

an S, and one end piece be moved carefully, all will move with it rigidly ; or, if the force be enough to break through the joint, the rupture will be with a crackling noise, but the pieces will still adhere, and in an instant become rigid again. As the adhesion is only by points, the force applied should not be either too powerful or in the manner of a blow. I find a piece of paper, a small feather, or a camel-hair brush applied under the water very convenient for the purpose. When the point of a floating, wedge-shaped piece of ice is brought under water against the corner or side of another floating piece, it sticks to it like a leech ; if, after a moment, a paper edge be brought down upon the place, a very sensible resistance to the rupture at that place is felt. If the ice be replaced by like rounded pieces of wood or glass, touching under water, nothing of this kind occurs, nor any signs of an effect that could by possibility be referred to capillary action ; and finally, if two floating pieces of ice have separating forces attached to them, as by threads connecting them and two light pendulums, pulled more or less in opposite directions, then it will be seen with what power the ice is held together at the place of regelation, when the contact there is either in the flexible or rigid condition, by the velocity and force with which the two pieces will separate when the adhesion is properly and entirely overcome.

II. "Notes on the apparent Universality of a Principle analogous to Regelation, on the Physical Nature of Glass, and on the probable existence of Water in a state corresponding to that of Glass." By EDWARD W. BRAYLEY, Esq., F.R.S. &c.
Received April 26, 1860.

1. Recent experimental investigations, and the reasoning founded upon them, have elevated the designation of an observed property of ice to the character of a principle in physics. The growth of crystals of camphor and of iodide of cyanogen, by the deposition of solid matter upon them from an atmosphere unable to deposit like solid matter upon the surrounding glass, except at a lower temperature ; and that of crystals in solution, by the deposition of solid matter upon them which is not deposited elsewhere in the solution, have been adduced by Mr. Faraday to illustrate the extension of the principle

of action which is manifested in regelation ; and “ many such like cases,” he remarks, “ may be produced.” In his reasoning on the nature of that principle, he also rests on the fact, that ice has the same property as camphor, sulphur, phosphorus, metals, &c., which cause the deposition of solid particles upon them from the surrounding fluid, that would not have been so deposited without the presence of the previous solid portions*.

In reflecting on these indications of the universality of the cause, whatever it may intrinsically be, which is operative in the phenomena alluded to, it occurred to me that the known fact of the incorporation of two or more plates of glass into one block, presented a curious parallel to the incorporation of two or more slabs or separate portions of ice into one mass ; and to determine in what manner these subjects were related to each other appeared to deserve careful investigation. Towards this the following suggestions are offered :—

Certain substances, both elementary and compound, appear to present, in what we term the solid state, phenomena corresponding to those which are presented by others in the liquid and solid states and the transitions from one to the other collectively regarded, and indicating the existence of a condition of matter which may be termed arrested liquidity, but yet is not, in the most perfect sense, solidity. Of these bodies glass is one. The fact in question, which exemplifies in a striking manner the property here alluded to, appears to have been first noticed as a subject of scientific importance by MM. Pouillet and Clement Desormes†. It is the incorporation, into one mass, of two or more plates of the kind of glass manufactured for mirrors, and called *plate-glass*, the polished surfaces of which have been placed, and have remained for some considerable time, at common temperatures, in close contact with each other, the entire area of one plate being in contact with the entire area of the contiguous one,—extensive mutual surfaces of contact being thus supplied. Under these circumstances, two, three, or four, or even a greater number of plates become converted into one block of glass, which it is impossible to

* Exp. Res. in Chemistry and Physics, pp. 380, 381.

† As far as my reading extends, it was first recorded by Pouillet in his ‘ *Éléments de Physique*,’ liv. vi. ch. ii. 2^{me} édit. Paris, 1832, tome iii. p. 41 (Bruxelles, 1836, p. 292). In the fourth edition, Paris, 1844, it appears to be omitted, together with other and established facts relating both to glass and to metals.

separate into the original plates, and which may be worked, and even cut with a diamond, as if the whole had originally been a single mass. In some specimens which I have examined, with the surface of one plate were incorporated portions of another, the surfaces of fracture of which were alone exposed, its substance having been torn through in the effort to separate the united plates by mechanical force*. The same effect took place in some experiments by Clement Desormes.

I assume it to be highly probable that the process by which the two plates of glass become one, is, in reality, analogous to that of regelation in ice, and finally dependent on the same principles, whatever their true character may be conceived or shall ultimately be determined to be. To this it may be objected, however, that there is no evidence, in the case of the glass, of the previous liquefaction, or even approach to liquefaction, of the surfaces which become united so as entirely to disappear (or, more properly speaking, to be altogether obliterated), and that the phenomenon is referable simply to the homogeneous attraction of the molecules of one plate for those of the contiguous one, the evenness of the two polished surfaces allowing them to be brought within a very minute distance of one another. But two remarkable facts greatly diminish the weight of this objection, if, indeed, they do not entirely remove it. First, unpolished plates of glass have no tendency to unite; the hard and compact siliceous film, to which Prof. Faraday, regarding glass "as a solution of different substances one in another," long ago referred its power of resisting agents generally †, and which previously bound together the outer molecules of each plate, must be removed by grinding and polishing, so as to render the actual surfaces of contact those of portions of the glass the chemical nature and condition of which are such as readily to admit of their rapid mutual action and union into one mass. Secondly, the polished plates sometimes have the forms and configurations of the surfaces of straw and other packing-materials impressed upon them (portions of straw, paper, &c. sometimes adhering inseparably to the glass, after having been taken to

* These and other facts of a similar nature I adduced as illustrative of the physical nature of glass, in lectures on that substance delivered before the Pharmaceutical Society of London in the year 1845. See *Pharm. Journ.* vol. v. (Oct. 1845) pp. 157-160.

† *Phil. Trans.* 1830; *Exp. Res. in Chem. and Phys.* p. 282.

hot climates*), in consequence of the soft nature of the substance exposed by the polishing, or of its nature being such as readily to soften by a temperature very much below that of the proper fusion, or even softening, of the glass in its integrity. The state of the interior portions of a plate of plate-glass appears, therefore, to be similar to that of glass in general at certain temperatures much below its fusing-point, when it presents such remarkable characters of plasticity, tenacity, and ductility†.

Is it possible that a lowering of the melting-point of glass, or of the exposed interior portions of it, by pressure, is concerned in the union of the two plates? The effect of the mere pressure of the atmosphere, ensuing upon the exclusion of the air from between the closely apposed plates, would of course be insignificant in depressing the temperature of fusion of the glass; but the pressure occasioned by the cohesive force—exerted, it will be remembered, through a very small thickness only of the material,—which finally unites two or more plates into one block, would probably be adequate to any conceivable effect of this nature which can be required for the production of the phenomenon observed.

It may appear at first sight, that the fact that glass belongs to that class of bodies which contract on passing from the liquid to the solid state, and the melting-point of which, therefore, would be elevated—not depressed—by pressure, is opposed to this possibility. The objection would be a valid one were we now concerned with glass in a crystalline state. But we are treating of that substance in its familiar and ordinary condition, into which it passes from liquidity by a continuous gradation of temperature, through equally continuous states of softness into the solid form, like melted phosphorus and selenium.

I am now tempted to ask, in conclusion of this part of the subject, Are all cases of the union of two apparently solid surfaces of

* These particular facts were communicated to me by Mr. Tite, F.R.S., who had himself observed them.

† We are reminded by these facts of the view taken by Person, and adopted by Prof. Forbes, of the similarity of the liquefaction of ice to that of fatty bodies or of the metals, “all which in melting pass through intermediate stages of softness or viscosity;” and Sir J. F. W. Herschel (Art. “Meteorology,” par. 119, Enc. Brit. eighth edit.), when he terms regelation “a sort of welding,” appears to concur in this view.

the same substance by cohesive attraction, cases of melting and regelation, an infinitesimally thin film of liquid being momentarily produced and as instantly solidified? Will two surfaces of perfectly dry ice, at temperatures much below 32° , but under favourable mechanical circumstances, unite by mere apposition and pressure (which ought to follow from Prof. James Thomson's theory), and thus prove the identity of the acting principle in the two cases of ice and plate-glass?

The negative of the last question does not appear to be proved by the fact cited by Faraday and Tyndall, that dry, hard-frozen snow has not the property of becoming compacted into a snow-ball. The cases seem not to be comparable, because the brittleness of the constituent crystals of snow when in this state, its porous nature as a whole, and its being consequently pervaded by air, will prevent the required apposition of surfaces. Nor, as I conceive, is it proved by Prof. Tyndall's most instructive experiment of crushing a ball of ice, cooled by carbonic acid and ether, into white and opaque hard fragments; for in this also the required apposition of surfaces would be wanting. Further, it may be asked, whether this very experiment does not demonstrate the limitation of the lowering of the melting- or freezing-point by pressure? and if so, there can be no tendency to union at 100° below freezing.

In discussing the philosophy of the union of two surfaces of glass, I have alluded to the theory of regelation enunciated by Prof. J. Thomson; but I wish to be understood as not adopting, exclusively, in these notes, any existing theory on the subject. Admitting the operation of cohesive attraction and consequent pressure in the first instance, the phenomenon, with respect to glass, readily admits of explanation by the original view of Mr. Faraday, which is, "that a film of water must possess the property of freezing when placed between two sets of icy particles, though it will not be affected by a single set of particles." If we regard the two apposed surfaces of glass, each consisting of a thin stratum of particles, taken together, as representing the film of water, then the other strata of particles in contact with them respectively, and making up the entire thickness of the plate on each side, will correspond to the two sets of icy particles, the action of which by freezing the film of water effects the union of the two portions of ice, and the phenomenon may be

consistently explained in the terms of Mr. Faraday's theory. And here we seem to find points of coincidence between cohesive force, as ordinarily considered, the principle of regelation, and that particular view of the former which has been announced by Mr. Faraday in accounting for the phenomena presented by and connected with the latter.

2. But we are led by the preceding facts and considerations to some further inferences, if not indeed to a definite hypothesis, upon the subject of the molecular constitution or physical nature of glass. Mr. Faraday's view of it has been cited already; he regards glass, it will be remembered, "as a solution of different substances one in another." Professor Maskelyne has suggested to me, in conversation, that the physical nature of glass most probably nearly resembles that of a solution of a crystallizable salt in water, immediately before crystallizing. These views are evidently coherent, and they harmonize with Prof. Graham's, who defines glass, chemically, as "a mixture of silicates*." But they all relate to the varieties of glass in common use, while we are concerned, at present, with the abstract vitreous condition of matter, such as it is represented by the phosphoric and boracic acids, probably by the heavy optical glass of Faraday, by the simple glasses of felspar and peridot obtained by Charles Deville, by the glassy condition of silica, natural and artificial, and still more perfectly, perhaps, by the glassy form of sugar.

Bearing in mind then the homogeneous, or comparatively homogeneous, nature of these glasses, and considering the uniformity of texture which the acoustic as well as the optical characters of perfect glass in general evince, especially when contrasted with that of

* These views of Mr. Faraday, Mr. Maskelyne, and Mr. Graham are confirmed by the experimental evidence of the structure of glass obtained by Leydolt, to whose researches Professor W. H. Miller of Cambridge had the kindness to direct me. By etching the surface of glass, he found it to have a porphyritic structure, consisting of crystals imbedded in an amorphous substance. But the peculiar characters of glass, especially its relations to sound and light, evince, as indicated in the sequel, that it is not a congeries of ready-formed crystals, though in all probability crystals will always be found on its surface. The amorphous substance recognized by Leydolt will answer, nearly, to what I shall call "simple glass." Other facts which he observed are perfectly in harmony with our previous knowledge of the dependence of the texture of glass upon the rate of cooling. See *Comptes Rendus*, tome xxxiv. (1852, April 12) p. 565.

crystalline plates in the acoustic researches of Savart, and how strongly distinguished that texture is from a crystalline texture or structure,—a nearer analogy than that of a solution ready to crystallize, I think, will be found in the condition of water cooled below the freezing-point but still remaining liquid, until by a tremor, or the percussive contact of a solid body, or the mere contact of a crystal of ice, its temperature rises to 32° and it becomes ice. If so, glass will be a substance in which this state of arrested liquidity, or potential solidity, is permanent. And this inference will harmonize with known facts. Gregory Watt proved that heat is evolved when mineral glasses crystallize or become (permanently and truly) solid *. The preparation of sugar called barley-sugar is the vitreous condition of that body, already taken as a type of simple glass; while granular sugar, and more perfectly sugar-candy, exhibit its crystalline state. Prof. Graham has shown that, at a certain temperature, by mechanical means the former may be converted into the latter, the temperature quickly rising 70° on the transition of the sugar from the glassy to the crystalline state. This and similar facts induced him to refer the peculiar constitution and properties of glass in general to the permanent retention of a certain quantity of heat in a latent state, which becomes sensible on its crystallization; and this will take place on its being preserved in a soft state at certain temperatures.

There are some remarkable and instructive parallels between the phenomena of the crystallization of water, and that of glass and some other bodies. It follows from the experiments and inductions of Gregory Watt already cited, that during the crystallization of glass a higher temperature must be communicated to the interior than that existing over its surface, by the evolution of heat at the points where the crystalline form is assumed, which will be gradually conducted throughout the mass. So that, in the express words of Faraday, in relation to ice, “by virtue of the solidifying [crystallizing] power at points of contact, the same mass may be freezing and thawing at the same moment;” and the “freezing process in the inside may be a thawing process on the outside,” and thus contribute to the slowness of the cooling, and allow the crystallization therefore to be the more perfect. We here seem to have the explanation

* Phil. Trans. 1804, pp. 285–290.

of the well-known fact, that in bodies which crystallize from a state of igneous fusion, the most perfect crystalline state is produced when the longest time intervenes between the commencement of solidification (now using that term in its ordinary sense) and the complete cooling of the melted mass. The cases cited from Mr. Faraday at the beginning of this paper, of the growth of crystals (including those of ice in ice-cold water) in solutions, all have their exact parallels in the accretion of crystals in cooling melted glass. "Crystals of ice," Mr. Faraday observes, "which could not be colder than the surrounding fluid, exhibited the phenomena of regelation"—that is, of incorporation into one—"when purposely brought in contact with each other." The same thing happens with melted glass slowly cooling, in which crystalline spherules, often forming spontaneously and independently, continue to form and to increase, even after the glass has become solid as such, by the operation of a principle in this view analogous to regelation, until the entire mass has become crystalline*.

3. No crystalline body has been longer or more extensively subject to human observation, than crystallized water, or ice. Its natural history and properties, as science has advanced, have been investigated with increasing generality and precision; and they have finally become objects of that systematic and exact research which characterizes the present era of physical inquiry,—as is evinced by the dis-

* If we should prefer to adopt Mr. Maskelyne's suggestion in a formal manner, and regard glass as resembling a solution about to crystallize, its analogue, agreeably to the preceding views, will be a saturated solution of a salt in hot water, allowed to cool undisturbed, and remaining fluid, until its cohesion is affected, when its temperature rises, and the salt crystallizes. Specimens of glass are common which have the aspect and distribution of parts of a crystallized salt in the mother-liquor; opaque crystallized spherules appearing in the midst of a transparent mass. To these correspond, among natural glasses, pitchstone and many examples of porphyritic obsidian, consisting of a vitreous base in which crystals have been formed and are imbedded.

But at the same time the view I have taken of the subject, and Mr. Maskelyne's, may be equally tenable; for the state of water remaining liquid at temperatures below 32°, and that of saline solutions remaining uncrystallized at temperatures below those of solidification, are evidently closely analogous.

Should I return to this subject, I shall refer to my friend Mr. Sorby's observations on the nature of glass, which I had not read when these notes were communicated to the Royal Society, but which are in entire agreement with the views I have suggested.—See *Quart. Journ. of Geol. Soc.* vol. xiv. p. 465.

cussion on regelation, to which these notes are intended to be supplementary. A most remarkable deficiency, however, still remains, apparently, in our knowledge of this substance:—*Water in the vitreous condition—Ice-glass—has never been observed.* While we know the antithetical vitreous state of so many different crystallized substances—minerals produced by heat, salts deposited from aqueous solution, neutral bodies of organic origin—and have great reason to believe that that antithetical condition to crystallization is universal, we have no knowledge of it in relation to water or ice. My own attention has been awake to the subject, without success, for many years. It would seem to be scarcely within the bounds of possibility that the glassy state of water, if possessing what we term solidity, should not, ere now, either have been observed in nature, or have occurred and been recognized in experimental research*.

I now venture to submit the inquiry, Does this apparent deficiency in our knowledge exist because—to use language recently introduced into physical science—the *homologue* of the glassy state of water is not what we ordinarily term solid—because the state of water cooled below 32° but still liquid is in fact the state which corresponds to the vitreous condition of other bodies, and to the physical nature of perfect ordinary glass? Is the one simply a case of potential solidity, and the other of the confluent or equivalent state of arrested liquidity?

It may be said that the homology which is here endeavoured to be established between liquid water below 32° and glass, is a forced one. That, in relation to each other, these are extreme cases is perfectly true; but intermediate terms of the series are not wanting, and some of them are supplied by sulphur and phosphorus, and in a remarkable manner by selenium. All these bodies, when melted, may be

* The crushed fragments of the ball of ice cooled in carbonic acid and ether, in Prof. Tyndall's experiment already mentioned, which "remained *white and opaque* as those of crushed glass," were still, he informs me, perfectly crystalline, resembling fragments of quartz.

The "points of analogy between the molecular structure of ice and glass" noticed by Mr. Drummond (Phil. Mag., August 1859, S. 4. vol. xviii. pp. 102–103) do not involve the physical condition of those bodies, but relate merely to the resemblance of one crystallized substance (ice) to another (Reaumur's porcelain), and of both to a third body (bottle- and window-glass), which, from its optical characters, is inferred—I think inconsequentially—to have assumed a state preparatory to crystallization.

cooled many degrees below their freezing-points and yet remain fluid. Sulphur presents, in its viscid form, an approach to the glassy condition; but it may be obtained in the crystalline form on passing from a state of fusion, and when cooled below freezing, instantaneously crystallizes, like water, by mechanical disturbance.

In phosphorus also there is the viscid state; and when cooling after fusion, it passes gradually, like glass, from the liquid to the solid condition without crystallizing, though crystals are deposited from some of its solutions. Selenium presents a state resembling the viscid state of the preceding substances; but when melted, and left to cool, remains fluid below its melting-point, and solidifies very gradually in its amorphous state (in which it has some of the characteristic properties of glass), and a thermometer immersed in it during the cooling does not remain stationary at any point, or indicate any temperature at which heat is evolved by molecular change in the substance, —as if the selenium passed continuously from the liquid glassy state to that of solid glass. At ordinary temperatures it retains this condition for a long time—as common glass does at higher, and as water and sulphur will at lower temperatures; but when heated again, between a certain temperature and its melting-point it becomes crystalline and gives out great heat*. When glass is raised to a certain temperature, and by its maintenance is preserved in a soft state, it does the same.

In sulphur, phosphorus, and selenium, therefore, the fluid state below the temperature of solidification—the intermediate condition between fluidity and solidity—the viscid state long retained—the

* These properties of selenium are here stated on the authority of Hittorff, cited in Graham's 'Elements of Chemistry,' second edition, vol. ii. pp. 688, 689.

The case of vanadic acid strongly resembles that of selenium, but extends this series of concurrent phenomena to a range of temperatures nearly approaching those which govern the molecular changes of glass. It fuses at a red heat, and crystallizes on cooling, but remains fluid below its freezing-point. At the moment solidification commences, it again becomes red-hot, and remains so as long as crystallization continues.

The crystallization of glass, it has been seen, takes place at a high temperature, from the ordinary state of solidity, heat being evolved. So the glassy variety of gadolinite (like glass, a silicate with a compound base), when its temperature is elevated above redness, remains solid, but evolves heat (becoming incandescent), and crystallizes; while the crystalline variety merely fuses and intumesces when similarly treated.

solid state of selenium which evolves heat on crystallizing—all appear to be homologues, at once, of liquid water below 32° , and of the glassy state of matter.

Should this hypothesis be verified, water below 32° , or rather, perhaps, from the temperature of maximum density downwards through that of freezing, may have to be regarded as the type of the vitreous condition of matter; and the causes of the peculiar characters of that condition, its effects on the transmission of the vibrations of sound and light, the conchoidal fracture, &c., may have to be discovered by researches on its molecular nature.

III. "On the Effect of the presence of Metals and Metalloids upon the Electric Conductivity of Pure Copper." By A. MATTHIESSEN, Esq., and M. HOLZMANN, Esq. Communicated by Professor WHEATSTONE. Received March 14, 1860.

(Abstract.)

After studying the effect of suboxide of copper, phosphorus, arsenic, sulphur, carbon, tin, zinc, iron, lead, silver, gold, &c., on the conducting power of pure copper, we have come to the conclusion *that there is no alloy of copper which conducts electricity better than the pure metal.*

May 3, 1860.

Sir BENJAMIN C. BRODIE, Bart., President, in the Chair.

In accordance with the Statutes, the Secretary read the names of the Candidates recommended by the Council for Election into the Society, viz.—

Frederick Augustus Abel, Esq.	Thomas Hewitt Key, Esq.
Thomas Baring, Esq., M.P.	Joseph Lister, Esq.
John Frederic Bateman, Esq.	Rev. Robert Main, M.A.
Edward Brown-Séguard, M.D.	Robert William Mylne, Esq.
Richard C. Carrington, Esq.	Roundell Palmer, Esq., Q.C.
Francis Galton, Esq.	John Thomas Quekett, Esq.
Joseph Henry Gilbert, Esq.	Edward Smith, M.D.
Sir William Jardine, Bart.	

The following communications were read :—