★ **Michalis Orfanakis**
General Lyceum of Makry Gialos, Ierapetra, Crete, Laboratory for Biophotonics and Molecular Imaging, IESL, FORTH, Greece
★ **Mikis Mylonakis**
Laboratory for Biophotonics and Molecular Imaging, IESL, FORTH, Greece

SCIENCE ON STAGE GREECE

Optical Tweezers

The Nobel Prize in Physics 2018 at your school

Keywords: optical tweezers, optical trapping, Nobel Prize, laser tweezers
Disciplines: physics, biology
Age level of students: 14+

Conceptual introduction

In science fiction movies and TV series, we have seen powerful light beams deflecting or destroying objects. In our everyday life, special light beams like lasers are used to cut, engrave, heat, burn objects or perform delicate surgeries. Despite these facts, it still seems like science fiction to grasp and move things with light. This is still true when referring to macroscopic objects, but in the microscopic world, catching things with light has been an everyday reality for more than three decades. Scientists use laser beams in modalities called optical tweezers. They can trap and manipulate micrometer or nanometer sized objects, such as polystyrene beads, cells, bacteria, viruses, molecules or even atoms. Therefore, optical tweezers and optical trapping techniques have played a significant role in studying sophisticated processes in biology and physics. The Nobel Prize in Physics 2018 was awarded, among others, to Arthur Ashkin, the pioneer scientist who led the research effort for the development of optical trapping [1][2][3][4].

Our optical tweezers project presents how an optical tweezers setup could be developed (figure 1) and utilized in science classes in secondary school. The aim is to present the students the principles of optical trapping, not only in theory but also experimentally, through observations and quantitative measurements with real experimental data. Students will discover the physics of the 2018 Nobel Prize and correlate it with the principles of the science curriculum. The physics behind optical tweezers includes concepts like momentum, Newton's second and third laws as well as ray optics to show the refraction of light through transparent particles.

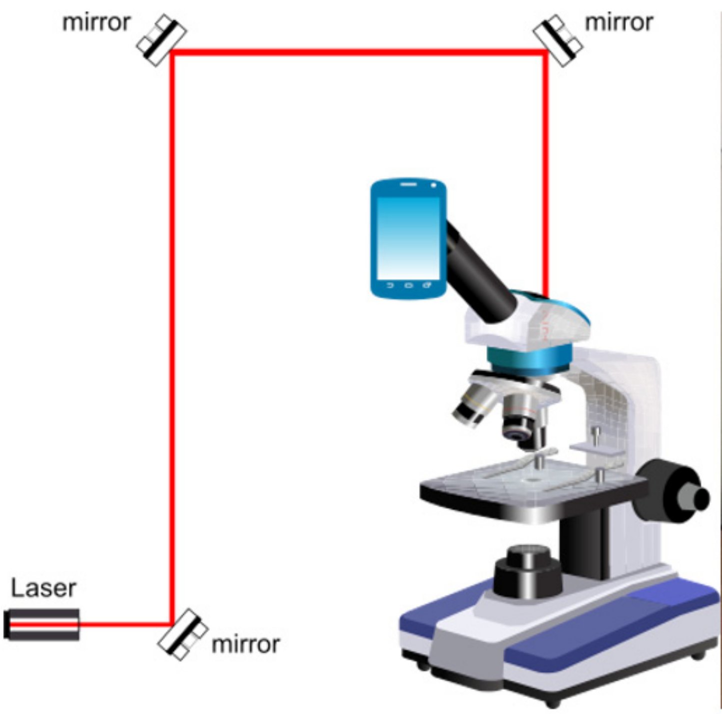
What the students do

There are several possible ways to introduce optical tweezers in your classes depending on the students' age and level. The ultimate goal, and most challenging one regarding effort and time, is to develop an optical tweezers setup to give your students the opportunity to work in the same way as scientists. We have created a four level approach to introduce optical tweezers in your class, in which the first three levels do not require you to develop the setup.

LEVEL 1 (~1 TEACHING HOUR)

The first level can be used with for younger students who don't have significant physics knowledge. In this case the readily available simulation from PhET Colorado[5] is an appropriate way to present the phenomenon of optical trapping (figure 2). This simulation is very easy

Fig. 1 Optical tweezers setup



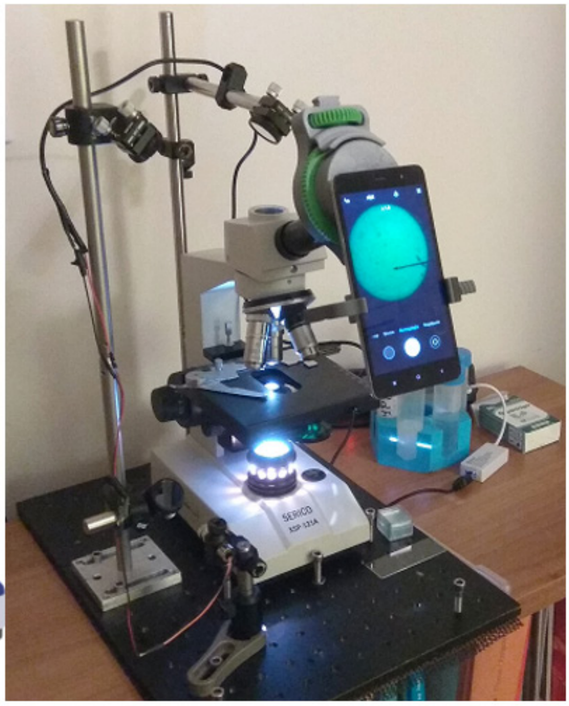
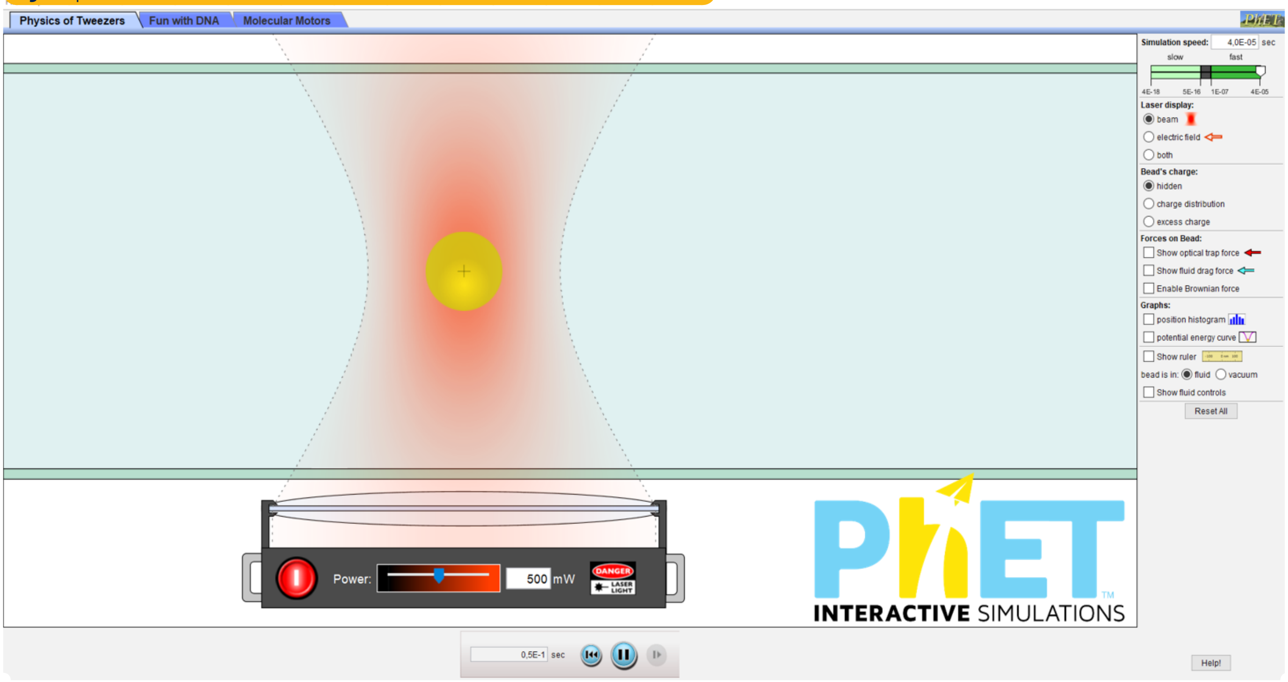


Fig. 2 Optical tweezers with PhET Interactive Simulations



to use, interactive and illustrative. It showcases optical tweezers and their basic applications in a simple way. Teachers can just present optical trapping as a phenomenon without entering any theory analysis. We suggest accompanying this activity with a demonstration of an actual optical trapping video recorded with our setup.

LEVEL 2 (~1-2 TEACHING HOURS)

For older students with a better background in physics, the teacher can add a theoretical introduction to the topic. We suggest presenting some educational material available on the official Nobel Prize website about optical tweezers[6]. The laws governing optical trapping as presented there can be demonstrated to students with high school level physics. These include using ray diagrams like in figure 3 and figure 4 and the concepts of momentum, conservation of momentum and Newton's laws. These diagrams correlate light refraction that occurs when the laser beam enters into a light transparent object with the change of light momentum. Refraction is necessary for trapping the object and this means that only light transparent particles are suitable. Figure 3 demonstrates how an unfocused laser beam exerts forces on a transparent bead particle in its path. It shows why the bead is pushed forward and to the center of the laser beam where the light intensity is at its maximum, but no trapping occurs in this case.

However, the situation changes if the laser beam is strongly focused using lenses, as in the case of a microscope objective and this can lead to stable optical trapping. Figure 4 shows how conservation of momentum results in the optical trapping of a bead particle that happens to be just below the laser focus. More details about the physics in figures 3 and 4 as well as all the educational material presented here, along with real experimental data, figures, photos and videos, are available at the project's repository[7].The model in figures 3 and 4 for presenting optical trapping is obviously a simplified model based on ray optics while in reality focused laser beams are Gaussian beams. However, this model is more than enough to introduce the concepts of optical trapping in secondary education and adequately present the underlying physics of optical tweezers for our purpose.

Apart from this theory introduction, it is suggested to utilize again the PhET optical tweezers interactive simulation[5]. This can be done as in level 1 but additionally in a more systematic way by using a worksheet that has been developed for the measurement of the maximum optical trapping force in a virtual optical tweezers setup.

Fig 3 Two rays of light (1, 2) of an unfocused laser beam are refracted when entering a bead particle. The bead particle is pushed forward and to the center of the unfocused laser beam. No trapping occurs.

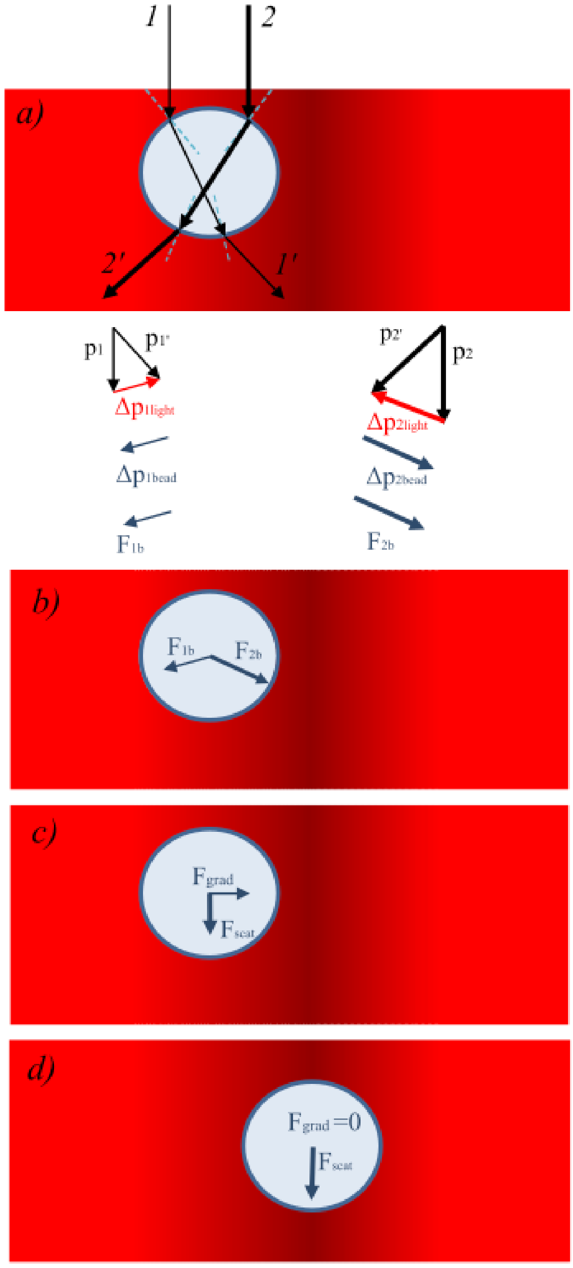
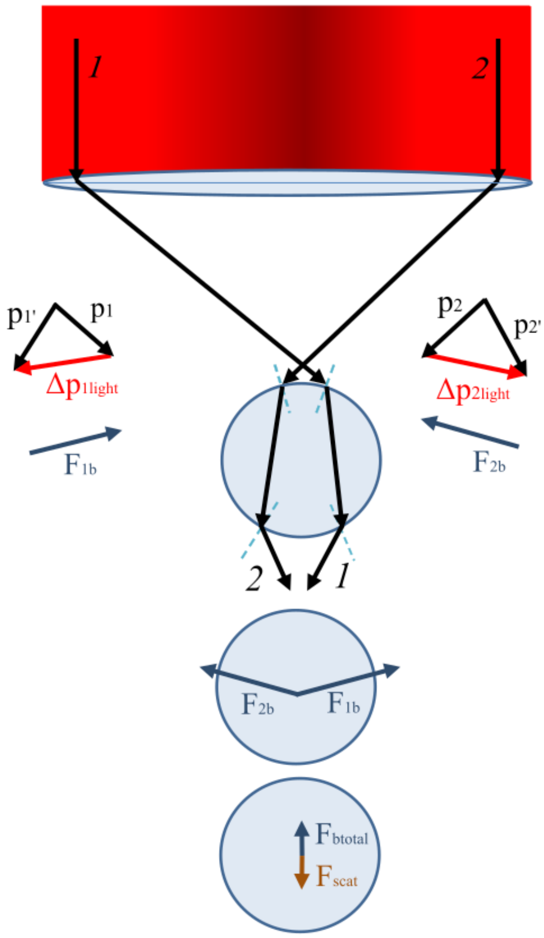


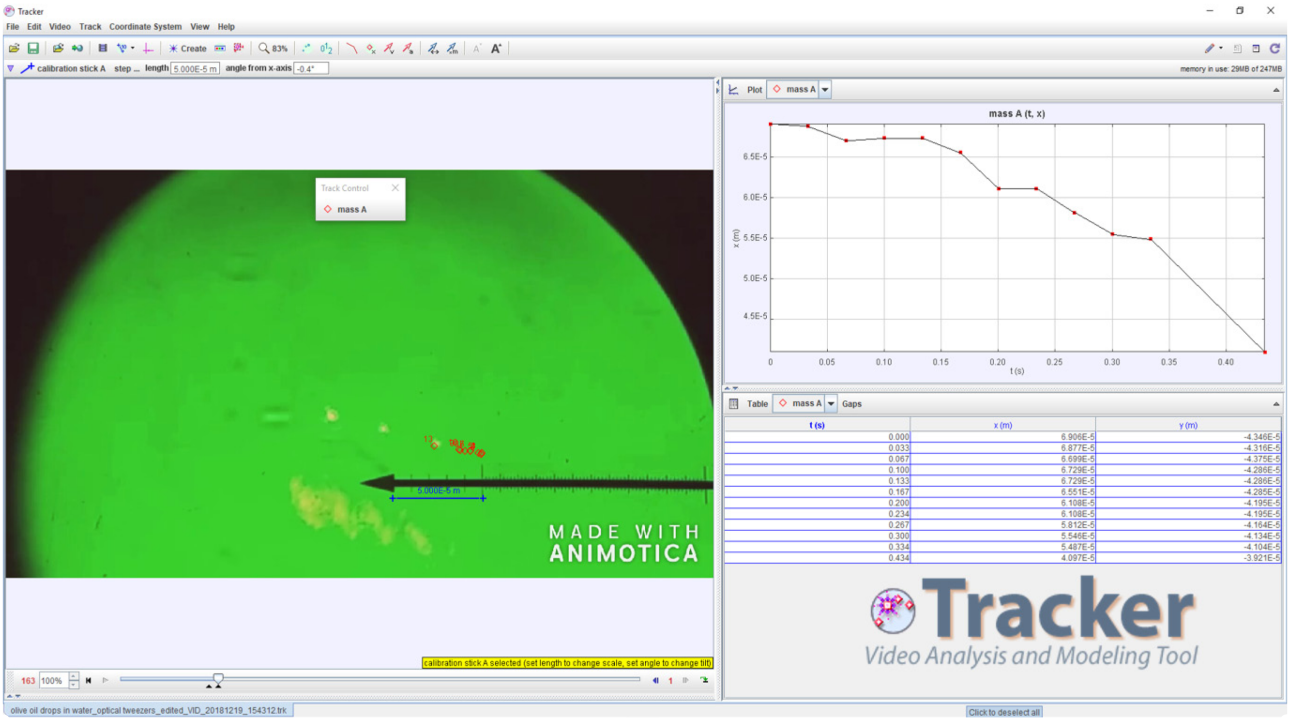
Fig 4 Two rays of light (1, 2) of a strongly focused laser beam are refracted when entering a bead particle that is just below the laser focus. In this case there is stable optical trapping of the bead particle.



LEVEL 3 (~2-3 TEACHING HOURS)

This level of implementation is very close to the experimental reality since it involves the study and the analysis of real experimental data recorded with our school optical tweezers setup. The theoretical approach is the same as in level 2 but this time instead of the data analysis of a virtual experiment, real data, available in the project's repository[7], is used. For this purpose, we use "Tracker"[8], an open source software for motion analysis (figure 5), along with a worksheet for the measurement of the maximum optical trapping force. The worksheet is based on the implementation of Newton's first law, Stoke's law for fluids and the analysis by "Tracker" of optical trapping videos recorded with our system. We have estimated, with significant uncertainty of course, the maximum trapping force of our optical tweezers with a magnitude in the order of tenths of piconewtons, which is typical in stable optical tweezers setups.

Fig 5 Data analysis of real experimental data with „Tracker" open source software for motion analysis



LEVEL 4 (3+ TEACHING HOURS)

This level includes the development of your own optical tweezers setup. This will allow your students to work like real scientists using similar techniques and methods for optical trapping.

You can develop a low cost optical tweezers setup using

- a school microscope
- a smartphone
- a very inexpensive but powerful diode laser
- respective optical filters
- 2-3 mirrors
- posts and mounts that can be easily found in the school lab

Having the above materials available it will take roughly 2-3 hours to setup your optical tweezers modality. The exact time is difficult to be estimated since it is based on your experience in handling laboratory optics and lasers. Using the above listed components and our school's 3D printer, we were able to develop, to the best of our knowledge, the most low-cost microscope optical tweezers ever made. The cost of building our model is more than ten times lower, than the most affordable model used for educational and demonstration purposes in universities[9]. Developing your own setup can be challenging because of the need of proper calibration and focusing of the laser beam[10] in the microscope and it definitely depends on the type of microscope. However, a complete list of all the required materials with information and links that you can either buy or 3D print is available in our project's repository[7].

Sample preparation is a very simple process. Particles that are suitable to be manipulated by our optical tweezers have to be a few micrometers in size. They have to be light transparent with a refractive index higher than the medium that they are diluted in, usually water. To about 15-20 ml of distilled water, you add two or three droplets of the particles you wish to trap. Stir it to produce a homogeneous mixture. A droplet of the mixture is put on a microscope slide using a plastic pipette and covered with a microscope cover slip. It is very easy for students to prepare their own samples. They can then test different particles for optical trapping and study the impact of different sample geometry, concentration, temperature or laser intensity in the quality and strength of optical trapping. With our optical tweezers modality, we have successfully trapped and manipulated a variety of samples that are safe to be used by students.

We have trapped particles of olive oil, liquid soap milk cream polystyrene beads, potato and corn starch particles, yeast cells from home dry yeast, soil particles, bacteria spirulina cells and others. In order to view our trap and the sample, a smartphone with camera is adjusted with an adaptor to the eyepiece of the microscope. In addition, it is more convenient to observe optically trapped particles on the smartphone screen, as more than one student can view at the same time. Moreover, we can easily take pictures and record videos of our experiments with the smartphone camera and share them for further processing and experimentation.

Important: It is not safe to view the sample directly with our eyes through the eyepiece due to the back reflections of the laser beam.

You and your students should always wear protective glasses appropriate for your laser. It is recommended that the teacher sets up and calibrates the system and that students only use the system when it is ready for the experiments. If the laser beam in the system is properly calibrated, whenever a particle of the sample is in the vicinity of the laser focus, it is attracted by the laser beam and becomes trapped.

Conclusion

This project presents the most low-cost and simple microscope optical tweezers setup ever developed and it demonstrates the concepts of optical trapping for the first time in secondary education. Having developed your own tweezers means that there is a new experimental modality for the school science lab that can be used for several inquiry-based interdisciplinary experimental activities in biology, physics or chemistry.

Students have the chance to get familiar with the physics of optical trapping and the importance of this technique in modern research. It presents in a simple way the physics of the 2018 Nobel Prize, using hands-on experimental activities, simulations and diagrams. It allows students to be engaged in inquiry-based activities by designing and implementing their own experiments. Students become familiar with the scientific approach and research techniques as well as developing valuable skills for their future engagement with science. This project brings modern science to secondary education and aims to inspire today's students to become the scientists of tomorrow.

Cooperation option

Optical tweezers activities with our setup in the school's science lab are always implemented with our students cooperating in groups of four to five. Students prepare their own samples and conduct their own experiments or implement the worksheets available.

This model could be adopted on a larger scale with cooperation amongst schools. Students can analyze our data and compare results with optical tweezers groups from other schools. They can also propose new experiments with different samples and of course, schools with optical tweezers setups can share their recorded data and experiments with the community and provide support to other schools that wish to build their own setup.

References

[1] "Acceleration and Trapping of Particles by Radiation Pressure". Ashkin, A., Phys. Rev. Lett. 24 (1970)(4): 156–159.
[2] "Observation of a single-beam gradient force optical trap for dielectric particles". , Ashkin A, Dziedzic JM, Bjorkholm JE, Chu S., Opt. Lett. 11 (1986)(5): 288 –290.
[3] Wikipedia, https://en.wikipedia.org/wiki/Arthur_Ashkin
[4] "Optical trapping and excitation of particles with Laser beams", Orfanakis Michalis, Master Thesis, Physics Postgraduate Programme in Microelectronics & Optoelectronics, Physics Dpt., University of Crete, (2001).
[5] PhET Interactive Simulations, https://phet.colorado.edu/en/simulation/optical-tweezers
[6] https://www.nobelprize.org/uploads/2018/10/popular-physicsprize2018.pdf
[7] Educational material, photos, videos, experimental data: https://goo.gl/1h1Zig
[8] Tracker, open source software for motion analysis, https://physlets.org/tracker/
[9] Thorlabs Portable Optical Tweezers Educational Kit, www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=6966
[10] Laser calibration tutorial, https://youtu.be/A1LIc-QTktGU
[11] Microscope image, https://all-free-download.com/free-vector/download/microscopes_312979.html
[12] Wikimedia,https://commons.wikimedia.org/wiki/Category:SVG_telephone_icons#/media/File:Emoji_u1f4f1.svg (©Google, Apache License 2.0)

Science on Stage Europe

ABOUT US

Science on Stage Europe brings together science teachers from across Europe to exchange best practice and teaching ideas and concepts with passionate colleagues from over 30 countries. Science on Stage Europe believes that the best way to improve science teaching and to encourage more schoolchildren to consider a career in science or engineering is to motivate and inform their teachers. The non-profit organisation was founded in 2000 and reaches 100,000 teachers Europe-wide.

A network of national steering committees in these member countries provides the interface to their science teaching communities. They organise national activities for teachers and select the teachers who represent each country at the European Science on Stage festivals.

The festival, hosted every two years in a different country, is the culmination of national events in the participating countries. Following the festivals the ideas are cascaded throughout participating countries and participants have the opportunity to work together and develop their teaching skills.

ABOUT OUR TEACHING MATERIALS

With this new series Science on Stage Europe wants to further distribute innovative teaching ideas from teachers for teachers. The presented projects have been selected by an international expert panel based on criterias such as inquiry-based learning, feasibility in everyday school life and their potential to promote students interest in science. Many of these teaching concepts can be used to collaborate with colleagues from other countries.

DISCLAIMER

IMPRINT

Science on Stage Europe e.V.
Am Borsigturm 15
13507 Berlin | Germany
+49 (0)30 400067-40
info@science-on-stage.eu
www.science-on-stage.eu
facebook.com/scienceonstageeurope
twitter.com/scienceonstage
instagram.com/scienceonstageeurope
Subscribe to our newsletter at
www.science-on-stage.eu/newsletter

Main supporter:
think ING. Die Initiative für Ingenieurnachwuchs