, or division (skins of quinoline, etc., breaking up into branched portions, and sub-division of large globules); and formation of cellular structure (tar-oil on water). And the conclusion we may legitimately draw is this: that mechanical forces may account for many observed phenomena in connexion with life which formerly were attributed to the action of “vital” forces. Modern biological research all points in the same direction, and it seems probable that the operations of the animate and inanimate are controlled by the same forces. But the mystery of Life still remains.

Conclusion.—I have endeavoured in these lectures to bring to your notice some of the remarkable results which may be produced by the use of water and a few other liquids, and the scientific conclusions which may be drawn from them. It may be that the phenomena we have considered have little or no commercial application; but science has other uses in addition to its fruitful alliance with commerce. The study of the methods by which Nature achieves her ends stimulates the imagination and quickens the perceptions, and is therefore of the highest educational value. It is a great scientific achievement to run a railway to the summit of the Jungfrau, but we should not envy the mental condition of the individual to whom that glorious mountain appealed only through the railway dividends. And I trust that we shall never become so imbued with the industrial aspects of science, as to lessen our appreciation of the works of Nature, whether manifested in the snow-clad peak or the equally wonderful drop of water.

[78]

APPENDIX

Apparatus and Materials required for Experiments on Drops and Globules.

Vessels.—For direct observation of liquid spheres, large drops, etc., beakers about 6 inches in height and 4 inches in diameter are suitable. It must be remembered, however, that a beaker containing water behaves like a cylindrical lens, and hence objects in the interior appear distorted in shape. In order to observe the true dimensions, flat-sided vessels must be used, in which the faces are of uniform thickness. Glass battery-vessels, which are made of a single piece of glass, have sides of irregular thickness, and are not to be recommended. A useful form of vessel is one in which the bottom and edges are made of copper, the sides being formed of windows of plate glass cemented to the copper framework. Water may be boiled in such a vessel without danger to the glass, starting with cold water; it is not advisable to pour hot water into the cold vessel, however, as the glass may crack. Suitable dimensions for a vessel of this kind are 6 inches high, and 4 inches in width and thickness. A beaker containing water, in which drops are formed may be placed in this square vessel, and surrounded by water, when distortion will be absent; and the whole of the contents may be kept hot—as required, for example, with the [79] automatic aniline drop. It is best to conduct the experiments in beakers immersed as described, as the materials used may then be easily recovered without having to clean out the flat vessel.

For the formation of liquid columns, test-tubes, of diameter 1 to 2 inches, or small beakers, may be used. Test-tubes provided with a foot, which will stand upright, are most satisfactory; and the true shape may be seen by immersing the test-tube or beaker in water in a flat-sided vessel of the form described above. The effect of heat on the shape of the column may be observed by warming the water in the vessel. The centrifugoscope (Fig. 7) and the apparatus depicted in Figs. 8, 13, and 32, may be procured from the makers, Messrs. A. Gallenkamp & Co., Sun Street, E.C.

Experiments with skins and globules may be conducted in beakers of about 4 inches diameter, or in small porcelain photographic dishes. If intended for lantern projection shallow cells, with a bottom of plate glass, are necessary, and may be obtained from dealers in scientific apparatus.

Materials.—Sufficient quantities of the various liquids used may be procured from dealers in chemicals at a small cost. Aniline and orthotoluidine, which figure largely in the experiments, should be obtained in the “commercial” form, which is the cheapest and most suitable. The remaining liquids should be of the variety described as “pure” in the catalogues. When used for the formation of films, they should be kept in bottles in which the glass stopper is prolonged into a tapered rod, which dips into the liquid, and which, on removal, carries a convenient quantity of liquid to drop on to the water surface.

[80] Accessories such as glass rods, plates, tubing of various diameters, thin copper wire, and an aluminium plate for the spheroidal state, can be obtained from any dealer in apparatus; and the same applies to clamp-stands for holding funnels, etc.

Water.—Ordinary tap-water suffices for all the experiments described, and for work with films and globules is superior to distilled water, which often possesses a surface so greasy as to retard or even entirely prevent the desired result. All experiments conducted on the surface of water should be performed in a clean vessel which has been rinsed out several times with tap-water before filling.

Lantern Projection.—In demonstrating the phenomena to an audience, a lantern may be used to advantage. It should be of the type now procurable, which is arranged for the projection of experiments conducted either in a horizontal or vertical position, by the use of the electric arc or other suitable source of light. Flat-sided vessels are essential for the successful projection of views of objects in a vertical position; and for showing globules, etc., on the surface of water, better definition is secured if cells with plate-glass bottoms are used instead of vessels made of a single piece of glass. The author has generally used a “Kershaw” lantern for lecture purposes, with quite satisfactory results. This lantern may also be adapted for projecting solid objects by reflected light—as, for example, a hot plate on which a spheroid of water is floating (Fig. 34). The contrivance known as the “Mirrorscope” may also be used, with slight modification, for producing a magnified image of solid objects on the screen.

[81]

INDEX

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Footnotes

[1] Mono-brom-benzene is better than chloroform for this experiment, but is more costly. It may be coloured with indigo. Chloroform may be coloured with iodine.

[2] Mr. C. T. R. Wilson has recently devised an apparatus for making visible the tracks of ionizing rays, by the condensation of water vapour round the freshly liberated ions.

[3] These movements were first recorded by Romieu in 1748 and were ascribed by him to electricity.

[4] The breaking-up of films on the surface of water was first noticed by Tomlinson about 50 years ago. He used essential oils, and called the patterns “cohesion figures.”

[5] An interesting discussion on cellular structures of this type may be found in *Nature*, April 16 to June 11, 1914.

Transcription note

The following minor typographical flaws have been corrected:

- Fig. 7: *missing period at the end of the caption*
- “feeler,”’ *unnecessary additional closing quote*
- **Index:** Drops of liquid, shapes of, 10, 29, 30, 31 *missing commas*
- **Index:** Mono-brom-benzene *added hyphen to conform with reference in text*

Footnotes have been renumbered progressively throughout the book.

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