Optical Contact*

By the Right Hon. Lord Rayleigh, F.R.S.

WHEN two glass surfaces are put together without special precautions, they do not come into close contact, and their separate individuality is completely preserved. Yet this is not what might be expected. If the two glasses were really close, they would be equivalent to one piece, and no reflexion would be observable from the interface. Ordinarily this does not happen, because various agencies prevent the glasses coming close enough together. Thus particles of dust and traces of grease tend to do this, and moreover, ordinary surfaces, such as those of spectacle prisms, are not flat enough to come into close contact, except over a very limited area.

However, by using really flat surfaces, scrupulously clean, and by sliding them together so as to exclude dust, two surfaces may be made to *contact*, that is to say, they will come into contact so close that the reflexion at the interface practically vanishes, and when once this has been achieved—and it is easier said than done—the glasses adhere with very considerable force. Such glasses are said to be in optical contact.

Although, as we shall see, the germs of this subject are to be discovered in much earlier work, optical contact has mainly come into notice in connection with the manufactures of Messrs. Adam Hilger, Ltd., under the management of Mr. F. Twyman; Mr. Green, the foreman of their optical shop, has been prominent in this. To mention one example, the echelon transmission gratings made by the firm have the glass plates put into optical contact, which improves the transparency and makes the instrument much more efficient. I have heard the late Prof. A. A. Michelson, who was perhaps not very lavish of praise, speak with enthusiasm of this great improvement in his invention. Nevertheless, the interface, even of contacted glass, does give a faint reflexion. I shall have more to say about this presently.

There is a strong force of adhesion between two contacted glasses. Glasses having an area of less than 2 square inches can be shown to withstand a pull of 56 lb. weight. On occasion, contacted glasses have been made to stand even considerably stronger pulls than this, up to 56 kilograms per square centimetre. However, there does not seem to be anything very definite about it, and there is little doubt that the separation starts at points of local weakness.

The germ of this subject can be discovered in the writings of long ago. Let me recall the well-known experiment of Newton's rings. Two glass wedges, one of which has a convex face of 50 ft. radius, are clamped together without any special precautions, except ordinary cleaning, and give by reflection a circular patch of optical contact—the familiar black centre, surrounded by a system of coloured rings. It is interesting to recall that the blackness of the centre was felt to be a difficulty by the early exponents of the wave theory of light. Yet a simple consideration shows that it ought to be black, the consideration namely that an infinitely thin crack is equivalent to no crack at all, and therefore cannot reflect light.

We obtain local optical contact at the centre of Newton's rings without the technical difficulties which are encountered in contacting flat plates. This is natural, because all the pressure that we use is taken locally, and if there is any dirt or obstruction in the way it is crushed.

It may seem a discrepancy in what I have been saying, that the optical contact which we get in this case is not accompanied by strong mechanical adhesion. This fact will conveniently serve as a starting point in considering the character of the adhesion between flat plates. Although the adhesion is very strong in resisting a fair pull, it is not at all strong in resisting what I may call an *unfair* pull, that is to say, a force tending to strip the plates apart. Such a force can be applied by wedging or pulling the plates apart at one edge or one corner, and we then overcome the adhesion in detail, for the force applied is all concentrated at the edge of the contacted area. It is like tearing a strip of calico when a start has been made by making a short cut with the scissors. All the force is concentrated locally, the breadth of the strip of calico contributing nothing to increase its strength. In the case of Newton's rings, when the convex surface is squeezed flat locally, as soon as the force is relaxed the elasticity of the material brings a stripping force of the kind to bear, and the two glasses separate themselves easily.

If, however, the convexity is very slight, and the amount of flattening involved in contact is consequently small, we may obtain Newton's rings with adhesive contact, no clamping being necessary to keep the glasses together (Fig. 1). This case may be regarded as intermediate between the case of Newton's rings and the case of accurately contacted flat plates.

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Newton's rings result when we have contact in the middle, and separation outside; but the converse case may also occur. If a piece of glass gets scratched, experience shows that it becomes difficult to contact it. The reason of this is that the hard particle that causes the scratch, ploughs up a sort of ridge, which of course prevents contact near it. If the scratch is short, we may nevertheless obtain contact at a distance from it by the flexure of the glass. A specimen of this kind shows the scratch in the middle, the interferential tints all around, with contact and blackness at the circumference. If it is allowable to be a little Irish, we might describe it as "Newton's rings with the black centre at the outside." The interferential tints enable us to determine the height of the ridge.

Fig. 1.

Although to a first approximation the reflexion from the interface of contacted plates is black, or in other words non-existent, yet there is a slight reflexion. In the ideal case when the surfaces are in contact the reflexion should be evanescent, but the intensity should increase as they are separated, all this occurring within the range when the interface reflexion is still black to the casual observer. The wave theory allows us to connect the intensity of reflexion with the distance, and it was hoped in this way to obtain a direct measure of the distance between the surfaces, which might be brought into relation with the energy required to separate them.

I found, however, that there was a very curious uncertainty in the amount of reflexion, particularly when surfaces of silica glass were used. I mean that one pair of contacted surfaces would give quite a different reflecting power from another, sometimes ten times as much. What could be the explanation? It was natural to seek it in the character of

the surfaces themselves. Since it is not so easy to modify the surfaces experimentally while preserving the flatness necessary for contacting, I thought of trying a single surface immersed in liquid of the same refractive index, which automatically adjusts itself to the shape of the immersed surface. This at once gave a clue to the mystery. Carbon tetrachloride has nearly the same index as fused silica, and by adding a little ether an exact adjustment can be made for green, the brightest part of the spectrum, so that green light passing through a prism of silica immersed in the liquid suffers no deviation.

In this way we get a liquid which matches optically the inside of the silica prism, irrespective of what the optical quality of the skin may be. The skin, on the other hand, determines the reflecting power of the immersed silica. If the skin is the same as the inside, then there should be no reflexion. When I tested a surface commercially polished, there was usually very little reflexion, and if a fired surface, or a surface slightly washed with dilute hydrofluoric acid was used, the reflexion became practically evanescent. On the other hand, any attempt to polish it further with the somewhat amateurish technique of my laboratory increased the reflexion largely; and rubbing it on a dry felt wheel with a very fine abrasive powder did so still more, until a practical maximum had been reached. An abrasive powder used in this way does not destroy the polish. The increase of reflexion produced is so great that it can readily be seen even without immersion.

The felt wheel with the fine abrasive produces a modified skin; and it is interesting to inquire what is the optical character of the skin and, also, what is its thickness? By putting the surface in a series of refracting liquids, we can find which liquid reduces the reflexion to a minimum. I find that a mixture of 75 volumes of carbon disulphide and 25 volumes of benzene, index 1.596, does this. It is to be concluded that the skin is quite as refractive as light flint glass, whereas the body of the silica (index 1.46) is much less refractive than crown glass.

This is a surprising result, and shows that the skin produced by the treatment is something quite different from any of the known modifications of silica. Yet it is difficult to see what else than silica can enter into its composition. By dipping part of the plate in dilute hydrofluoric acid we may dissolve off the modified layer from that part, leaving a kind of step. To estimate the height of this step, we apply a flat test plate and observe the dislocation of interference fringes when they cross the step. In this way the height of the step, and hence the thickness of the layer, has been estimated at $\frac{1}{20}$ th of the wave-length

of light in air. Fig. 2 shows a strip of this kind; it has, however, been etched more deeply than is necessary to remove the layer. Similar effects to those with silica can be obtained with glass surfaces, but the layer produced by the felt wheel with abrasive is definitely less refractive than in the case of silica, and since the material is more refractive to begin with, the change is a good deal less conspicuous.

Fig. 2.

Returning to the contacted surfaces, it will now not be difficult to understand why some have a stronger reflexion from the interface than others. It is because the ordinary process of polishing is somewhat haphazard. It may produce a modified layer, as the felt wheel with fine abrasive does, or it may remove the layer already produced. This depends on the exact conditions of the polisher. I have verified this, using a cloth polishing wheel with rouge, which was quite wet to begin with and was allowed to dry. The reflexion of the silica surface was tested at intervals, and was found to pass through a minimum at a certain degree of moisture of the polisher. Concurrent weighings showed that this was the stage at which material was being most rapidly removed.

It is evident that if the contacted surfaces are not exactly alike, residual reflexion is to be expected, even if there is no separation of the surfaces. Further, even if they are alike, there will be reflexion at the separating surface between the skin and the body of the material in each of the glasses. If therefore we wish to reduce the interface reflexion to a minimum, we must get rid of the skin. I have tried contacting two glasses which have been deprived of their skin by means of hydrofluoric acid or caustic potash, but this is not as satisfactory as might have been hoped, because the chemical treatment develops all kinds of defects which were latent in the polished surface, and the light scattered by these makes it very difficult to investigate the faint residual reflexion. I have not been able to determine with certainty that the reflexion is in any case less than would correspond to about 10 Å. distance between the

planes. This is three or four times as much as the distance apart of the atoms in crystals.

In conclusion, I wish to explain how we may determine the amount of work done in separating two contacted surfaces, or even the amount of work which can be gained by the action of the attractive forces when they are contacted. These amounts of work are not the same, for the process of decontacting and contacting again is not, in the thermodynamic sense, reversible. We must start with a contacted surface and slowly tear the contact away. A square of glass is contacted diagonally on to a larger piece, but one corner of the square overlaps the edge (Fig. 3). For security, the two pieces are clamped together as shown by the dotted outline, and the non-contacted surface of the smaller glass is blackened to diminish false light. Projecting the reflexion through the larger basal glass, initially, all is dark. On pulling the corner of the smaller glass away from the larger one with the forefinger, the contact is stripped away, and interference fringes spring into view (Fig. 3*b*). These extend as the pull is increased, five or six orders of colours being brilliantly developed. On releasing the corner, the glass becomes flat again, the contact is restored, the fringe system recedes, and a moment later it vanishes entirely, leaving all dark as at first.

The quantitative experiment is on the same principle; but the pulling apart is done by weights gradually added, instead of by the finger. The glasses are horizontal, and to find how far the weights attached to the corner have descended, we count the number of interference fringes. This shows how much the corner, initially in the plane of the larger glass, has been depressed from it. Hence the work of decontacting may readily be

Fig. 3.

calculated. On removing the weights, the plate recontacts, and the work recovered may be determined. The work spent in bending the glass is readily allowed for. Experiments made in this way gave 71.2 ergs per square centimetre for the work of stripping, and for that recovered by recontacting about half this amount.

It is interesting to note that the work done in creating a liquid surface (surface tension $\times$ length) is of the same order as this.