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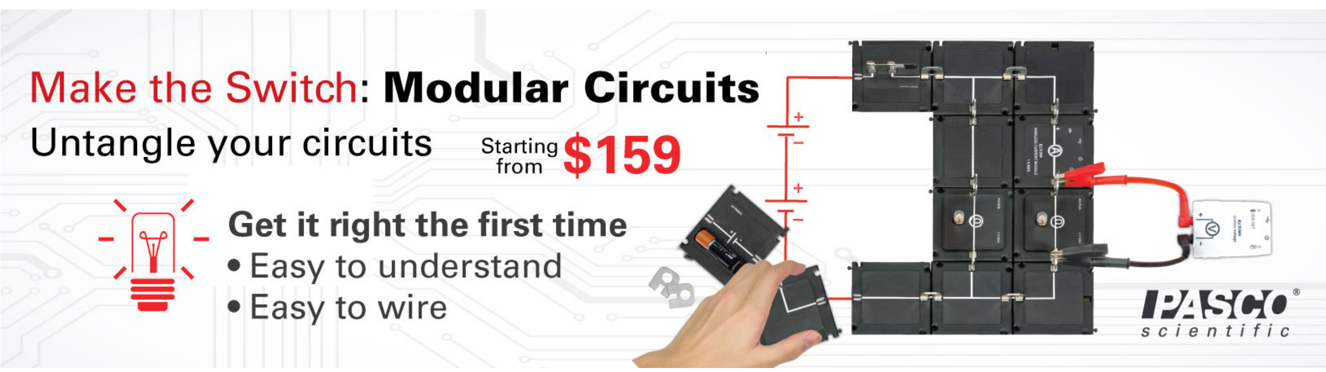

Smartphone Magnification Attachment: Microscope or Magnifying Glass

Timo Hergemöller and Daniel Laumann, Westfälische Wilhelms-Universität Münster, Germany

Today smartphones and tablets do not merely pervade our daily life, but also play a major role in STEM education in general, and in experimental investigations in particular. Enabling teachers and students to make use of these new techniques in physics lessons requires supplying capable and affordable applications. Our article presents the improvement of a low-cost technique turning smartphones into powerful magnifying glasses or microscopes. Adding only a 3D-printed clip attached to the smartphone's camera and inserting a small glass bead in this clip enables smartphones to take pictures with up to 780x magnification (see Fig. 1). In addition, the construction of the smartphone attachments helps to explain and examine the differences between magnifying glasses and microscopes, and shows that the widespread term "smartphone microscope" for this technique is inaccurate from a physics educational perspective.

Fig. 1. Smartphone image magnification of a human hair using 3D-printed clip with glass bead and click light source.

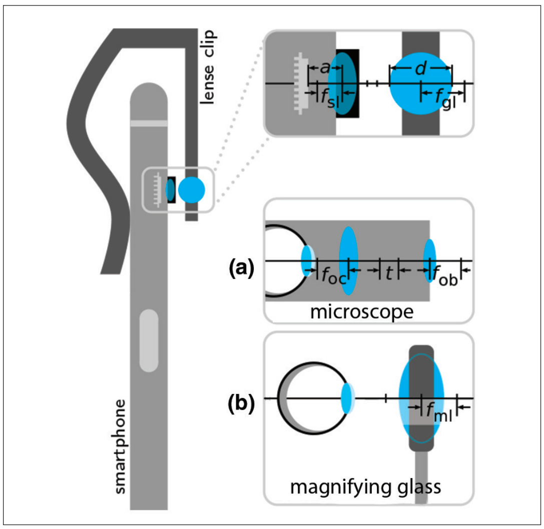

Fig. 2. Smartphone magnification attachment compared to a microscope (a) and a magnifying glass (b). The focal length of the smartphone camera lens f_{sl}, the glass bead f_{gl}, the microscope ocular f_{oc} and objective f_{ob}, and the magnifying lens f_{ml}, as well as the distance *a* between image sensor and smartphone lens and the diameter *d* of the glass bead as relevant parameters are displayed.

What is the purpose of smartphone image magnifications?

While many schools do not possess a sufficient amount of experimental tools for STEM education, one can assume that many students are bringing their smartphones or tablets in schools. Empirical studies show that in the United States, approximately half of the teenagers carry their smartphones to school.[1] Since these mobile items are already present in classes, it seems logical to use smartphones for different kinds of experiments in STEM education.

In recent years smartphones and tablets have become important as experimental tools used as resources for free-fall experiments,[2] the measurements of acoustic phenomena,[3] or the investigation of planetary transits.[4] However, the usage of smartphones or tablets as magnification instruments is not prevalent in physics education research yet. Nevertheless, the idea of magnification attachments for smartphones is a recognized method in biology used to detect specific kinds of bacteria.[5,6]

This invention has been labeled as a "smartphone microscope."[7-9] Our article shows how this method can be adapted and improved for physics experiments. Moreover, from a physics education perspective, this magnification technique gives an interesting opportunity to discuss the difference between a magnifying glass and a microscope. An example for a typical experiment being performed with the help of smartphone image magnification is the investigation of the Brownian movement.[10] Other fruitful applications of this technique can be found in interdisciplinary STEM projects. Such projects combining, e.g., physics and biology in the field of bionics are identified to cause an affirmative impact on students' learning processes.[11]

Smartphone + 3D-printed clip + one glass bead = microscope?

The current method that will be discussed in this paper uses a 3D-printed clip attached on the smartphone holding a small glass bead, which causes the image's magnification (see Fig. 2). Furthermore, a suitable light source is needed for this kind of transmitted-light microscopy. It is recommended to use a homogeneous light source with sufficient brightness. For all investigations discussed here, an LED push light with three white LEDs is used. Since the glass bead serves as a spherical ball lens in this setting, the degree of magnification depends on its diameter *d* (see Fig. 2). Referring to former research we investigated the magnification of two different sizes of glass beads.[8,9] To determine the magnification of the spherical lenses, images taken by the smartphone magnification attachment were matched against those of a Nikon Eclipse E200 with given degree of magnification. To compare these images we took pictures of a multiple-slit arrangement

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(lattice constant a =125 μm). Our experimental results show that spherical lenses with diameter d = 3 mm supply about 100x magnified images, whereas smaller glass beads (d = 1 mm) are able to produce approximately 350x magnifications (Table I). Hence, the 3D-printed smartphone magnification attachment represents a powerful tool for a variety of experiments.

Table I. Overview of different smartphone magnification attachments.

glass bead 1 mm	glass bead 3 mm	degree of magnification	spatial resolution $\Delta\varepsilon x_m$ in μm
magnifying glass			
X	✓	100x	$1.8 < \Delta x_m < 10$
✓	X	350x	$1 < \Delta x_m < 1.8$
microscope			
✓	✓	780x	$1.8 < \Delta x_m < 10$

At first sight it seems logical to label the smartphone with its magnification attachment as a microscope for two reasons. On the one hand the degree of magnification is comparable to a "real" microscope, and on the other hand the existence of two lenses (spherical glass bead lens plus smartphone camera lens) seem to represent the typical objective and ocular lenses of a microscope. The label "smartphone microscope" is typically used in former descriptions of this technique.[7-9] In this case the ball lens would serve as the objective lens and the lens of the smartphone camera would serve as the ocular lens (see Fig. 2). However, a more detailed analysis [see Fig. 2 (a)] reveals that this identification of the different lenses is not appropriate because each microscope consists of at least three different lenses. Two of them, the objective lens and the ocular lens, affect the magnification, while the human eye lens is essential to create a sharp picture. As a consequence the smartphone with its magnification clip misses one lens to act as a microscope and rather constitutes a magnifying glass [see Fig. 2 (b)]. This reasoning is consistent with the typical definition in ray optics of a magnifying glass, or simple magnifier, and microscope as discussed in the standard textbooks of university introductory physics courses.[12-14]

This argument is supported by two more reasons. At first taking a picture with the magnification attachment reveals that the image is not laterally inverted, which is a typical feature of a magnifying lens and not a microscope. Secondly, one can easily calculate the physical thickness of a smartphone plus magnification attachment, comparing this to the required optical path of an analogous microscope (see Fig. 2). For example, an iPhone 6 Plus exhibits a total thickness, including camera, of 7.7 mm. Adding a magnification attachment including a 3-mm lens results in an entire length of 10.7 mm. The experimental results show that a 3-mm lens causes a magnification $M_{3\text{ mm}} = -100$. The negative sign indicates that we see a true-sided picture being reversed by our brain. Assuming the smartphone magnification attachment would correspond to a microscope, which is, as mentioned, typically assumed in former descriptions of this technique,[7-9] the magnification $M_{\text{mic, 3 mm}}$ could be calculated as

$$M_{\text{mic,3mm}} = -\frac{t}{f_{\text{gl}}} \times \frac{250\text{ mm}}{f_{\text{sl}}}, \tag{1}$$

with the focal length of the ball lens f_{gl} and the focal length of the smartphone camera lens f_{sl}.[15] Being able to determine f_{gl}, we use the lens-maker's equation in air:

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{d(n-1)}{nR_1R_2}\right], \tag{2}$$

typically describing the focal length of a thin lens, to obtain the focal length of a thick spherical or ball lens. The radius R_1 is the radius of the curvature of the lens, d is the thickness of the lens, and n the refractive index of the lens material. For a spherical lens we can assume $R = R_1 = -R_2$ and $d = 2R$, leading to

$$f_{\text{gl}} = \frac{nR}{2(n-1)}, \tag{3}$$

corresponding to the relation specific to a ball lens.[16] We obtain f_{gl} = 2.36 mm as focal length of the spherical glass bead lens (thickness d = 3 mm) consisting of borosilicate glass (experimentally determined refractive index $n = 1.466 \pm 0.012$). Since f_{sl} describes the smartphone's focal length, the technical data of the iPhone 6 Plus mentions a value of f_{sl} = 4.15m.[17] For the experimentally measured magnification $M_{3\text{ mm}}$ =100, a tube length t = 3.92 mm follows (see Fig. 2). Furthermore, one needs to consider a distance a = 4.2 mm between the image sensor and the smartphone lens of the iPhone 6 Plus.[17] Referring to the assumed setup of the "smartphone microscope" (see Fig. 2), this results in a total length of 16.99 mm. Comparing the real thickness 10.77 mm of the iPhone 6 Plus with magnification attachment against this value, one can easily notice that the assumed setup is inappropriate. Calculating the magnification $M_{\text{mag, 3mm}}$ for a magnifying lens using the formula

$$M_{\text{mag,3mm}} = -\frac{250\text{ mm}}{f_{\text{gl}}} \tag{4}$$

reveals $M_{\text{mag, 3 mm}} \approx 106$, which is in agreement with the experimentally determined magnification. Thus, we can conclude that the current technique, shown in Fig. 2, corresponds to a magnifying lens and not a microscope.

In the next section, Eq. (1) is used to calculate the magnification of a real smartphone microscope consisting of two ball lenses.

Smartphone + 3D-printed clip + two glass beads = microscope!

In order to design a true smartphone microscope, two glass beads instead of just one are needed (see Fig. 3). We enhanced the former technique and designed a clip capable of holding two glass beads, where one lens can serve as an objective lens (d = 3 mm → f_{ob} =2.36 mm) and the other one corresponds to an ocular lens or eyepiece (d = 1 mm → f_{oc} = 0.79 mm), and both lenses cause the total magnification of

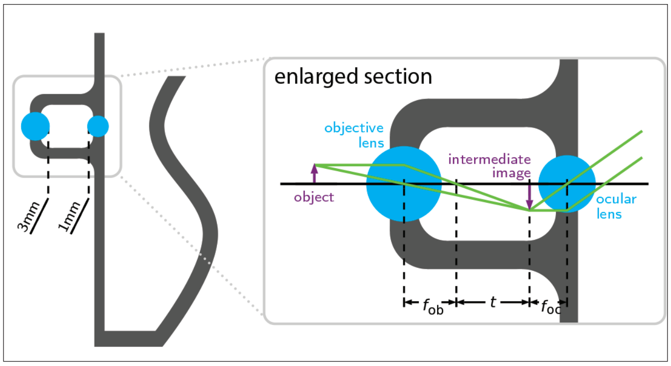

Fig. 3. Smartphone microscope magnification attachment. The 3-mm objective lens with focal distance f_{ob} = 2.36 mm creates the real intermediate image on the image plane of the 1-mm ocular lens with focal distance f_{oc} = 0.79 mm. The total magnification consists of the individual magnifications of both lenses.

this setup. Note that contrary to a standard microscope, the focal length of the ocular is less than that of the objective for technical reasons, not for reasons of physics. This magnification clip features a tube length $t = 5.85$ mm, resulting in a total $M_{mic} = 780$ magnification being determined theoretically using Eq. (1) as $M_{mic, theo} = 784 \pm 128$. The corresponding experimental value $M_{mic, exp} = 783 \pm 30$ has been determined taking pictures of a multiple-slit arrangement (lattice constant $a = 125$ µm). The experiments reveal that an image being taken with this microscope clip is laterally inverted.

Altogether three different magnification clips are available covering a degree of magnification from 100x over 300x up to 780x (see Table I.) Theoretically it is possible to insert even smaller lenses to reach higher magnifications, but our experiments show that it is very difficult to realize images of an acceptable quality and sharpness with those lenses ($d <$ 1 mm). Therefore, we would not recommend those lenses for investigations in the classroom.

To show the differences between all three magnification attachments, we investigated tiny butterfly scales (lepidopteran anatomy) of the paper kite butterfly, also known as large tree nymph (Idea leuconoe, see Fig. 4). Up to a million of those scales cover a butterfly's wing entirely, typically 0.1 mm in length and 0.05 mm in breadth.[18] The internal structure of butterfly scales causes structural colors by wavelength-selective scattering of the sunlight and creates, for instance, the beautiful blue color of morpho butterflies due to interference effects. It would be worth investigating those particles.[19]

Figure 4 shows different magnification images of paper kite butterfly scales. The optically magnified images were all taken with different clips in accordance with the different attachments described in the previous sections. Obviously one is able to reach increasing magnifications using lenses of different sizes or a microscope clip combining two different lenses. However, the images reveal that the spatial resolution and quality of the images diminishes. The spatial resolution Δx_m for the different attachments was determined experimentally. Our experiments show that both 100x and 780x magnifications correspond to a spatial resolution of 1.8 µm < Δx_m <10 µm, while the 350x magnification shares the spatial resolution 1 µm < Δx_m < 1.8 µm (see Table I). This indicates that the 3-mm lens present in the 100x and 780x magnification attachment strongly influences the spatial resolution. Reasons for this could be not perfectly round glass beads, surface deficiencies, or effects of the light source being used, as well as spherical aberration. Another important aspect influencing the resolution and quality of the images is the distance between the object and the first lens determining the sharpness of an image. Controlling this distance by hand is especially difficult for the 350x and 780x magnification attachments. As the spatial resolution of a digital image depends both on the optical resolution of the microscope and on the image resolution of the camera, the spatial resolution could be further improved using a digitizing device with a higher image resolution. After obtaining the best possible images, we developed a 3D-printable microscope table in which the distance between object and magnification attachment can be adjusted for precise measurements (see Fig. 5). Furthermore, Fig. 4 shows that digitally magnified images can be extracted from lower magnifications, causing better image qualities of the 350x and 780x magnification. Especially the 350x magnification attachment being digitally enlarged to

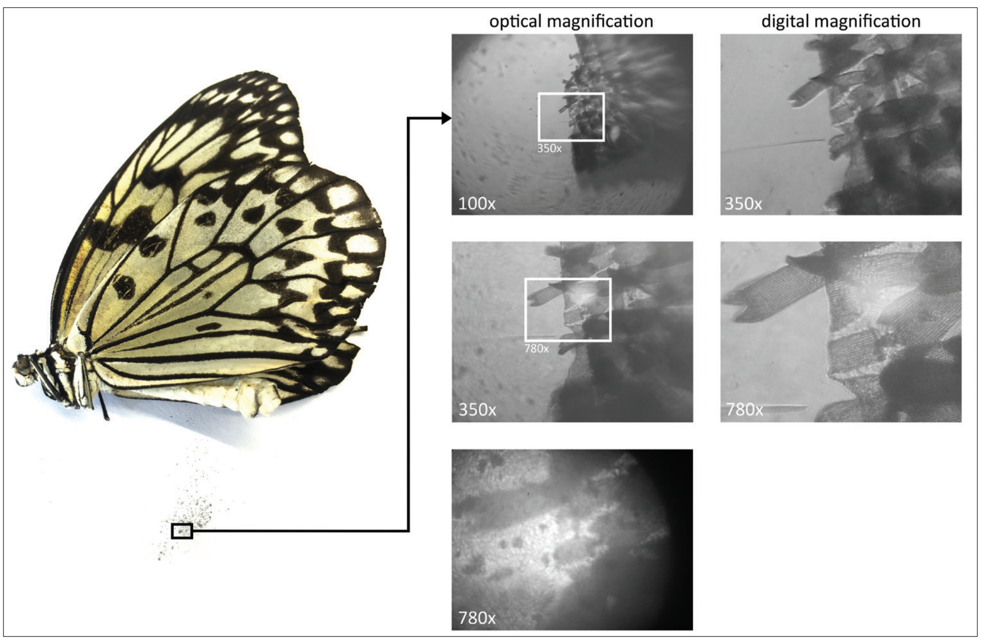

Fig. 4. Optically and digitally magnified images of butterfly scales of the paper kite butterfly (Idea leuconoe) taken with an iPhone 6 Plus using 3D-printed magnification attachments.

780x supplies a great image of the butterfly's scales yet illustrating the internal structure.

Conclusion

Smartphone magnification attachments are able to enrich physics and STEM education in many ways. At first the attachments serve as handy tools to gain strongly magnified images or videos in different experimental settings. Regarding this the low costs should be emphasized because the students already carry their smartphones with them and the costs for the glass beads and the 3D-printed attachments are under $1. In general, 3D-printing constitutes a future technology useful for science, engineering, and education, and 3D-printed objects are a great way to provide inexpensive experimental tools for the whole class.[20] Teachers without access to a 3D-printer could replace the 3D-printed clip with, e.g., a clothespin, boring a hole and inserting the glass bead. However, our further development of this technique constitutes a novel opportunity for an experimental approach separating the specific properties of microscopes in contrast to magnifying glasses. The construction of different magnification attachments in the form of 3D-printed clips corresponding to magnifying glasses or microscopes is useful for emphasizing the differences of these two common techniques in terms of physics education. Students can identify the different components of a microscope on the one hand and magnifying lenses on the other hand, they can apply their theoretical knowledge about ray optics to distinguish the distinct concepts, and first and foremost they become enabled to conduct their own experiments in schools and at home. All in all 3D-printed smartphone magnification attachments are great to gain high-quality and low-cost images with up to 780x magnifications and to emphasize students' knowledge in ray optics.

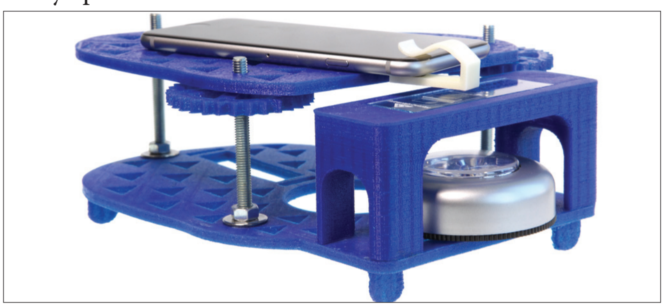

Fig. 5. Microscope table with 3D-printable components completed with threaded rods.

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Timo Pascal Hergemöller *studied physics and mathematics at Münster University. After his Master of Education, he graduated as a teacher. Within his master's thesis at the Physics Didactics Institute at Münster University (supervisor: Prof. Stefan Heusler), he investigated optical magnifications using glass beads, 3D-printed holders, and smartphones.*

Daniel Laumann *studied physics and mathematics at Bochum University. After his Master of Science and Master of Education, he came to the Physics Didactics Institute at Münster University, where he earned his PhD in physics education (supervisor: Prof. Stefan Heusler). His main research interests are student experiments, multimedia applications in education and multimedia-based learning processes.*
daniel.laumann@uni-muenster.de