# Mechanical model aids understanding of light interference

## Student's difficulties with the theory of double-slit interference

Almost all physics textbooks, while constructing the quantitative theory of double-slit interference (Young's interference experiment), follow the same conceptual and modelling sequence. First, the principle of superposition of waves, Huygens' principle and Young's method for obtaining two coherent light sources are introduced. Then it is shown (using the arrangement in figure 1) that the path length difference from the two slits to the arbitrary point P on the screen determines the resulting amplitude of the waves at that point. If the path length difference $r_1 - r_2$ is multiple of the wavelength, the waves arrive at P in phase and they produce a maximum. If the path length difference is an odd multiple of half a wavelength, the waves interfere destructively and produce a minimum.

Most of the students will follow the lecture up to this point. And then comes the derivation of the famous formula

$$d \sin \theta_N = N\lambda ,$$

which gives the angular directions of interference maxima (expressed by $\theta_N$). The derivation is based on a geometrical construction, which, for most

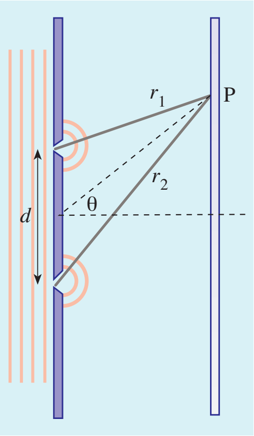


**Figure 1**. *A typical arrangement for theoretical treatment of double-slit interference.*

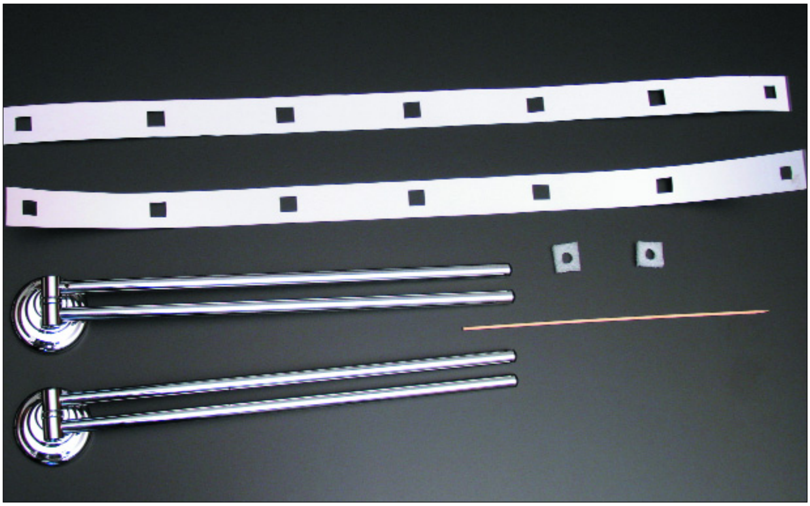


**Figure 2**. *The mechanical device to demonstrate double-slit interference is made from two towel hangers, a length of ribbon, two washers and a stick.*

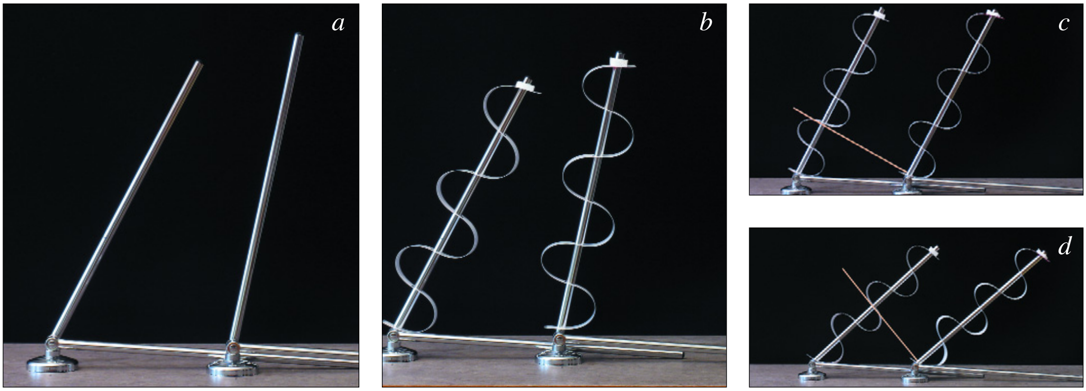


**Figure 3**. *Mechanical model for double-slit interference:* (a), (b) *Setting up the mechanical analogue,* (c) *constructive interference,* (d) *destructive interference.*

students, proves difficult to follow and distracts their attention from the physical content of the phenomenon. The main difficulty with the derivation is that its abstract reasoning involves some confusing elements [1, 2]. Namely, the triangle near the slits is treated as the 'triangle with two right angles' or the 'triangle with parallel sides', while, at the same time, these 'two parallel and very long sides', being different in length, meet at the screen.

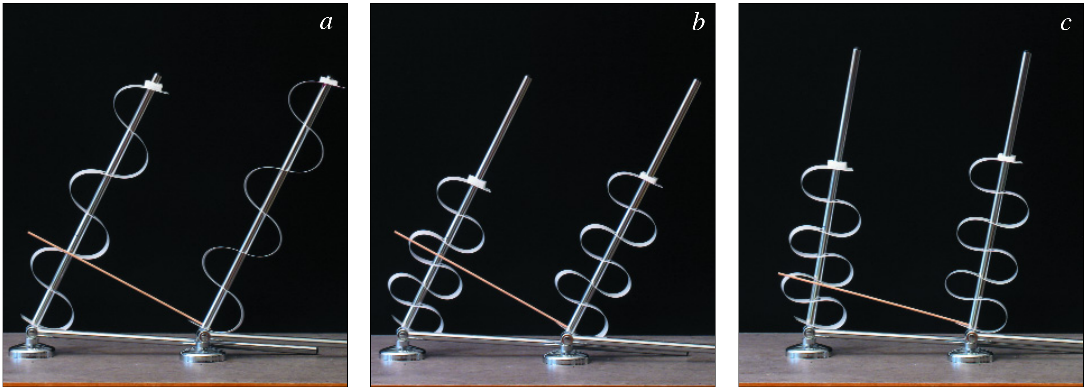
It has been well known for some time that among students entering university, only 25–30% have developed abstract thinking abilities [3, 4]. The remainder are unable to learn physics by listening to abstract arguments or through mathematical reasoning. Even if they are told that the derivation is an approximation, concrete thinkers will not be able to overcome the abstractness of the model and construct a useful mental picture of the phenomenon.

The lack of understanding of the physical background of the phenomenon and the physical meaning of the diffraction formula can be revealed in several ways. One is to ask students to give a qualitative prediction of how changing a variable affects an interference pattern. For example:

**Q1** How would the distance to the first maximum in the double-slit interference experiment change if we use green laser light instead of red laser light? Would the distance decrease, increase or remain unchanged?

**Q2** How would the distance to the first maximum

**Figure 4**. *(Left.) The direction of the principal maximum does not depend on the wavelength or slit-to-slit distance*. **Figure 5**. *(Below.) How will the double-slit interference pattern change if the wavelength is reduced?* (a) *The initial direction of the first maximum;* (b) *and* (c) *For the light with shorter wavelength, the first (and higher) maxima move closer to the principal maximum.*



> in the double-slit interference experiment change if the distance between the slits were reduced? Would it decrease, increase or remain unchanged?

Most students who give the correct answers to these questions will base their answers solely on carrying out a mathematical operation using the formula. So they haven't grasped the physical reason for the relationship between two variables, and are confusing it with the mathematical expression.

Here we propose a simple demonstration tool that can be used as a mechanical model of Young's experiment and which may help the majority of students, who might be lacking formal thinking abilities, to construct a functional mental picture of the phenomenon. Once the students construct a proper mental picture about double-slit interference and relate it to the mathematical expression, the later treatment of the diffraction grating will appear as a less troubling extension. The application of the mechanical model will be demonstrated through four exercises (described later), including two exercises based on Q1 and Q2 stated above.

### Mechanical model for double-slit interference (figure 2)

The core of the mechanical model consists of two two-arm towel hangers. For the best performance, try to obtain towel hangers with arms of uniform thickness, though the device will still work with arms of variable thickness. You will also need two ribbons (we cut ours from flexible plastic foil) for making 'light waves', two washers (made from rubber or Styrofoam) to limit the extension of the 'waves' and a thin wooden or metal stick to visualize the perpendicular line to the 'light beam' (figure 3). The ribbons in figure 2 are 3 cm wide, 75 cm long and the holes are 12 cm apart. The holes should be large enough that the arms of the towel hanger can easily pass through. Drill a small hole into one of the arms close to the hinge and facing the direction of the arm's rotation (barely seen on the upper towel-hanger in figure 2). The diameter of the hole must be the same as the diameter of the wooden stick. The parts that make up the mechanical device are shown in figure 2.

### Introduction of the mechanical model to the class

First, explain to the class that this is not an interference experiment but only a demonstration using a mechanical tool of how the interference pattern behind the two slits is formed or, in other words, how the features of the pattern depend on the variables involved.

Place the two towel hangers on the table as shown in figure 3a. Ask the students to imagine that the slits are at the hinges and that the plane waves are incident on the slits from the floor side. Remind the class of Huygens' principle while rotating one of the towel-hanger arms for a half circle. Let them realize that the hanger arm is always perpendicular to the imaginary circles (representing the wave fronts of outgoing waves) and that the role of the arm is equivalent to the light ray. Make sure that one of the arms on each towel hanger is touching the table at all times, thus stabilizing the whole construction. If necessary, fix an arm to the table using tape.

### Constructing a functional mental picture of the phenomenon

Take a plastic ribbon and put it on one of the arms by folding it between the holes so that the final form of the ribbon resembles a sine wave (figure 3b). Fix the wavelength by putting a rubber washer on the end of the arm. Following the same procedure make an identical wave on the other arm. Make sure that the phases of the two waves are equal.

Now, rotate the arms to make them almost parallel. Explain that the ribbon represents light waves (an oscillation of electric field) that emerge from the slit and travel along the direction of the arm. Explain that because the wave directions are almost parallel, the light waves meet and add (superimpose) somewhere far from the slits. We are trying to predict how the two waves combine somewhere far away from the slits. In particular, we want to know if the waves add constructively or cancel each other out. Ask the students what determines the answer to this question.

When they understand that the answer depends on the path difference between the waves, then proceed by asking how the distance to the place where the light rays meet would change if the the angle between the arms were increased. Continue when you are sure that they understand this part.

Now, as the arms are nearly parallel, ask the students if they can tell what the path-length difference between the two light rays is. Push the wooden stick into the hole on the lower arm and explain that this is the marker that helps us to visualize the path difference and determine it more accurately. Discuss the type of interference for the given case. Then rotate both arms to a new position (make sure they are again parallel) and discuss the type of interference there. Discuss the cases of constructive and destructive interference (figures 3c and 3d). Emphasize that you are interested in how the light waves combine far away from the slits and that you can predict this only by observing the short section of the wave paths near the slits.

Now you are ready to do the following exercises.

1. Rotate both arms to a vertical position. Show that there is always a principal maximum in the direction perpendicular to the grating irrespective of the wavelength or slit-to-slit distance (figure 4).
2. Count how many maxima can be observed for a given slit-to-slit distance and wavelength. Rotate the arms from 0 to 90° and pause every time constructive interference occurs. Show that the number of maxima on each side of the principal maximum is equal to the number of complete wavelengths that fit into the spacing between the slits.
3. Ask students to predict how the interference pattern will change if you use light with a shorter wavelength (see Q1). Set the mechanical analogue to first maximum as shown in figure 5a, then reduce the wavelength by sliding the washers down equal distances on both arms (figure 5b). Discuss the type of interference in this case. Then ask: 'How should I rotate the arms to get the first maximum at this wavelength?' At this point,

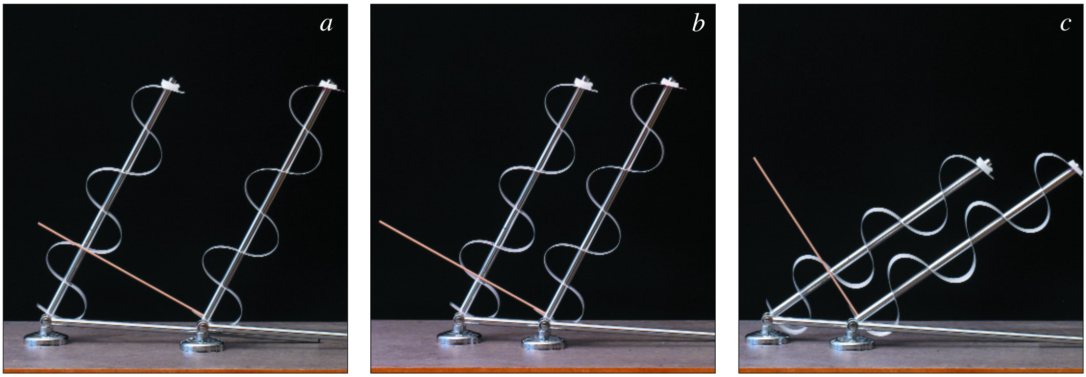


**Figure 6**. *How will the interference pattern change if the slit-to-slit distance is reduced?* (a) *The initial direction of the first maximum;* (b) *and* (c) *For the shorter slit-to-slit distance the first (and higher) maxima move away from the principal maximum.*

every student should provide his or her suggestion along with a verbal and visual justification. We recommend that students form groups of three or four and share their thoughts with each other [5]. Needless to say, you should give the class enough time to formulate and discuss ideas about the change in interference pattern. When you are sure that the majority of the class has the right answer, rotate the arms to obtain the new maximum (figure 5c) and demonstrate the solution. Proceed with a discussion on how a change in wavelength affects the interference pattern on screen.

4. Ask students to predict how the interference pattern will change if the distance between the slits is reduced (Q2). Set the mechanical model to first maximum again, as shown in figure 6a. Then move the hinges closer (figure 6b). Discuss the type of interference in this case. Then ask: 'How should I rotate the arms now to get the first maximum at this slit-to-slit distance?' As before, personal and group suggestions and justifications are expected. When the majority of the class gets the right answer, rotate the arms to obtain the new maximum (figure 6c) and demonstrate the solution to the class. Proceed with a discussion on how the change in slit-to-slit distance will affect the interference pattern on screen.

It is important that every prediction emerging from the performance with the mechanical model is followed by a direct experimental demonstration. The experimental verification of the qualitative prediction establishes the relevance of the subject to the real world and increases students' confidence in their thinking abilities.

The double-slit experiments that would fit in the discussion above can be carried out using green and red laser pointers and different sized double slits. As many teachers may already know, you can use CDs and DVDs for the slits, which are easy to obtain and give clear diffraction patterns that can be easily shown in front of the whole class. Unfortunately, in this case, theoretical treatment becomes more complex. As an approximation, only the reflection and diffraction on the grating should be considered.

## References

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