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Teaching air wedge interference

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Several A-level syllabuses include the experiment shown in figure 1. An air wedge is formed between two glass plates G inclined at a small angle, α, by means of a thin spacer, X. Light from an extended monochromatic source, S, such as a sodium lamp, is reflected onto the wedge by the glass plate R, and the light reflected up from the wedge is observed through a microscope M. Part of the light is reflected by each surface of the wedge, and the two reflections, which are coherent, have a geometrical path difference of $2d$, where d is the wedge thickness. One therefore observes interference of a type which depends on d. If the surfaces bounding the wedge are optically flat, d varies linearly with distance across the wedge, which gives evenly spaced fringes of separation $\lambda/2\alpha$, where λ is the wavelength of the light.

The essential physics is thus very simple. However, problems arise when one tries to explain more fully what is happening. A glance at some popular A-level textbooks reveals diagrams such as those shown in figure 2. (In each case refraction at the air/glass boundary is ignored, as it will be in this article.) To a teacher, it will be clear that figures 2a and b are not attempting to show what actually happens to the incident ray, but any student who remembers the laws of reflection is likely to be confused. Presumably the intention behind such diagrams is that, if details are avoided, the essential physics will stand out more clearly. However, I believe that, for all but the weakest students, details are more likely to recede into the background if they have first been clearly explained.

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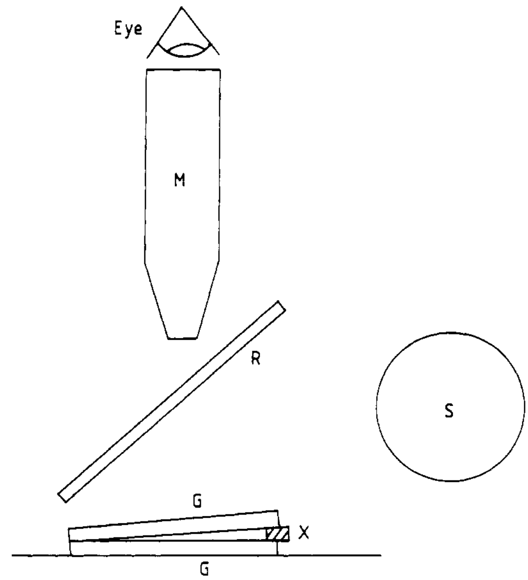

Figure 1

Figure 2c, where the law of reflection is obeyed and the two reflected rays are not parallel, is more realistic. But even here there are difficulties if one attempts to discuss the localisation of the fringes. Clearly, one should observe interference if the microscope is focused at P, where the rays intersect. But suppose one looks elsewhere? In fact, the fringes are not sharply localised, but may be seen for some distance above the wedge, depending on the angle of the wedge and how it is viewed.

More advanced textbooks solve these problems by abandoning the 'ray' approach, and discussing sets of intersecting wavefronts reflected from the two faces of the wedge. Although this approach is seldom used at school level, it is within the scope of good 'S' level students, particularly if it is related to Young's fringes, with which they are very familiar. Such a treatment is outlined in the last section of this article. However, what is needed for everyday purposes is to make the 'ray' treatment work properly, and this is done in the next section.

No originality is claimed for the approaches adopted here. However, they do not seem to be common in textbooks, and they may be of interest to other teachers.

Improving the ray approach

The trouble with the diagrams in figure 2 is that, by asking what happens to a single incident ray, they

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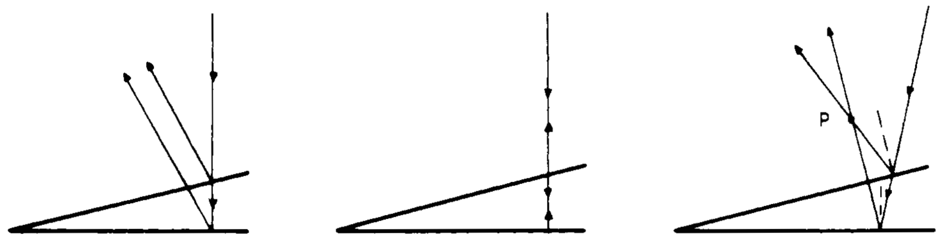


Figure 2

approach the problem from the wrong end. In practice, one can focus the microscope on any point one wishes, and all rays which pass through that point into the eye will be superposed on the retina. We should therefore begin by specifying the observation point, and then ask what light arrives there.

Consider first a *point* source S (figure 3). With the apparatus shown in figure 1, S will be the virtual image formed by plate R of a point source in the lamp. If the microscope is focused on an arbitrarily chosen piont P, then the two rays which superpose are those shown in figure 3. Each obeys the law of reflection, but they are *not*, in general, part of the same incident ray. Since S is a point source the rays are coherent, and the result of superposition depends on their path difference.

To find the path difference, assume that S is a *distant* source, so that SX and SY are approximately parallel. Then PX and PY are also nearly parallel, because α is very small. The important part of figure 3 then looks like figure 4a.

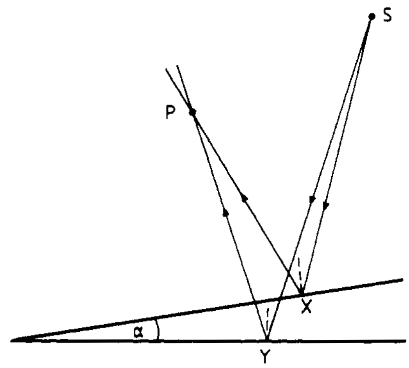


Figure 3

$$\begin{aligned}\text{The path difference} &= BY+YA\\ &= XY\ [\cos\theta+\cos(2\gamma+\theta)]\\ &= 2XY\ \cos(\gamma+\theta)\ \cos\gamma\\ &= 2d\cos\gamma,\end{aligned}$$

where γ is the angle of incidence on the bottom surface, and d is the wedge thickness at X. For near-normal incidence ($\cos\gamma\approx1$), the path difference is $2d$, as is clear from figure 4b.

Having discussed the details, one can summarise

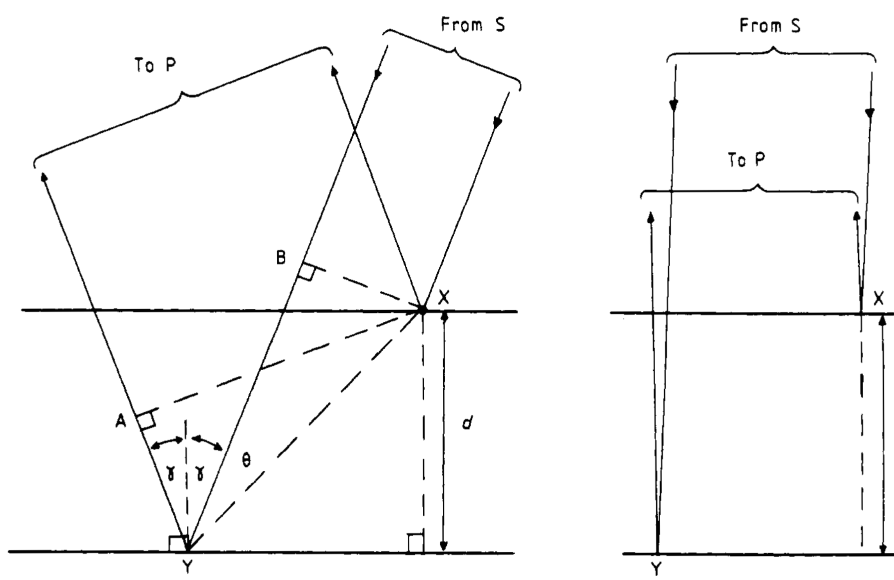


Figure 4

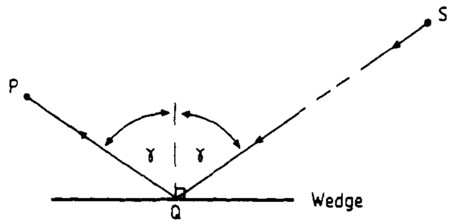


Figure 5

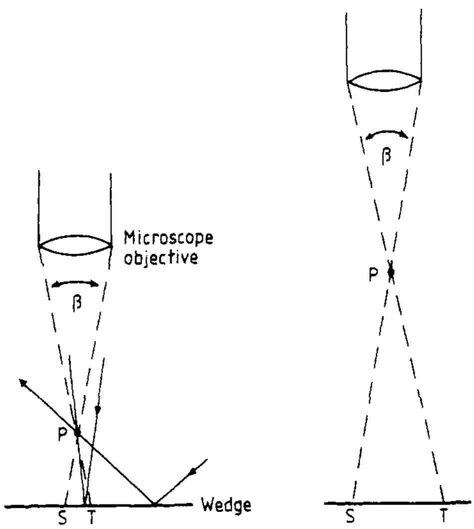


Figure 6

the result with reference to figure 5, which takes due account of the smallness of the wedge angle. Light will arrive at P from 'point' Q on the wedge if there is a point source S in the appropriate direction. The light will consist of a pair of coherent rays with geometrical path difference $2d \cos \gamma$, where d is the wedge thickness and γ the angle of incidence at Q.

Fringe localisation is now readily explained. With an *extended* source, light strikes all parts of the wedge with a range of angles of incidence. Therefore pairs of coherent rays arrive at any observation point from all parts of the wedge. However it is clear from figure 6a that not all such rays enter the microscope. The microscope objective subtends an angle β at the point P on which the microscope is focused, and β defines the region of the wedge, ST, which contributes to the image. Only light reflected from within ST can enter the microscope and so contribute to the image of P. For all such rays, $\gamma \leq \beta/2$, and β is usually small enough for the 'normal incidence' approximation to be valid. However d varies across ST. If ST is small enough, this variation is negligible (i.e. $\ll\lambda$), and the path difference is essentially the same for all coherent pairs of rays passing through P into the microscope. In that case, fringes will be observed in a horizontal plane passing through P. However if the microscope is focused higher up (figure 6b), the effective region of the wedge ST is enlarged, and so is the variation of d across it. If this variation is large enough, the interference effects from different parts of ST will average out, and no fringes will be seen.

This leads to a rough criterion for fringe visibility. The change in d between S and T is αST, giving a change in path difference of 2αST. Fringes will not be observed if

$$2\alpha \mathrm{ST} \gtrsim \lambda$$

or

$$\mathrm{ST} \gtrsim \lambda/2\alpha$$

i.e.

$$\mathrm{ST} \gtrsim \text{the fringe spacing.}$$

If P is a distance z above the wedge, then

$$\mathrm{ST} \approx \beta z,$$

so fringes will not be observed if

$$z \gtrsim \lambda/2\alpha\beta = (\text{fringe spacing}\ /\beta).$$

This result is easily tested experimentally. I used the arrangement shown in figure 1, with a sodium lamp as the extended source S. The travelling microscope had an objective of diameter 6 mm, focused on a level 47 mm below, giving $\beta = 6/47 = 0.13$ radian. Observing fringes of separation 1 mm, I found that the microscope could be raised about 10 mm above the position where they were clearest before they disappeared. This agrees quite well with the value of (fringe separation/β) which was $1/0.13 \approx 8$ mm. With a wedge of smaller angle, or a viewing arrangement which ensured more nearly normal incidence, the fringes would have been less localised.

It is not, of course, suggested that the detailed treatment given here should be expected of an A-level candidate. Most A-level examiners would, rightly, be satisfied with the account given in the first paragraph of this article, together with a mention of the need for near-normal incidence, the phase change at the bottom reflection, and the calculation of the fringe spacing. However I have found that, in teaching the topic, a presentation based on figures 3, 4b, 5 and 6 is accessible to students, and improves their understanding of the phenomena.

The air wedge as a case of Young's fringes

An interesting alternative, for able students, is to take advantage of their familiarity with Young's experiment. In figure 7a, S is again a *point* source, a distance D from the wedge apex O. Each reflecting surface produces a virtual image (I_1 and I_2). Simple geometry shows that S, I_1 and I_2 all lie on a circle of radius D centred at O, and that I_1 and I_2 subtend an

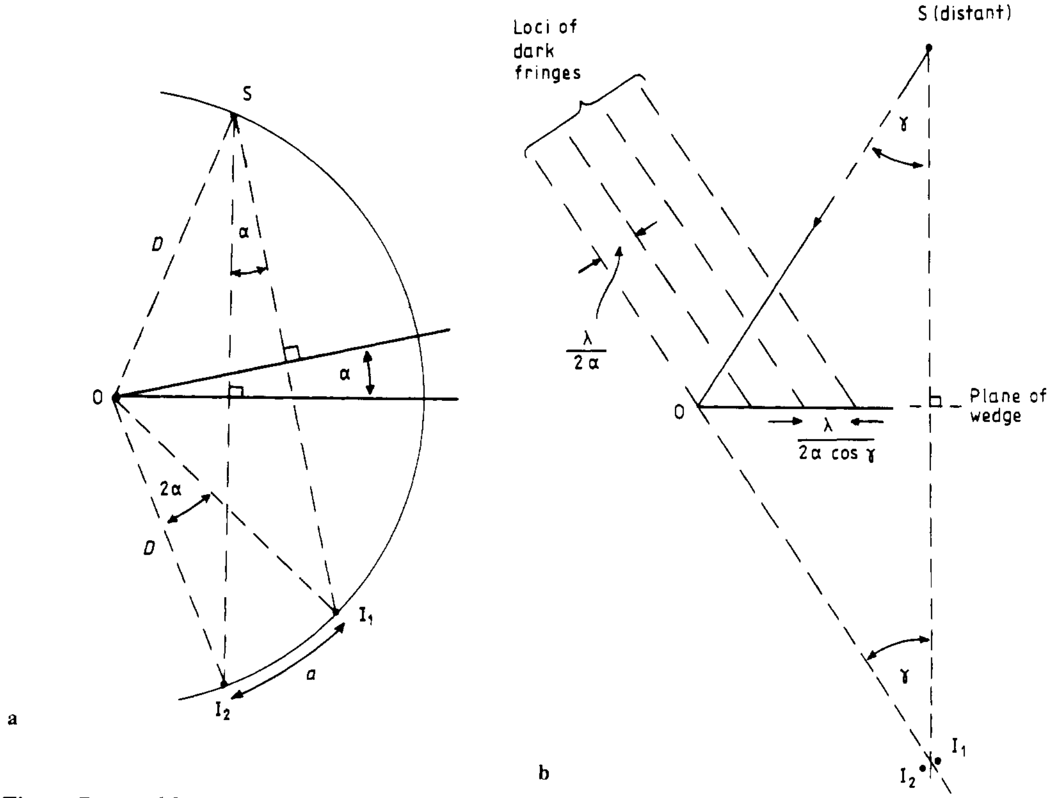


Figure 7 a and **b**

angle of 2α at O. Their separation $a=2\alpha D$. Since I_1 and I_2 are coherent sources, Young's fringes will be produced in the region above the wedge.

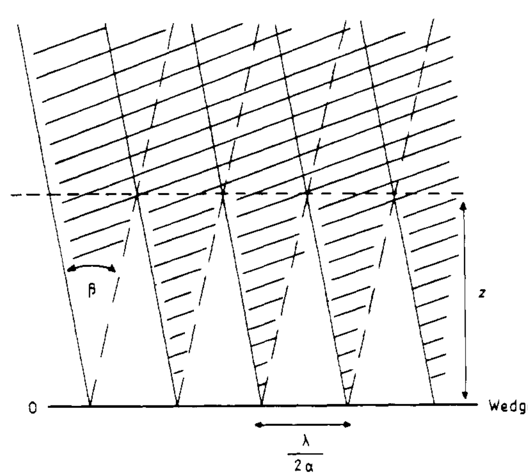
Assuming, as before, that D is large (S a distant source), and remembering that 2α is small, we can use the usual formula $\lambda D/a$ for the fringe spacing, and obtain a spacing of $\lambda D/2D\alpha=\lambda/2\alpha$ in the vicinity of the wedge. D has cancelled out because, as long as it is large, we simply have two sets of plane waves intersecting at an angle of 2α.

Figure 7b shows the result, taking account of the fact that α is very small. The orientation of the fringe loci depends on the angle of incidence γ of the light. The fringe spacing *along the wedge* is $\lambda/2\alpha\cos\gamma$, which reduces to $\lambda/2\alpha$ for near-normal incidence.

With an *extended* light source, each direction of incident light gives rise to its own fringe system, but in every case the line of zero geometrical path difference passes through O. If, as before, the viewing arrangements restrict γ to small values ($<\beta/2$), all the fringe systems have essentially the same spacing at the wedge, and so the fringes coincide there and are visible. However, as one moves up from the wedge, the fringe systems get increasingly out of step with each other.

In figure 8 the full and broken lines represent the loci of *bright* fringes for the two extreme angles of

Figure 8



incidence, $\pm\beta/2$. At any point in the shaded region there will be a bright fringe due to one or more angles of incidence in between. Clearly one cannot expect to observe interference at a distance above the wedge greater than roughly z, where $\lambda/2\alpha z=\beta$, i.e. $z=\lambda/2\alpha\beta$, which is the same condition as derived in the previous section.

Aside

It is an interesting exercise to consider interference in a *parallel*-sided film from the Young's fringes point of view. Again one obtains a Young's fringe system fom each point on an extended source, only this time the different systems coincide at infinity. The fringes are therefore best viewed by a relaxed eye, as is usually assumed. The conditions under which they may be seen by an accommodated eye can be worked out by methods similar to those used above.

Acknowledgment

I am grateful to Dr I R Gomersall for some helpful suggestions, and to my sixth-form pupils whose scepticism prompted this work.

Queries in physics

Q601 (from *QIP* 66) From a fairly recent examination: a spaceship has an external tank of volume V, which contains oxygen gas at pressure p_0. A meteorite punctures the tank producing a small hole area A in the side. Obtain an expression for the pressure in the tank after time t in terms of p_0, A, V and t.

Q602 In Deschanel's *Natural Philosophy* translated and modified by J D Everett (1901), there is a mention of Mr Wimshurst later (1892) showing a version of his machine which produced *alternating* charges. Can anyone throw further light on this?

The above items were selected from *QIP*, a thrice-yearly broadsheet. It is available on subscription at a rate of £2.75 (£4 overseas airmail, £3.50 surface mail) from the Editor, Mr W H Jarvis, Salewheel House, Ribchester, Preston PR3 3XU. All correspondence concerning this feature should be addressed to Mr Jarvis.

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