of the area is built upon, the remainder being streets and open spaces.

THE Paris Geographical Society has awarded the grand prize for geographical research to M. Maistre, for his great journey from the Congo to the Shari.

FLAME.[1]

THE subject on which I have the honour to address you this evening is, I am aware, one of the most hackneyed among the topics that have served for popular scientific lectures. I can only hope that it has not quite lost its charm. The chemist is often twitted with having to deal with mere dead soulless things, which at the best only set themselves into angular and unpalpitating crystals. There may be a certain amount of truth in this, but in flames we surely have phenomena of some liveliness. Our flame must be fed ; it has its anatomy and varied symmetry ; it is vigorous, mobile, and fleeting. I do not wish to make extravagant claims, but I do think that one may be excused for feeling almost as much interest in the study of flame as, for example, in the contemplation of the somewhat torpid evolutions of an amœba or the circulation of water in a sponge. To our guileless ancestors, at any rate, flame was a phenomenon of the rarest mystery ; unable as they were to discriminate between the material and the immaterial, unable to track the solid or liquid fuel to its gaseous end, this radiant nothingness called flame became to them one of the primary inscrutable, irresolvable things of Nature—an all-devouring element, often of peculiarly divine significance.

The essential nature of flame appears to have been discovered at the beginning of the seventeenth century by the Belgian, Van Helmont. This remarkable man is well known to chemists as one of the acutest and least superstitious of the whole band of alchemists. He was somewhat speculative in the domain of physiology, but in chemistry Van Helmont made discoveries of fundamental importance. From our immediate point of view, one of the most important things he did was to sweep away the mystery that had so long attached to the gaseous state of matter. In so far as he distinguished between different gases obtained from different sources, he may be said to have been the first to bring aëriform matter within the range of substantial things that might be submitted to experimental investigation. It was in consequence of this that he was led to the discovery of the nature of flame. I will quote the important passage from his writings.

" But the flame itself, which is nothing but a kindled smoke, being enclosed in a glass in the very instant perisheth into nothing.

" The flame indeed is the kindled and enlightened smoke of a fat exhalation ; be it so ; but as the flame is such and true fire it is not another matter, being kindled and not yet kindled, neither doth it differ from itself ; but that light being united in its centre, hath come upon a fat exhalation which is the same as to be inflamed.

" Let two candles be placed which have first burned awhile, one indeed being lower than the other by a span ; but let the other be of a little crooked situation ; then let the flame of the lower candle be blown out ; whose smoke, as soon as it shall touch the flame of the upper candle, behold the ascending smoke is enlightened, is burnt up into a smoky or sooty gas, and the flame descendeth by the smoke even unto the smoking candle. Surely there is there, the producing of a new being, to wit, of fire, of a flame, or of a connexed light ; yet there is not a procreation of some new matter or substance.

" For the fire is a positive artificial death but not a privative one, being more than an accident and less than a substance."

We can best understand the meaning of this somewhat oracular statement by repeating Van Helmont's experiment. We take a bundle of lighted tapers so as to get a large flame, we hold over " in a little crooked situation " another lighted taper, and now blow out the lower flame. We note the ascending column of smoke, and observe that when it touches the upper flame it ignites, and the flame descends several inches through the smoke to the bundle of tapers. Flame therefore, says Van Helmont, is burning smoke ; it is not a new substance nor a mere chance occurrence, but the incandescence of a vapour or smoke that already existed.

Van Helmont only recognised in a vague way the important part played by the atmosphere in the phenomenon. This was

realised much more perfectly soon afterwards by Hooke, who speaks of "that transient shining body which we call flame", as " nothing but a mixture of air and volatile sulphureous parts of dissoluble or combustible bodies which are acting upon each other whilst they ascend," an action so violent, he says, " that it imparts such a motion or pulse to the diaphanous parts of the air " as was requisite to produce light.

Without entering further into early historical details I may say that it was only towards the end of last century that the essential chemistry of the phenomenon was fully expounded by the great Lavoisier. He showed that, as Hooke had surmised, flame is the region in which combination attended by the evolution of light takes place between the components of a gaseous substance and the oxygen of the air.

The next step in the history of our knowledge of flame brings us to the memorable researches of Humphry Davy, whose name more than that of any other man is associated with this subject. Of Davy's work I shall have more to say presently ; but at this moment I will only make one allusion to it, an allusion which will provide us with a proper starting-point this evening. It is interesting to note that Davy's discoveries concerning flame were the consequence and not the cause of the discovery of the miners' safety-lamp. In this case practical application preceded purely scientific discovery.

I need not describe the safety-lamp to you in Nottingham, where it has recently received such important improvements at the hands of Prof. Clowes. When the lamp is placed in an explosive mixture, you know what happens—the explosive mixture burns with a quiet flame within the lamp, but the flame cannot pass through the wire gauze to ignite the mixture outside the lamp. I can demonstrate this by means of this large gas-burner, which is primarily a Bunsen burner, that is, a burner which by means of holes at the base of the tube draws in sufficient air to enable the gas to burn with a practically non-luminous flame. If I turn on the gas and apply a light to the top of the burner, you observe that I get a flash and a small explosion within the tube, but no continuous flame. The fact is that the mixture of gas and air within the tube is highly explosive. Placing a gauze cap over the burner and applying a light, I now get a steady flame. The explosive mixture made in the tube passes through the gauze and is inflamed, or, if you like, exploded ; but the explosion cannot pass through the gauze, because the metallic wires withdraw the heat so rapidly that the mixture below it never reaches the temperature of ignition. Above the gauze we have the continuous flame.

" These results are best explained," says Davy, " by considering the nature of the flame of combustible bodies, which in all cases must be considered as the combination of an *explosive mixture* of inflammable gas or vapour and air ; for it cannot be regarded as a mere combustion at the surface of contact of the inflammable matter."

Davy, then, regarded flame as being essentially the same as explosion ; it was, in fact, a kind of tethered explosion.

Since Davy's time we have learned much about the nature of gaseous explosions, and we now know that such explosions, when fully developed, proceed with enormous rapidity and are of great violence, incapable of arrest by such simple means as we have just used. Still there is not much to correct in what I have said. I think I cannot do better than show you the transition of flame into explosion by an experiment which was first shown by Prof. Dixon in the lecture which he gave at the meeting of the British Association in Manchester in 1887.

The apparatus before you consists simply of a Bunsen burner surmounted by a long glass tube. If I turn the gas on and light it I obtain at the top of the glass tube a steady flame. The mixture ascending the tube can scarcely be called explosive at present, but if I alter the proportions of gas and air suitably it becomes distinctly explosive. Observe what happens when this is the case. The flame can no longer keep at the top of the glass tube ; it passes within it, and descends with uniform velocity till at a certain point it flickers and then shoots down almost instantaneously to the bottom. This sequence of events is exhibited in all cases when flame develops into explosion. We are concerned only with the first phase, viz. that of comparatively slow inflammation and a flame, we may say, is a gaseous explosion brought to anchor in the period of incubation.

There is one other point connected with explosion that we must note on account of its important bearing on the chemistry of flame. When we are dealing with explosive mixtures of gas and air, we find practically that the composition of the

mixture may vary considerably and still retain its explosive properties. There is, of course, a certain mixture which presents the greatest explosive power ; a further quantity of the combustible gas or of the air will diminish the explosibility, but not entirely destroy it till a large excess is used. With hydrogen, for example, two and a half times the volume of air (which contains exactly the oxygen requisite to combine with the hydrogen and produce water) is the right quantity for the maximum explosive effect, but we still get explosion when we have much more than two and a half times as much air as hydrogen, or when, on the other hand, we have much less. In one case there will be oxygen left uncombined, in the other case hydrogen. I dwell upon this in order that we may be prepared to find the same thing in flames, in order that we may not be surprised to find combustion taking place in mixtures where either gas or air is in excess of the quantity actually required for the purpose of chemical combination. Bearing this in mind, let us revert to the experiment that I have just shown. It consists, you remember, in mixing air with gas before burning it, to such an extent that the flame strikes down the tube. On a close examination we find that this is not quite a correct statement, for when I regulate the air with nicety you see that it is only part of the flame that strikes down the tube. There remains all the while at the top of the tube another part of the flame which is not mobile. With a little care I can adjust the proportion of air and gas so that the part of the flame which is mobile shall move up and down the tube like a piston. All the while you see the pale steady flame at the top of the tube. When in this critical condition a little more air determines the descent of the movable part of the flame, a little less sends it to the top.

Let us now turn to the explanation of this phenomenon. It is clear, in the first place, that coal-gas and air form an explosive mixture long before there is enough air to burn all the gas. For it is only part of the flame that descends the tube, and there is enough gas passing through this part to form a second flame as soon as it reaches the outside air at the top of the tube. There is, as a matter of fact, only about two-thirds as much air entering the tube at the bottom as would be necessary to burn the whole quantity of gas. We see, in the next place, that the explosibility varies greatly according to the proportions of gas and air. For what is the cause of the descending flame? It is simply that we have an explosive mixture in process of inflammation. The inflammation is tending downwards ; opposed to it is the movement of the explosive mixture upwards. If the upward movement of the unburned mixture is more rapid than the downward tendency of the inflammation, the flame cannot descend. We can only make it descend by making the downward tendency greater. This we do by adding more air, and making the mixture more explosive. We see that we can balance these two opposite velocities with the greatest nicety by a careful adjustment of the proportions of the explosive mixture.

In order to ascertain what proportion of gas is being burnt in this movable flame, and what is the chemical character of the products there formed, it is necessary to keep the two parts of the flame separate, and to take out some of the gases from the intervening space.

This is very easily done. The flame descends, we have seen, because its rate of inflammation is greater than the rate of ascent of the combustible mixture. If now we can make this rate of ascent more rapid at one part of the tube than it is anywhere else, we may expect to stop the descent of the flame at that point and keep it there. We can do this simply by choking the passage, for just as a river must flow rapidly where its banks are close, so must the stream of gas rush more rapidly where the tube is choked than either below or above, where there is a wide passage. If, then, I replace the plain glass tube by one that has a constriction in one part, and if I cause the inner cone of the flame to descend as before, it stops, as you see, at the constriction, and will remain there any length of time. Its rate of descent is greater than the rate of ascent of the gas where the tube is wide, but not so great as that where it is narrowed by the constriction. We have now got the two cones of flame widely separated. In this state of things we can, if we choose, draw off the gases from the space between the two cones by putting in a bent glass tube and aspirating. We could then analyse these gases and see what has happened in the first cone. (Fig. I, A.)

I will now show you another method in which the two cones can be separated. It is based on the same principles as the one just used. I have here a two-coned flame burning at the top of a glass tube. I shall let the air supply be liberal, but not quite sufficient to cause the descent of the inner cone. The rate of ascent of the gas is now just a trifle greater than the rate of descent of the flame. If now I retard the rate of ascent of the gas, the balance will be disturbed and the inner cone will descend. I can easily do this by laying an obstacle *along* the stream of gas, for at the end of it there will be no more current than you would find over the stern of a boat anchored in mid stream. I take this obstacle, then, in the form of a glass rod fixed centrally along the current of gas ; I push it up until it touches the tip of the inner cone, and then pull it down again. You observe what has happened. The cone has followed the rod into the tube, and remains attached to it. You will notice, too, that the cone is inverted. That is easily understood. It is only at the tip of the rod that the current is slowed down ; there only is the rate of ascent of the stream less than the rate of inflammation. The tendency in every other part of the stream is for the cone to go to the top ; hence the inversion. (Fig. I, B.)
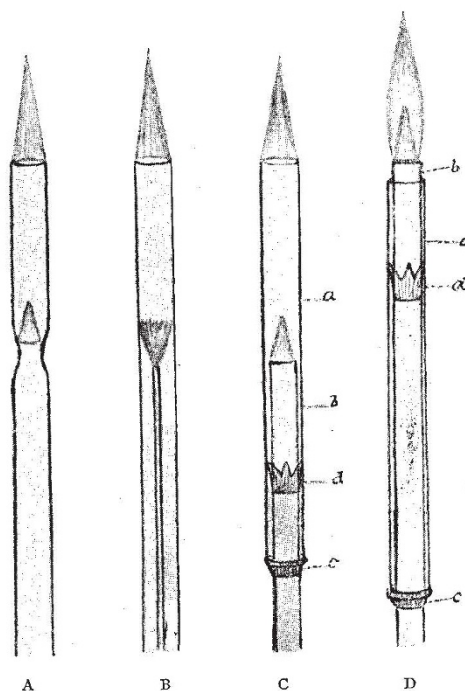

FIG. 1.—Methods of separating the two cones of an air coal-gas flame.

We can get a still more convenient apparatus by a modification of the first method. Instead of choking the bore of the single tube by a constriction, we may use two tubes of different diameter, one sliding within the other. This apparatus is shown in Fig. I, C ; *a* is the wider tube, *b* the narrower one. The two tubes are connected by an india-rubber collar (*c*), and kept steady by the brass guide (*d*). The outer tube can be slid up and down the inner one as desired. If we place this apparatus over a Bunsen burner and turn on the gas, we shall have a tolerably rapid upward current in the inner tube, but as soon as the gas emerges into the wider one its velocity will of course diminish. The consequence is that if we now light the gas and gradually increase the air supply, the inner cone will descend until it reaches the orifice of the narrower tube ; but at that point, meeting with the rapid stream, its progress is arrested, and it remains perched on the end of the tube. By sliding the tubes we can thus separate the cones any desired distance, or we can bring their orifices level and restore the original flame. Lastly, we can reverse the experiment, for we can begin with a two-coned flame burning at the protruding end of the narrower tube, and by sliding up the wider tube detach the outer cone and carry it upwards. (Fig. I, D.)

Having now learnt the relation of flame to explosion, having

discovered that flames have separable regions of combustion, and having armed ourselves with an appliance for dissecting the flame, we may proceed to discuss the main question.

I do not intend this evening to enter seriously into chemical details, but there are one or two simple points to which I must draw your attention. Flame, we see, is a region in which chemical changes are taking place with the evolution of light. It is to be expected, therefore, that the character of a flame, its structure and appearance, will vary according to the chemical changes that give it birth ; and we should naturally anticipate that the more complex the chemical changes the more complex would be the flame. The kind of complexity to which I refer is illustrated by the diagram.

| Name | Composition | Products | |
		Partial Combustion	Complete Combustion
Hydrogen		water	water
Carbon monoxide	carbon and oxygen	carbon dioxide	carbon dioxide
Carbon		carbo monoxide	carbon dioxide
Cyanogen	carbon and nitrogen	carbon monoxide and nitrogen	carbon dioxide and nitrogen
Hydrogen sulphide	hydrogen & sulphur	(?)	water and sulphur dioxide
Hydrocarbons	hydrogen & carbon	carbon monoxide carbon dioxide hydrogen & water	carbon dioxide and water

In the first column are the names of five combustibles ; their chemical composition is stated in the second column. All these substances in burning combine with the oxygen of the air. The case of hydrogen is the simplest. This gas, when it burns, unites with half its volume of oxygen, and forms steam. The process is incapable of any complication. We might predict, therefore, a very simple structure for a hydrogen flame. The same is true for the next gas carbon monoxide, which, although a compound, unites at once with its full supply of oxygen and burns, forming carbon dioxide. The third combustible, carbon, presents a new feature ; in burning it can combine with oxygen in two stages, forming in the first instance carbon monoxide, which, as we have just seen, can itself combine with more oxygen to form carbon dioxide. We cannot vaporise carbon and use it as a gas, so that we shall not actually deal with this example. But the next combustible on the list, cyanogen, will serve almost as well, for it is a compound of carbon with nitrogen, and nitrogen is, under ordinary circumstances, practically incombustible. To use cyanogen is thus much the same as to use carbon vapour. We may expect some complexity in the cyanogen flame in consequence of the fact that carbon can burn in two steps. The next combustible, hydrogen sulphide, presents a further degree of complexity. It is composed of two elements, each of which is combustible on its own account. Lastly, we come to the great class of hydrocarbons, which includes all ordinary combustibles, oil, tallow, wax, petroleum, and coal-gas. The carbon and hydrogen are both separately combustible elements, and one of them—carbon—is, as we have seen, combustible in two steps.

We will now consider the problem in its simplest aspect. For this purpose I choose the gas carbon monoxide. I should choose hydrogen were it not for the fact that its flame is almost invisible. We will allow a stream of carbon monoxide to issue from the circular orifice of this glass tube. Lighting the gas we get a blue flame. On examining this flame closely we perceive that it is simply a hollow conical sheath of pretty uniform character. I need scarcely demonstrate that it is hollow, but I may do so in a moment by using Prof. Thorpe's simple device of thrusting a match-head into the centre of the flame—a pin passing through the stick of the match, and its ends resting on the tube. The match-head is now thrust well up inside the flame, and you observe that it remains there sufficiently long without burning, to make it quite clear that there is no combustion within the cone. The conical form of the flame is easily explained. As the stream of gas issues from the tube the outside portions become mixed with the air and burn. The inner layers must successively travel further upwards, like the successive tubes of a telescope, before they can get enough air to burn, and in this way we arrive at the conical form.

There still remains one thing to account for, and that is the luminosity and colour of the flame. The questions here involved are perhaps the most interesting of all, but they are complicated, and I will not say more than a few words about them. The most obvious answer to the question, "Why is the flame luminous ?" is to say that the heat developed during the chemical

combination raises the product of combustion to a temperature at which it glows—a "blue heat" in the present case. Now if we put a thermometric instrument into the carbonic oxide flame, it does not register at any point as high a temperature as 1500° C., but if we take carbon dioxide and heat it in a tube by external heating to 1500° C. we get no signs of luminosity whatever. On these grounds several eminent investigators have been led to abandon the simple explanation above given, and to say that the luminosity of a carbon monoxide flame must depend not on the heat of chemical combination, but on something in the nature of electrical discharges between the combining substances, which discharges produce the disturbances of the ether perceptible as light. This view seems to be fraught with a fundamental error. The temperature registered by any instrument introduced into a flame is an *average* temperature, uncorrected for losses by conduction. It is not the temperature of the newly-formed gas, but of the mixture of that and the unburned gases. If we had a very small instrument which we could apply to the particles of newly-formed gas, we should undoubtedly find them at a very much higher temperature than any indicated by the ordinary thermometric apparatus, and it is not unlikely that the temperature would be several thousand degrees, approximating indeed to the temperature at which we arrive by calculation from the heat of combustion of the gas and the heat capacity of the product. We cannot say that the flame is luminous from some other cause than simple hotness, for we have no means of seeing whether carbonic acid glows when raised by external heating to a temperature of several thousand degrees.

At the same time one cannot help remarking on the similarity between such a flame as that of carbon monoxide and the appearance presented by an attenuated gas when submitted to the
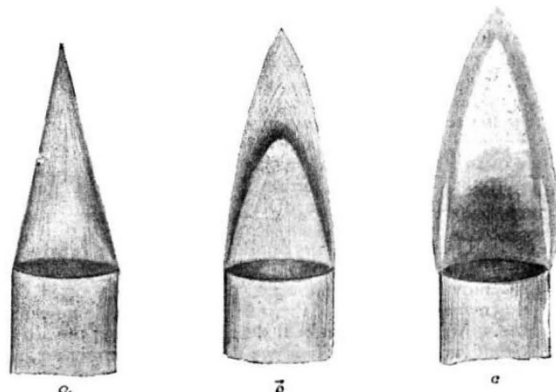

FIG. 2.—Typical Flames. (*a*) Carbon monoxide, single coned ; (*b*) Cyanogen, two coned ; (*c*) Small coal-gas flame.

electrical discharge in a Geissler tube. I have here such a tube, containing carbon dioxide, and I have placed a mask over it, so that we see a long triangular piece of it. When I pass the discharge you see it lights up and presents an appearance strikingly like that of our conical flame of carbon monoxide. There may be a close relationship between the phenomena, but we cannot affirm it yet. No doubt we shall soon learn a good deal more about both phenomena.

We have now done with the simplest kind of flame. We see that it consists of a single conical sheath of combustion, at every point of which the same chemical change is taking place, and every point of which in consequence has the same appearance.

We pass to the cyanogen flame. This flame is one of remarkable beauty ; it consists, as you see, of two distinct parts : one a rose or peach-blossom coloured cone, surrounded by a paler cone, which is bright blue where it is near the inner cone, and shading off to a kind of greenish grey. What is the cause of this double structure ? It might be that part of the gas is burning round the orifice, the rest further out in the second cone ; but a similarity of the chemical processes in the two parts of the flame is here rendered improbable by the difference in colour. The only satisfactory way of answering the question is to separate the cones, and analyse the gases in the intervening space. This we can easily do in the cone-separating apparatus.

I now form the flame at the top of our cone-separating apparatus, and supply a certain amount of air along with the cyanogen. You observe the rose-coloured cone contracts somewhat. The gas burning there now gets its air supply easily, and has not to wander outwards. If I still further increase the air supply, and make the ascending mixture explosive, you see the inner cone begins to descend into the tube, and passes down until its progress is checked at the narrow tube, where the up-rush of gas is more rapid. We have now got the cyanogen flame dissected, and by taking out a sample of the gases from this interconal space and analysing it, we shall find what chemical change has taken place in the inner rose-coloured cone. The analysis shows that what takes place is the combustion of the carbon of the cyanogen to form carbon monoxide almost exclusively; the carbon monoxide then ascends, and when it meets with more oxygen in the outer air, burns in a second cone to form carbon dioxide.

Reverting then to the flame of the pure unmixed gas burning at the top of a tube, we see that the gas and air will interpenetrate. When there is just enough oxygen to burn the gas to carbon monoxide, we get the rose-coloured cone, and outside it, where this carbon monoxide gets more air, we have a second cone. The two-coned structure corresponds then to two chemical stages of combustion.

Now we might go further and anticipate that if we supplied a very large quantity of air to the cyanogen, as in a blowpipe, the two-coned structure would disappear, for the carbon should be burnt up at once to the ultimate product, carbon dioxide. We can easily try this. I will separate the two cones again in our apparatus, and increase the air supply still further. When I do so you observe that the second cone gradually fades away, and now the whole of the combustion is taking place at the end of the inner tube. Though this is so, the flame is not quite a simple cone. It is, as you see, surrounded by a greenish halo. This halo is due, I believe, as Prof. Dixon has suggested, to the fact that the nitrogen of the cyanogen is not, strictly speaking, incombustible. This has been proved by Mr. Crookes in his beautiful air flame, and besides, the greenish halo is frequently noticeable in cases of combustion where oxides of nitrogen are present.

Keeping to our list we ought next to deal with the combustible hydrogen sulphide or sulphuretted hydrogen. This gas, you remember, is composed of two separately combustible elements, each burning in one stage. The flame is, as you might expect, two-coned, but I will not dwell upon this case—partly because it is not yet fully worked out, and partly because any prolonged experimenting with this gas would, I feel sure, be resented even by the most indulgent audience.

I am obliged, therefore, to pass to compounds of carbon and hydrogen, in which there are not only two combustible elements, but one of them, as we have seen, combustible in two chemical stages. Here we have an almost unlimited choice of materials, for we come amongst the combustibles which ordinarily supply us with light. I shall, for the sake of convenience, use coal-gas. This is really a very complex combustible, consisting one half of hydrogen, the other half of at least a dozen different compounds of carbon and hydrogen. But experience has shown that the chemical phenomena attending its combustion are quite of the same character as those to be observed with a single compound of hydrogen and carbon.

It will, I imagine, be scarcely necessary for me to point out the various parts which are to be seen in the flame of a candle or of coal-gas. There is on the diagram (Fig. 2, *c*) before you the picture of a somewhat small coal-gas flame, produced at a circular orifice. It is, of course, enormously enlarged in the diagram. Four distinct parts are to be recognised. First, the central and darkest part; this contains the unburnt gas, just as we saw in the case of the carbon monoxide flame. Perhaps it is wrong to speak of this at all as part of the flame, for it is really a region of no flame. At the base of the flame are two blue strips embracing the lower portion of the flame. This appearance you will understand results from the mode in which we view the flame. The strips are really due to a sheath which goes right round the flame like an uninterrupted calyx. It looks bright where we view it edgewise. When we look through, as in the middle of the diagram, it is very pale indeed. Next we have to notice the bright yellow patch, so bright in the reality as to mask the other parts. Though it looks bright and dense, it is merely a hollow sheath. Lastly, there is surrounding the whole flame a pale mantle of flame of very slight luminosity,

and of an almost indescribable tint, which perhaps we may call lilac. These parts are discernible in all ordinary flames. They do not always occupy the same relative space. In the flame given by a good gas-burner the yellow part is made by intention as large as possible; in the flame of a piece of string or a spirit-lamp you will see the outer investing mantle very distinctly developed.

If we are to understand flame, then, we must find an intelligible explanation of the existence of these distinct parts of its anatomy. One important point we can settle at once. An ordinary flame owes its differentiated structure to the slowness with which it gets the oxygen necessary for combustion. If there is an immediate and sufficient supply of air, the characteristic structure disappears. This we can secure by making the stream of gas sufficiently rapid. I have here a steel cylinder containing coal-gas at very high pressure. If I allow the gas to escape slowly, we get a flame in which we should find the ordinary parts. But if now I allow the gas to issue rapidly, the admixture with air is so rapid, and, as you see, we have a pale flame quite undifferentiated in structure. We reach the same result by introducing a strong current of air into an ordinary flame, as in the blast blow-pipe. The flame, you see, is then homogeneous, as in the previous case.

We see then that the structure of an ordinary gas flame is largely dependent upon the slowness with which the gas gets the air necessary for combustion. There is still one other evidence of this. It is obvious that a very small flame will have a much better chance of getting its oxygen quickly than a larger flame. It is, I am sure, within everyone's knowledge that a very tiny gas flame is blue, and, as a matter of fact, we can learn a great deal about flame structure by carefully watching the development of a very small flame. I am going to show you on the screen a series of photographs of actual flames. The photographs have been tinted as faithfully as possible.

The first slide (Fig. 3, *a*) shows a tiny gas flame burning at the end of a glass tube; it consists of a bright blue cone surrounded by a fainter one. Both are quite continuous. By putting in another slide, and using the "dissolving view" arrangement of the lantern, I will show you the effect of turning on the gas. The flame (Fig. 3, *b*) you see is larger, and now is observed a third region in the flame—namely, a patch of bright yellow at the tip. The original cones are still there, but are slightly interrupted at their apices. Turning on more gas, the flame (Fig. 3, *c*) again enlarges, the yellow patch increases in size, and the original cones are further broken into. But you see the yellow patch is indented at points corresponding to the inner cone, which, as it seems, is striving to maintain its integrity. Turning on still more gas, we have now a great preponderance of yellow, the original blue cone is reduced to mere vestiges, and the outer cone forms a faint surrounding to the whole flame (Fig. 3, *d*). This is flame as we ordinarily know it. I wish now to show you another series of changes. We must suppose the gas supply fixed, and the photographs I will show represent the changes which take place in the flame when air is gradually added beforehand to the coal-gas. The supply of coal-gas is, I repeat, the same in all cases. The first change seen is, you will notice, that the yellow patch diminishes in extent (Fig. 3, *e*). If I add more air it diminishes still more, and the inner cone is growing in distinctness (Fig. 3, *f*). If I add a trifle more air, the yellow patch disappears altogether, and we have now complete and distinct inner and outer cones (Fig. 3, *g*). I think you will admit that these two sets of photographs show a close correspondence, and you can see it more plainly if I throw them on to the screen in a group. There is really nothing surprising in this similarity. The smallest gas flame has obviously the best chance of getting air, and when it gets enough it burns in a two-coned flame. The same effect is reached by adding air to the gas before it is burned. If we have a larger gas flame it has, of course, less chance of getting its oxygen rapidly, and we see that in whatever way we starve the flame of oxygen, we lose the simple structure, and come upon the yellow patch.

Now, when we come to inquire into the chemical changes occurring in such a flame, we may, I think, feel confident that the chemical actions which determine the existence of the blue cone and the outer cone are the same, whether these cones are complete, as in a small flame, or fragmentary, as in a larger one.

If that is so we can soon make progress, for, as I have shown you, we can easily separate these cones and find what is going on in each. I again use the cone-separating apparatus. First we have an ordinary luminous gas flame at the top of the outer

tube. I pass in air, the flame loses luminosity, and rapidly becomes an ordinary two-coned Bunsen flame. I push the air supply further; the inner cone enters the tube, and descends until it rests on the end of the inner tube. The two cones of a hydrocarbon flame are thus widely separated; we can aspirate a sample of the gases, and see what changes have taken place in the first region of combustion. The result is one that we might await with curiosity, for we have now a competition. There are both carbon and hydrogen to burn, and not enough oxygen to burn both; the question is, which will have the preference? I think I may say that the off-hand opinion of any chemist who has not had his attention drawn specially to this point would be that the hydrogen would easily have the preference. But, as a matter of fact, this question was settled long ago by Dalton, and in the opposite sense, and in the present case analysis would confirm this conclusion. If we analysed

About two-thirds of the carbon is burnt to form carbon monoxide, one-third to form carbon dioxide, whilst rather less than two-thirds of the hydrogen is burnt, and more than one-third remains altogether unburnt. We need not dwell on the details, especially as the analysis of the gases was made after they had cooled. The four gases—carbon monoxide, carbon dioxide, steam, and hydrogen—act upon one, as a matter of fact, while they are cooling down, and the distribution of the oxygen that we find in our analysis of the cold gas is not precisely that which exists in the gases as they just leave the inner cone. We shall only draw a general inference, and it is one that has been recently verified in a very complete manner by Prof. Dixon and his pupils. This inference is simply that the carbon in the inner cone is for the most part burnt to carbon monoxide, and that the hydrogen to a considerable extent is set free. So much then for the inner cone. The outer cone is

d   *c*   *b*   *a*
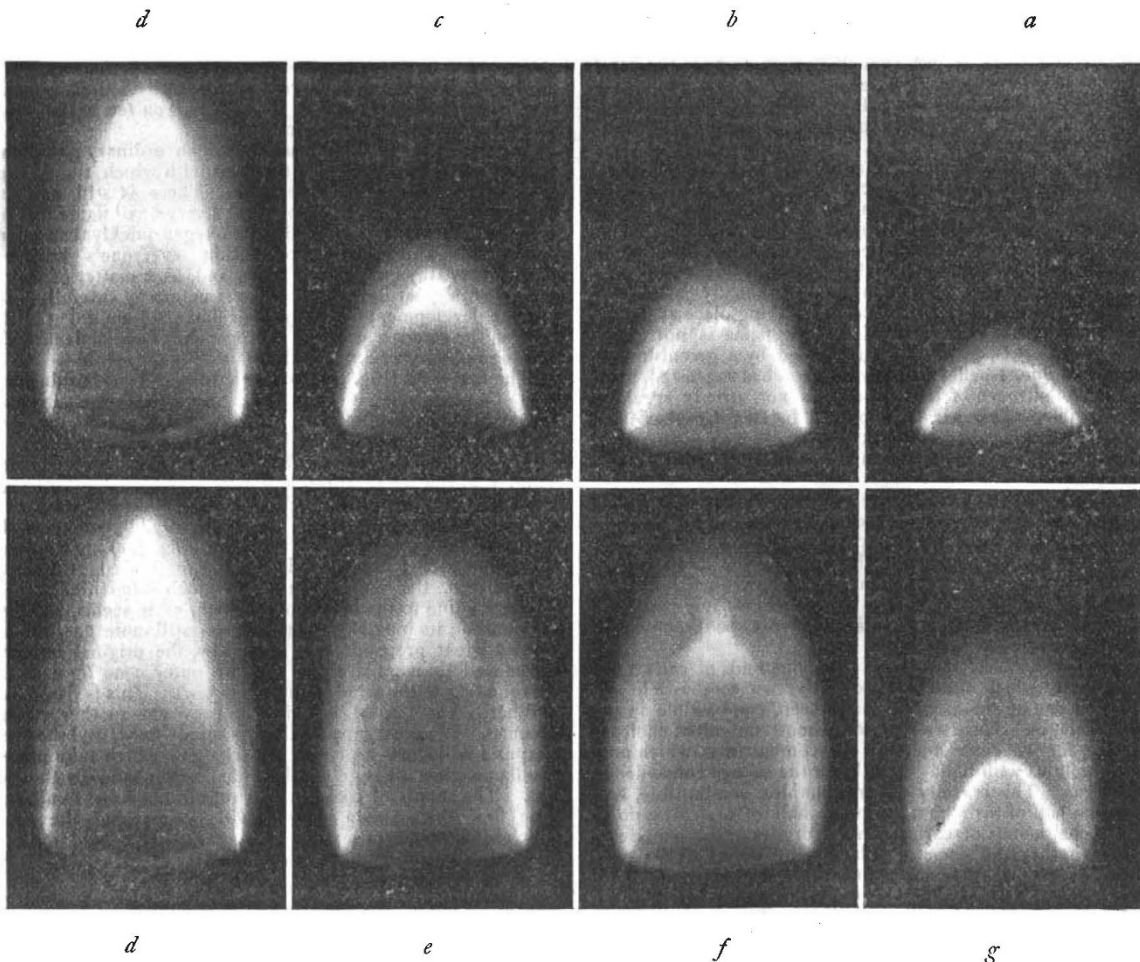

d   *e*   *f*   *g*

FIG. 3.—*a, b, c, d*, flames with successively increasing quantities of coal-gas. *d, e, f, g*, flames with fixed supply of coal-gas and successively increasing quantities of air.

the gases we should find that all the carbon is burnt in the first cone, whilst a considerable part of the hydrogen passes through unburnt. The change is not quite so simple as these words might apply, as you will see from the actual figures of analysis.

ANALYSIS OF INTER CONAL GASES FROM A COAL GAS AIR FLAME.

Carbon monoxide	8·7	} 17·9 combustible gases.
Hydrogen	9·2	
Carbon dioxide	4·1	} 20·1 burnt gases.
Water	16·0	
Nitrogen	62·0	
	100·0	

Amount of air used	78·5	{ Oxygen ... 16·5
		{ Nitrogen ... 62·0
Amount of air still needed	42·9	{ Oxygen ... 9·0
		{ Nitrogen ... 33·9

due simply to the burning of the carbon monoxide and hydrogen which escape from the inner cone. When they meet with oxygen in the free air their combustion is completed. We are now in possession of the explanation of the two-coned gas air flame. Applying this to the tiny gas flame to which no air has been previously added, we see that the inner core will be formed where the air has penetrated the gas sufficiently to produce such a gaseous mixture as we had in the lower cone of our separator. The gases coming from this burn further out when they meet with more air, and form a second cone.

The last thing we have to explain in the ordinary gas flame is the production of the yellow luminous patch, which, from the illuminating point of view, is the most important feature of all.

Now I need scarcely remind you that the general opinion is

that this yellow patch in the flame is due to glowing carbon in a solid and very finely-divided state. The very familiar fact that a cold object introduced into the yellow part becomes coated with a black solid deposit, composed almost wholly of solid carbon, confirms this view. That this carbon or soot is solid in the flame, is shown by the fact that it is deposited as a solid even when a highly-heated object is placed in the flame, and there are other proofs—some of them very pretty—which I cannot show for lack of time and of a means of magnifying.

This explanation is due to Davy, and constitutes his most celebrated discovery on the subject of flame. He describes it in the following words :—

"When a wire-gauze safe-lamp is made to burn in a very explosive mixture of coal-gas and air, the light is feeble and of a pale colour, whereas the flame of a current of coal-gas burnt in the atmosphere, as is well known by the phenomena of the gas-lights, is extremely brilliant. . . . In reflecting on the circumstances of the two species of combustion, I was led to imagine that the cause of the superiority of the light of the *stream* of coal-gas might be due to the *decomposition* of a part of the gas towards the interior of the flame where the air was in smallest quantity, and the deposition of solid charcoal which, first by its *ignition*, and afterwards by its *combustion*, increased in a high degree the intensity of the light ; and a few experiments soon convinced me that this was the true solution of the problem.

"I held a piece of wire-gauze of about 900 apertures to the square inch over a stream of coal-gas issuing from a small pipe, and inflamed the gas above the wire-gauze which was almost in contact with the orifice of the pipe, when it burned with its usual bright light. On raising the wire-gauze so as to cause the gas to be mixed with more air before it inflamed, the light became feebler, and at a certain distance the flame assumed the precise character of that of an explosive mixture burning within the lamp, but though the light was so feeble in this last case, the heat was greater than when the light was much more vivid, and a piece of wire of platinum held in this feeble blue flame became instantly white hot.

"On reversing the experiment by inflaming a stream of coal-gas and passing a piece of wire-gauze gradually from the summit of the flame to the orifice of the pipe, the result was still more instructive, for it was found that the apex of the flame intercepted by the wire-gauze afforded no solid charcoal, but in passing it downwards solid charcoal was given off in considerable quantities, and prevented from burning by the cooling agency of the wire-gauze ; and at the bottom of the flame, where the gas burnt blue in its immediate contact with the atmosphere, charcoal ceased to be deposited in visible quantities."

Only one attempt has been made to disturb the conclusion here drawn by Davy. In 1868 Prof. Edward Frankland, to whom we are indebted for many important discoveries respecting flame, came to the conclusion that the light-giving agency in flames was not solid carbon, but certain complex vaporous compounds of carbon and hydrogen. I regret very much that time will not admit of my detailing the evidence in favour of this view, or the counter evidence by means of which most chemists have been persuaded that Davy's explanation was, after all, the correct one. It is, however, right to remark that Prof. Frankland not only adheres to his own view, but promises to adduce further evidence in its favour.

Let us for the present, at any rate, stick to the opinion of the majority, and admit that the bright light of ordinary flames is due to incandescent particles of solid carbon. The next question is, How does this carbon become separated?

This question is dealt with by Davy, but in language of some ambiguity. He says, "I was led to imagine" . . . . that it "might be due to the *decomposition* of a part of the gas towards the interior of the flame where the air was in smallest quantity, and the deposition of solid charcoal which first by its *ignition*, and afterwards by its *combustion* increased in a high degree the intensity of the light."

Whatever these words may have been intended to mean, or whatever interpretation is the fair one, it is certain that Davy's explanation was soon presented as if it implied lack of air to be the chief cause of carbon separation. As there was a large quantity of hydrocarbon, and only a small amount of oxygen in the central parts of flame, the hydrogen, it was said, being the more inflammable element, will seize upon this oxygen and leave the carbon uncombined. The fact that this version was given by Faraday lends some countenance to the belief that it was a fair representation of Davy's view.

Now this doctrine was really incompatible with facts known, though apparently not widely known, at the time. I have already referred to the fact that Dalton at the beginning of the century showed that when a hydrocarbon is exploded with a supply of oxygen insufficient to burn both the hydrogen and the carbon, it is the carbon, and not the hydrogen, which has the preference. If, therefore, we follow Davy in regarding flame as a tethered explosion, we cannot explain the separation of carbon as being due to the preferential combustion of the hydrogen. This fact was clearly pointed out by Kersten in 1861 ; but notwithstanding this, and other investigations tending to the same conclusion, the old view has somehow kept its ground down to the present day.

We must now turn to the alternative explanation. It is supplied by the words, and, I think, by the intention, of Davy. He says that the carbon separation might be due to the *decomposition* of the gas towards the interior of the flame. If this decomposition be not due to chemical action, it must be due to heat ; and certain it is that hydrocarbons when strongly heated do decompose, and do deposit carbon. Here is a result of this action occurring on the large scale. This gas-carbon, as it is called, is deposited in gas-retorts owing to the action of intense heat on the hydrocarbons of the gas.

In another place Davy says : "I have shown in the paper referred to in the introduction, that the light of common flames depends almost entirely upon the deposition, ignition, and combustion of solid charcoal, but to produce this deposition from gaseous substances demands a high temperature."

This explanation of carbon separation in flames seems perfectly adequate and free from objection. There is, as we have seen, surrounding all ordinary hydrocarbon flames a shell of almost non-luminous combustion. The gas which passes upwards within this shell must be highly heated, and in the absence of air will be decomposed so as to deposit solid carbon. This carbon is intensely heated, and glows, and as it reaches the air will burn to form carbon dioxide. The fact that the upper parts of flame are the most luminous in itself indicates that the more we roast the gas the more do we separate the carbon ; and there are other proofs, which I cannot stop to explain.

We have now got pretty well to the end of the explanation of the structure of ordinary luminous flames, and I will show you an experiment which epitomises the explanations that have been given.

We turn once more to the cone separating apparatus, and use as fuel a substance particularly rich in carbon. This substance, benzene, is a liquid, so I shall have to vapourise it by means of a current of air. When I apply a light to this current of air strongly impregnated with benzene, we get, as you see, a very bright flame. This flame exhibits the usual structure. This is one extreme. Now I will reduce the amount of benzene vapour very rapidly without altering the air, and we shall get the other extreme, that is, a scarcely luminous flame consisting of one single cone. The whole of the combustion is now taking place in a single cone of flame. If I still further reduce the benzene, this flame enlarges slightly and becomes paler. There is now excess of air. A little less benzene still, and you see the flame rises from its perch and disappears ; we have got past the limits within which combustion is possible. Let us next move in the other direction, and gradually increase the supply of benzene to the single cone. It becomes smaller and brighter as we proceed up to a certain point. At length we have evidently got more benzene than there is air to burn, and now appears the second cone at the top of the tube. By sliding the tubes we can unite the flame and make a Bunsen flame. Separating the cones again, let us add still more benzene. The result is very remarkable. The two cones remain intact, but stretching between them are thin luminous streaks of glowing carbon. The excess of benzene is being decomposed by the heat, so that the carbon separates and glows. The more benzene I add the broader do these streaks become, until eventually the inner cone ascends, the luminous streaks coalesce, and we have the ordinary luminous hydrocarbon flame.

I have now put before you the considerations and methods which will serve, I believe, for the elucidation of all problems of flame *structure*. I am not aware, at any rate, of any flame which does not accord with the general principles which I have explained to you.

There are many other flame problems besides that which relate to mere structure. Of these one of the most interesting concerns the colouration of flame. I will refer to it for a moment

only to show how closely that question is connected with the points we have been discussing. I have here a gas flame to which I feed air until its yellow luminosity has disappeared. If I add to the air supply the fine spray of a dissolved copper salt, the flame assumes a green tint characteristic of the metal. This green tint seems to belong to the whole flame, but if we dissect it by the apparatus already so often used, we find that the green tint is developed only in the outer cone. It is due, in fact, to oxide of copper, which can only exist on the outside of the flame. Similar peculiarities are noticed with some other coloured flames, and it is hoped that their study, which leads us into the domain of spectrum analysis, will yield some interesting information on points which are at present very obscure.

I have directed your attention this evening to terrestrial flames of small dimensions, but in conclusion I should like to remind you that at one time there were probably quite other flames upon this earth. The globe we inhabit is in the process of cooling and of oxidation ; at one time we believe, in fact we know, that it was incandescent. If we take a chemical retrospect and imagine as we recede in time our present cool earth becoming hotter, we may follow out some interesting changes. We should soon reach a temperature too high for the persistence of liquid water ; our oceans would be evaporated and surround the globe as an envelope of steam. In remoter times and at higher temperatures this steam could not exist even as steam, but would be dissociated into hydrogen and oxygen. At that time, too, many of the elements now existing as oxides in the solid crust of the earth would be floating in a gaseous state in the vast atmosphere. Let us stop our retrospect at this point, and look towards the present with a cooling earth. At a certain point chemical combination must have begun in the fringe of the ancient atmosphere, and it must have been the scene of colossal chemical activities, the hydrogen and vaporous metals flashing into their oxides. On gravitating to hotter regions, these combinations may have been again undone, the elements sent again into circulation. How long such a period may have lasted we need scarcely stop to ask. If the retrospect is reasonable, it is enough. It is interesting to think how such an earth as we have pictured must have resembled the sun as we know it at the present day.

There was formerly a chemical theory of the sun, which ascribed both its heat and light to the act of chemical combination. That theory has long since been refuted and discarded, and with it ordinary laboratory chemistry banished from that luminary as altogether unsuited to its high temperature. There is cause, I think, to ask if this is quite warrantable. We know extremely little of chemistry at high temperatures, but if the sun could be shown to have its reasonable share of oxygen, we might well ask if its surface phenomena were not largely ascribable to ordinary chemical activities and of the nature of flames. It is certainly remarkable, when we consider the unity of plan in which heavenly bodies are seen more and more to move and have their being, that the sun should not exhibit the possession of its fair share of that element—oxygen—which has ruled the chemistry of the earth throughout all geological time and long precedent ages of its evolution. But this is ground which the terrestrial chemist must tread with care. He still has many unsolved problems lurking in the flame of a common candle, and flame, wherever we find it, is still a mystery.

"The power of *Fire* or *Flame*," says Carlyle, "which we designate by some trivial chemical name, thereby hiding from ourselves the essential character of wonder that dwells in it as in all things was with the old unknown Loke, a most swift subtle *Demon* of the brood of the Jötuns. The savages of the Landrones Islands too (say some Spanish voyagers) thought Fire, which they never had seen before, was a devil or god, that bit you sharply when you touched it, and that lived upon dry wood. From us, too," adds Carlyle, "no Chemistry, if it had not stupidity to help it, would hide that Flame is a wonder."

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

OXFORD.—On Monday, the 20th inst., Prof. E. B. Poulton, the President of the Ashmolean Society, gave a *conversazione* in the University Museum, which was numerously attended by members of the city and University, who were specially invited to meet the Local Executive Committee of the British Association. The features of the entertainment were : an interesting lecture on features in the past history of science in Oxford, by Mr. Falconer Madan ; physical experiments, by Prof. Clifton and Mr. J. Walker ; exhibits of various entomological specimens from the Hope Collection ; glass-blowing, by Herr Zitzmann ; living animals and museum preparations, by Dr. Benham and Mr. Goodrich ; physiological exhibits, by Messrs. Pembrey, Gordon, and Howard ; and many other exhibitions which cannot be noticed for want of space.

The Junior Scientific Club, whose proceedings have been hitherto published in a somewhat haphazard manner, have decided to issue a series of fortnightly numbers, each of which contains an account of the papers read at the previous meeting. The first of these was published on the 17th inst., and is in all respects a credit to its editor. It contains, besides abstracts of papers read by Messrs. M. H. Gordon, S. A. Simon, and W. J. Waterhouse, a syllabus of all the papers read before the club during the past year, an obituary, and notes on the distinctions gained during the past year, by present and former members of the club.

At a meeting of Convocation held on Tuesday last, Dr. Arthur Thomson, University Reader in Human Anatomy, was appointed Professor of Human Anatomy.

CAMBRIDGE.—Mr. M. R. James, of King's College, has been appointed Director of the Fitzwilliam Museum in succession to Prof. Middleton.

An election to an Isaac Newton studentship in astronomy, astronomical physics, and physical optics, will be held in the Lent Term 1894. The candidates must be B.A.s and under the age of twenty-five. The studentship is worth £200 a year for three years. Applications to be sent to the Vice-Chancellor by January 26, 1894.

A syndicate has been appointed for the purpose of obtaining specifications and tenders for the erection of the Sedgwick Memorial Museum of Geology, in accordance with the plan of Mr. T. G. Jackson.

An influential deputation waited upon the Chancellor of the Exchequer on Tuesday in order to place before him the necessity for continuing, and, if possible, increasing, the Parliamentary grant of £15,000, which was conceded to the University Colleges in 1889. Sir W. Harcourt said that though he was prepared to recommend the renewal of the grant, the present condition of public finances would not permit him to propose its increase.

SCIENTIFIC SERIALS.

American Journal of Science, November.—On New England and the Upper Mississippi basin in the glacial period, by James D. Dana. During the recent discussions concerning the unity or otherwise of the glacial epoch in North America, it has appeared that workers in the central and western portions have mostly advocated two glacial epochs, while New England geologists have been the chief advocates of unity. The author has not found any facts in New England geology that require for their explanation an appeal to two glacial epochs, but has found an explanation of the appearances which have led western geologists to that opinion. The cause of this sectional divergence is mainly meteorological. Even at the present time, the precipitation in the east is far above that of the west, and in the glacial epoch the difference must have been still greater, owing to the greater elevation of the east. The conditions of the ice-sheet in the interior being near the critical point, a small meteorological change, if long continued, might carry off the ice for scores or hundreds of miles from a southern limit, while the eastern border was all the time gaining in ice, or was making only a short retreat.—On the use of the name "Catskill," by John J. Stevenson. Mr. Darton's suggestion that the term Catskill should be applied to the whole of the Upper Devonian period is inappropriate, since Catskill has been shown to belong to an epoch only, whereas "Chemung" carries with it the conception of those physical and biological characteristics which mark the great closing period of the Devonian.—The finite elastic stress-strain function, by G. F. Becker. This is an investigation of finite stress and strain from a kinematical point of view, and of the function which satisfies the kinematical conditions consistent with the definition of an isotropic solid. The bearing of the theory upon finite sonorous vibrations is compared with the corresponding deductions from Hooke's incomplete law.—A larval form of Triarthrus, by C. E. Beecher. Since the discovery of antennæ and other appendages of this