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Pushing the Boundaries of Science Demonstrations Using Modern Technology

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> The first principle is that you must not fool yourself – and you are the easiest person to fool. (Richard P. Feynman)
>
> It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong. (Richard P. Feynman)

Abstract

This paper describes the benefits and the challenges of using modern technology for designing and implementing in-class science demonstrations. We suggest that state-of-the-art instrumentation, such as a fast-speed video camera, can turn traditional lecture demonstrations from mere entertainment to the effective means for physics learning. We describe an experimental set-up – a Slow-Motion Chamber, which we have used as a demonstration tool in large lectures. Finally, we provide examples of experiments used in introductory physics courses, which might greatly benefit from the analysis of a slow motion playback, and suggest how instructors can help students experience physics in action during lectures.

1. Introduction

Physics is an experimental science that in the words of one of the most ingenious scientist of the 20th century, Richard Feynman, allows people curious about the natural world not to fool themselves or at least to be aware of many ways they can be fooled by nature. To reduce the probability of being wrong, physicists rely on experiments that are at its core. Thus, it should not be surprising that laboratory experiments and lecture demonstrations have played a key role in teaching physics for centuries [1, 2]. For example, the famous Royal Institution Christmas Lectures initiated by Michael Faraday almost 200 years ago and continuing to this day always feature carefully chosen science demonstrations. First televised in 1936, Faraday's Christmas Lectures have inspired millions of people all around the world to engage in physics, chemistry, biology, medicine, and science in general. Moreover, some of the most important physics discoveries even started from a serendipitous observation that happened during a lecture demonstration. For example, Oersted's discovery of electromagnetism took place on April 18, 1820 when he passed electric current through a wire and noticed the resulting deflection of the compass needle [3].

Nevertheless, there is an ample and growing research evidence that the pedagogical impact of traditional physics lecture demonstrations performed in large introductory physics courses is somewhat limited, even when the experiments are well prepared and work as intended [4, 5]. According to the results of physics education research, there are many possible reasons for the low effectiveness of traditional physics lecture demonstrations. The following five are relevant to this paper:

R1: Design flaws of the demonstrations that do not account for the inability of novice (inexperienced) learners to separate signal from noise: students do not pay attention to the key physics phenomena and are distracted by the superficial and irrelevant features [6, 7]. As a result, students often fail to challenge their own prior knowledge and expectations, thus remembering inaccurate or even contradictory experimental results [4, 8]. For instance, shattering of a wine glass by a resonant sound wave (an experiment we describe in detail below) may be perceived as an instantaneous effect instead of a resonant transfer of energy from the sound wave to the vibration of the glass.

R2: Students are being distracted by superficially similar but conceptually different physics experiments and everyday life experiences [6, 9]. For example, when shown the demonstration of a colorful thin soap film, students would often connect the observed colors with the colors of painted objects, which they see all around them, completely missing the true mechanism behind the color of the film, related to the interference of light.

R3: Many students perceive demonstrations solely as entertainment. Moreover, student understanding and interpretation of the experiments are rarely challenged during the lecture or in homework assignments [10, 11]. In addition, students naturally see what they had expected to see in the demonstration as opposed to what is actually happening, they often remember inaccurate or even contradictory experimental results and incorrect interpretations [4, 7, 8]. After seeing the demonstration in class, students seldom have an opportunity to revisit it using its video recording. Thus, as their memories of the demonstration fade, it becomes difficult for the students to rely on the demonstration while studying new concepts. Unlike the information written in a course textbook, physics demonstrations performed during lectures are ephemeral. Consider the case of an acoustically shattered wine glass – one of the most entertaining physics demonstrations, which is rarely followed by quantitative analysis. The excitement of breaking an object with sound, as if by direct mechanical contact, may lead students to remember a sound wave as a mechanical "hammer" hitting the glass at a localized spatial location – in sharp contrast with the real excitation of an extended resonant wave.

R4: Refined and idealized physics demonstrations, unlike authentic experiments that imply the ability to measure and carefully examine physical quantities, are commonly used to confirm already known results, instead of opening doors to discussing competing explanations and theories. Thus, during lectures these carefully chosen "idealized" demonstrations are being implemented in a very different way than they would have been performed in the lab. Thomas Kuhn alluded to that when he described how textbooks have a tendency to disguise the process of scientific discoveries trying to present science as a logical linear process, which rarely reflects the reality [12]. The same can be said about traditional lecture demonstrations. This contributes to students forming a limited, if not an inaccurate, view of the nature of science [13] and of the scientific method [14]. In the shattering wine glass experiment discussed earlier, by pre-tuning the frequency of an audio generator to match the vibration mode of a wine glass prior to the beginning of the lecture, one can perform the demonstration in less than a minute – a "quick success" which may leave the wrong impression about resonant phenomena. In reality, finding the resonance frequency of a vibrating system is a difficult and often time-consuming task. Showing and analyzing this process in front of the class would lead to a much deeper physics understanding and longer lasting memory.

R5: Scientific progress is driven in big part by advances in technology. We believe that modern technology should also be one of the major driving forces behind the progress in science education in general and physics teaching in particular. Yet demonstrations in introductory physics courses rarely incorporate state-of-the-art authentic research equipment, such as ultrafast oscilloscopes or high-speed cameras, capable of providing new insights into otherwise classic demonstrations. As a result, in introductory physics lectures students have few opportunities to engage with lecture experiments that produce authentic, measurable, and somewhat unexpected results that have not already been discussed in the textbook or shown by popular YouTube videos [15].

In summary, classic lecture demonstrations may provide much needed entertainment relief to make conceptually and mathematically dense physics lectures less overwhelming [16]. Despite that, for the reasons mentioned above, students rarely gain significant conceptual physics understanding as a result of seeing these demonstrations [5, 6, 17]. Moreover, with the proliferation of alternative sources for physics experiments (such as online YouTube physics channels) the appeal of traditional physics lecture demonstrations might diminish. Contradictory to a common belief that seeing a demonstration makes the students understand or at least remember the underlying physics phenomena, many physics instructors and physics education researchers have documented that after seeing a demonstration the majority of the students "remember" the wrong interpretation of the demonstration or even non-existing phenomena and explanations [18]. While traditional wisdom says that "seeing is believing", one can never know what exactly students see in physics lecture demonstrations and what beliefs and understandings they gain as a result.

To address this problem, physics educators have proposed a number of solutions, such as Interactive Lecture Demonstrations and Real Time Physics experiments [10, 19], Interactive Lecture Experiments [17], demonstrations utilizing Video Analysis [20], and Virtual Experiments with computer simulations, such as PhET [21]. All these solutions utilize modern technologies to push the boundaries of physics demonstrations instead of repeating traditional physics experiments that have been performed for centuries. These modern tools allow physics instructors to address many of the concerns mentioned above, and yet none of these tools uses state-of-the-art equipment inaccessible to the students outside of the classroom (see Reason 5 above).

As we alluded earlier, in the last decade physics students have gained an unprecedented access to freely available video recordings of high quality online physics experiments and lectures [15, 22]. Therefore, one might ponder the following questions. What effect might this unprecedented access to online experiments and demonstration have on how we teach secondary or undergraduate physics and on the choice of physics demonstrations used during lectures? Will traditional lecture experiments lose their inspirational and motivational appeal as a result of growing pool of virtual demonstrations? How can physics instructors reinvent physics demonstrations for contemporary students? Finally, how can modern technology help physics instructors re-invent physics demonstrations, so that 200 years after Michael Faraday we can use state-of-the-art instrumentation for giving physics lectures a new breath? This paper attempts to answer these questions and provide examples of possible solutions.

2. Physics Demonstrations as a Teaching Tool

In our previous studies, we found that creating educational videos of science experiments motivated pre-service physics teachers to delve deeply into these phenomena and consequently use these experiments in their own classes during the practicum [23, 24]. In contrast to passively watching videos created by others, future physics teachers had to go through the entire experimental process and later communicate it to the audience through the video. In addition, the video allowed them to pause the process and focus on different aspects of the experiment that could have been easily overlooked if the experiment were performed live without being recorded. Some of the future physics teachers even started using the slow-motion feature on their phones and cameras to slow down fast experiments for further analysis. Slowing down physics phenomena for the purpose of a deeper analysis was a big part of the process. It motivated future teachers to slow down their thinking, ask new questions and pay attention to different aspects of the phenomena. Encouraging future physics teachers to slow down their thinking forced them to challenge their intuitive physics understandings (prior knowledge and possible misconceptions) and to start gaining the knowledge of physics that will be especially useful for them in their future teaching. The interplay between the fast intuitive thinking, which students often rely on to make judgements about physics phenomena during the lectures, and the slow deliberate thinking that they had to do for creating an educational video of the physics phenomenon, was at the centre of this activity. Thanks to the availability of modern video recording technology, future science teachers were able to challenge their intuitive science understanding, and to consider how they can address potential physics misconceptions of their future students.

For his study of the role of slow and fast thinking in making decisions and judgements, Daniel Kahneman, a world renowned cognitive psychologist, received his 2002 Nobel Memorial Prize in Economic Sciences [25]. Interestingly, his work on the psychology of judgement and the decision-making process, and the role of heuristics and biases in it has direct implications for physics learning. Students have to analyze natural phenomena and solve physics problems, where they are forced to make decisions. Yet too often students make these decisions too fast, without having an opportunity to slow down, challenge their assumptions and prior knowledge, and carefully check their reasoning. This also applies to live physics demonstrations that often happen fast and do not provide students with an opportunity to pace their thinking through seeing the phenomenon in slow motion. While instructors often try to discuss the demonstrations afterwards, being able to see an experiment in slow motion provides a unique opportunity for its careful examination and analysis.

This motivated us to consider the use of modern technology, such as a fast-speed camera, for enhancing the impact of physics experiments on introductory physics teaching and physics teacher education. To implement this project in a large introductory physics course, we built a robust set-up for recording experiments with a fast-speed camera and designed the experiments that despite their complexity can be reliably and effectively performed in front of the students in a large lecture auditorium.

3. Slow-Motion Demonstrations in Introductory Physics Lectures

Slow-motion videos are widely used in science, sports, and industry. They allow careful measurement-based analysis of the processes that happen in a split of a second and are invisible to a naked human eye. Many of these processes are discussed in university introductory physics courses, as well as in the secondary physics curriculum. For example, fast-occurring linear and circular motion, collisions and explosions, oscillations and vibrations, to mention a few. In traditional physics courses, many of these phenomena are described theoretically while students rarely have an opportunity to witness them live and follow the experiment with a video analysis. To make the invisible visible and help students analyze the physics behind these natural phenomena we incorporated a fast-speed camera and created a series of live slow motion lecture demonstrations for introductory physics courses.

3.1. Fast-Speed Camera

Physics demonstrations described below were recorded with the Edgertronic SC1 fast-speed camera [Fig. 1]. This camera allows video recording at a rate of up to 17,791 frames per second (fps), more than an order of magnitude faster than what can be achieved with most commercial video recording devices, e.g., a high-end smartphone. Such high fps rate brings a myriad of new possibilities for physics demonstrations. For example, a tuning fork oscillating with a frequency of the middle C note (C_4), which is equal to 261.6 Hz, will take about 0.0038 s to complete one full oscillation. Thus, in order to observe a few points per period, the camera has to operate at more than 2,000 frames a second. For comparison, a slow-motion camera on the new Galaxy S9 and S9+ phones offers an option of a slow-motion video, which captures 0.2 seconds of footage at 960 frames per second. In addition to the insufficient frame rates, most consumer-market cameras suffer from the deficiency of a "rolling shutter": as different parts of the camera chip are exposed to light at different time moments, the image is distorted (the faster the process the higher the distortion!). The "global shutter" technology of Edgertronic camera eliminates this problem.

Recording fast processes during physics lecture demonstrations requires a recording device equipped with a "pre-trigger buffering". The finite average reaction time of a person to a visual event (around 0.25 seconds) means that the trigger button (e.g., the record button on a smartphone) will always be pressed too late to capture the beginning of a fast-occurring process, or often the whole process entirely. The pre-trigger functionality of Edgertronic camera, with its large memory buffer and fast buffering mechanism, guarantees that no important video data will be missed. Finally, that video data need to be transferred to a computer and shown to the students, preferably right after the demonstration. Here again, fast and efficient data transfer requires a scientific grade recording device, such as Edgertronic camera, whereas a consumer-market recorder will be too slow.

<INSERT FIGURE 1 HERE>

3.2. Slow-Motion Chamber

In order to set up slow-motion demonstrations during the lecture quickly and to ensure that the instructor can focus on the scientific aspects rather than being preoccupied with the technical details, our team built a Slow-Motion Chamber (CMS) shown in Figure 2. The SMC has a special mount for the fast-speed camera (right side in the figure), a built-in ultra-bright Direct Current light source to avoid flickering and a set of add-ons, each specifically designed for a separate lecture demonstration, as described below. To help the instructor with the initial set-up, each experiment comes with an accompanying text and video instructions outlining the recommended hardware and software configurations, such as camera sensitivity, shutter speed, frame rate, pre-trigger time, etc. [Fig. 3].

<INSERT FIGURE 2 HERE>

<INSERT FIGURE 3 HERE>

3.3. Choosing Demonstrations

In this section, we briefly discuss our choice of specific demonstrations for the slow motion video analysis. While some of them may be obvious, such as a shadattering wine glass demonstration or an oscillating tuning fork, many others may not come to mind immediately in the context of an introductory physics course. Our main goal was to utilize the benefits of observing a particular physical phenomenon in slow motion. We asked ourselves the following questions: What can the students see in a slow-motion experiment that they could not have observed otherwise? What are the benefits of a slow-motion demonstration as compared to using a computer simulation of a related phenomenon? What are the benefits of doing this demonstration in front of the students as opposed to watching a video of a similar experiment online? What are the possible pedagogically valuable deviations of an experiment from its typical refined version and what can the students learn from this experiment? Can we extract real physical quantities from the post-analysis of a slow-motion playback? What conceptual questions could accompany each demonstration and how could they be used as a pre- or post-analysis?

Some of the demonstrations that made our list (Table 1), such as the falling cup or the shuttering wine glass demonstrations are difficult and time consuming to set up, which would normally discourage physics instructors from using them consistently. On the other hand, some other demonstrations from Table 1, such as the popping soap bubble or the falling cup, are only possible if the instructor has a fast-speed camera set-up. Our SMC system makes it reliable, safe, and quick to implement. Owing to these improvements, slow-motion experiments became an integral part of our lectures and provided students an opportunity to see physics in the making and not only to witness the results of “old” physics discoveries. Importantly, a consistent use of the fast-speed camera drew students’ attention to the demonstrations, which could have been, otherwise, perceived as boring. Students were also motivated to use the capabilities of their smartphones for later experimentation on their own, which showed their increased interest in the studied material.

<INSERT TABLE 1 HERE>

	Physics demonstration	Relevant physics topics
1	Falling cup with water	Hydrostatic pressure
2	Falling slinky	Wave propagation
3	Oscillating string	Standing waves, one-dimensional object
4	Chladni plate	Standing waves, two-dimensional object
5	Chinese spouting bowl	Standing waves, three-dimensional object
6	Vibrating tuning fork	Acoustic waves
7	Shattering wine glass	Resonance, resonant energy transfer
8	Popping soap film	Thin-film interference
9	Oscillators in a water tank	Doppler effect
10	Waves in a water tank	Wave diffraction and double-slit interference

Table 1. Slow motion physics demonstrations we used in introductory physics courses.

4. Examples of Slow-Motion Experiments

4.1. Shattering wine glass with sound: Resonant energy transfer

This rather famous experiment is designed to show the effect of a resonant energy absorption. An oscillator (here, a wine glass) is excited by an external field (here, an acoustic wave), as shown in

Fig.4 (a). When the frequency of the field is matched to that of an oscillator, the latter absorbs the energy carried by the sound wave. As the vibrational energy of the wine glass grows, so does the amplitude of its oscillations, until the glass deformation becomes too large to withstand and the glass breaks [Fig.4 (b-d)]. Recording the event requires a frame rate above 7,000 fps and a pre-trigger capability discussed earlier in the text.

The fast-speed camera enables students to see and appreciate the violent and often long-lasting vibration of the glass before it breaks. Observed by a naked eye, the event is virtually instantaneous and leads to a common misconception that sound is acting on the glass similarly to a hammer, i.e., via a strong point contact. Seeing the process in slow motion helps students recognize the mechanism of spatially extended resonant excitation, which involves the whole glass surface and, being a wave phenomenon, shows periodicity both in time and space. Such resonant absorption of energy can be connected to modern technology used in everyday life (microwave ovens) and modern science techniques extensively used in science labs, medicine, and industry (light absorption spectroscopy).

<INSERT FIGURE 4 HERE>

4.2. Falling cup with water: Pressure in liquids

In an introductory physics course on fluids, students learn about hydrostatic pressure. In liquids, such as water, this pressure originates largely from the weight of the liquid, i.e., the force exerted by the liquid on the walls of the container due to gravity. Hydrostatic pressure is responsible for the liquid streaming out of the hole in the container's wall. In a weightless environment, however, when both the liquid and the container are in a free fall, the gravitational contribution to hydrostatic pressure becomes zero. As a result, water will not escape through the hole in the bottom of a free falling cup. The aim of this experiment [Fig. 5(a)] is to demonstrate this effect by observing that the stream of water stops when the cup is dropped.

A third of a second – the time of a free fall over a convenient distance of 50 cm, is way too short for students to notice the change in the water stream, occurring due to the significant decrease in the hydrostatic pressure inside the liquid. In contrast, a fast-speed camera set to 4,000 fps rate captures the effect very well [Fig. 5(b-d)]. The slow-motion playback helps student visualize the free falling dynamics and appreciate its consequences.

<INSERT FIGURE 5 HERE>

4.3. Popping soap film: Thin film interference

Thin-film interference is one of the hardest concepts in introductory physics courses, even though it produces visual effects experienced by students in everyday life. The students are asked to think of light as a wave and to consider how the waves reflected from the parallel surfaces of a thin film can interfere with one another. The appearance of colors in the reflection of light from a thin film is a result of such interference and of its dependence on the thickness of the film. As is often the case for many phenomena involving light, students are struggling with the provided explanations, which are rather abstract due to the very short length scale involved (wavelength of visible light 380-700 nm).To tell a student that a soap bubble's walls might range from 10 to 1,000 nm is not very helpful, as students have no tangible experience with such a small scale. Even comparing a soap bubble's wall thickness with the diameter of a human hair (usually 40,000-60,000 nm) is not instructive, as few undergraduate students are used to think in terms of the order of magnitude and temporal and spatial scales. While most of the students have seen this phenomenon in soap bubbles before, few students can connect what they see with the physics concepts discussed during the lecture. The goal of this demonstration is to connect the abstract concept of wave interference with the real world around us by using a familiar soap film. Caught on camera, the colorful interference fringes may be counted. From this count, students can calculate the thickness of the film at the location of each colored band *as long as they know* which fringe is the "first one", i.e., corresponds to the thinnest location on the film. Imagining the film as a wedge, with its vertex at the top, is not very intuitive to a novice physics learner (again, due to the extremely small thickness of the film). Recording the popping of the film at 5,000 fps presents the true experimental evidence of the wedge geometry: the film is indeed collapsing from its weakest (thinnest) point at the top. Moreover, the analysis of the interference pattern around the moving edge of the film provides a unique way of observing the fast liquid dynamics at the time of collapse. This demonstration leaves the students with a satisfying feeling of being part of a true physics experiment performed with the state-of-the-art instrumentation.

<INSERT FIGURE 6 HERE>

5. Conclusions

The goal of this paper was to propose how slow-motion video recording technology might help physics instructors, and possibly secondary physics teachers, to increase the effectiveness of physics demonstrations in introductory physics courses. We propose how slow-motion video experiments can be used in large introductory physics lectures to turn traditional physics lecture demonstrations from mere entertainment to effective tools for learning physics concepts, while engaging students in doing authentic science experimentation with modern state-of-the-art tools. To do so, we devised an experimental set-up for slow-motion video demonstrations (Slow-Motion Chamber (CMS)) during lectures. We also designed and piloted ten experiments for introductory physics that successfully used this set-up to help students understand difficult physics concepts and observe their experimental applications. We were able to evaluate student conceptual understanding using classroom response system with specifically designed multiple-choice questions [26]. However, more research needs to be done to evaluate the effectiveness of this pedagogy more broadly.

This slow-motion recording of live experiments conducted in front of students during large lectures and consequently discussed with the students is what makes lectures exciting and worthwhile for many undergraduates. For example, student end-of-the course anonymous feedback on the use of SMC in introductory physics lectures by one of us (VM) was overwhelmingly positive. In addition to the official end-of-semester university feedback, on the

Rate my Professor web site, many students mentioned demonstrations as one of the key elements of the course that influenced their decision to come to class. One of these students became the designer of SMC and a co-author of this paper (OA). While physics teachers might not have expensive equipment at their disposal, the experiments discussed in this paper might encourage teachers and students to use their smartphones as tools for recording and analyzing slow-motion videos.

This paper does not claim to produce an exhaustive list of all possible physics demonstrations that can benefit from slow-motion analysis. However, we have shown that with the current rapidly increasing access to video recording technology, physics instructors might want to pay closer attention to the video recording tools that have been traditionally used in research labs. These modern tools can also be used during physics lectures. We strongly believe that physics students can benefit greatly from participating in slow-motion physics demonstrations performed live in their secondary and post-secondary physics classes. We hope more physics instructors will join us in designing and implementing these slow-motion demonstrations and investigating their impact on physics learners.

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References

[1] G. Holton and S.G. Brush, *Physics, The Human Adventure: From Copernicus to Einstein and Beyond*. 3rd ed. 2001, New Brunswick, NJ: Rutgers University Press.

[2] K. Miller, et al., Role of physics lecture demonstrations in conceptual learning. *Physical Review Special Topics - Physics Education Research*, 9 (2013) 020113.

[3] R. Hawkes, et al., *Physics for scientists and engineers: An interactive approach*. 2nd ed. 2018, Toronto: Nelson Education.

[4] M. Milner-Bolotin, A. Kotlicki, and G. Rieger, Can students learn from lecture demonstrations: The role and place of interactive lecture experiments in large introductory science courses. *Journal of College Science Teaching*, 36(4) (2007) 45-49.

[5] C.H. Crouch, et al., Classroom demonstrations: Learning tools or entertainment. *American Journal of Physics*, 72(6) (2004) 835-838.

[6] W.-M. Roth, et al., Why may students fail to learn from demonstrations? A social practice perspective on learning in physics. *Journal of Research in Science Teaching*, 34(5) (1997) 509-533.

[7] J.D. Bransford, A.L. Brown, and R.R. Cocking, *How people learn: Brain, mind, experience, and school*. 2002, Washington, DC: The National Academies Press.

[8] G.J. Posner, et al., Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change. *Science Education*, 66(2) (1982) 211-227.

[9] M.T.H. Chi, J.D. Slotta, and N. deLeeuw, From things to processes: a theory of conceptual change for learning science concepts. *Learning and Instruction*, 4(27-43) (1994).

[10] D.R. Sokoloff and R.K. Thornton, *Interactive lecture demonstrations: Active learning in introductory physics*. Physics Suite. 2004: John Wiley and Sons, INC.

[11] M. Milner-Bolotin and R.F. Moll, Physics exam problems reconsidered: Using Logger Pro technology to evaluate student understanding of physics. *The Physics Teacher*, 46(8) (2008) 494-500.

[12] T.S. Kuhn, *The Structure of Scientific Revolutions*. Third ed. 1996, Chicago: University of Chicago Press. 210.

[13] I. Galili, Towards a Refined Depiction of Nature of Science. *Science & Education*, (2019).

[14] I. Galili, *History of physics as a tool for teaching*, in *Connecting Research in Physics Education with Teacher Education*, M. Vicentini and E. Sassi, Editors. 2008, The International Commission on Physics Education.

[15] D. Muller. *Veritasium*. [YouTube Channel] 2019 [cited 2018 May, 5]; Available from: https://youtube.com/veritasium.

[16] J. Middendorf and A. Kalish. *The "Change-Up" in Lectures*. 1996 [cited 2006 01-01-2006]; Available from: http://www.ntlf.com/html/pi/9601/article1.htm.

[17] R. Moll and M. Milner-Bolotin, The effect of interactive lecture experiments on student academic achievement and attitudes towards physics. *Canadian Journal of Physics*, 87(8) (2009) 917-924.

[18] M.H. Schneps, et al., *A Private universe*. 1989, VT: Annenberg Media: S. Burlington.

[19] D.R. Sokoloff, R.K. Thornton, and P.W. Laws, *Real Time Physics*. Physics Suite. Vol. 1. 2004: John Wiley and Sons.

[20] T. Antimirova and M. Milner-Bolotin, A Brief Introduction to Video Analysis. *Physics in Canada*, 65 (April-May) (2009) 74.

[21] C.E. Wieman, et al., Teaching physics using PhET simulations. *The Physics Teacher*, 48(4) (2010) 225-227.

[22] Massachusetts Institute of Technology. *MIT Open Courseware*. 2019 [cited 2018 May 6]; Available from: https://ocw.mit.edu/index.htm.

[23] G. Tembrevilla and M. Milner-Bolotin, Engaging physics teacher-candidates in the production of science demonstration videos. *Physics Education*, 54(2) (2019) 025008-025018.

[24] M. Milner-Bolotin. *Science & Math Education Videos for All*. YouTube Channel of Online STEM resources 2019 [cited 2018 March 20]; Available from: https://www.youtube.com/channel/UCHKp2Hd2k_dLjODXydn2-OA.

[25] D. Kahneman, *Thinking Fast and Slow*. 2011, New York: Farrar, Straus and Giroux.

[26] M. Milner-Bolotin, Tips for using a peer response system in the large introductory physics classroom. *The Physics Teacher*, 42(4) (2004) 253-254.

Fig. 1. Edgertronic fast-speed camera used in our experiments.

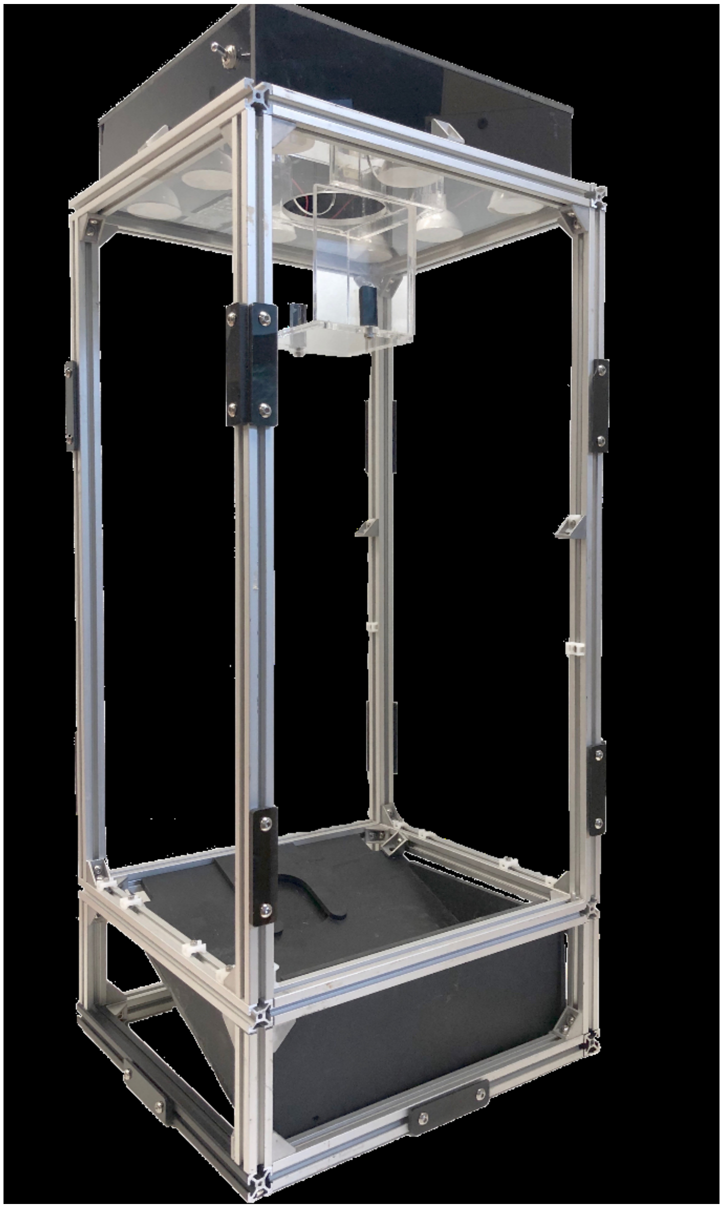
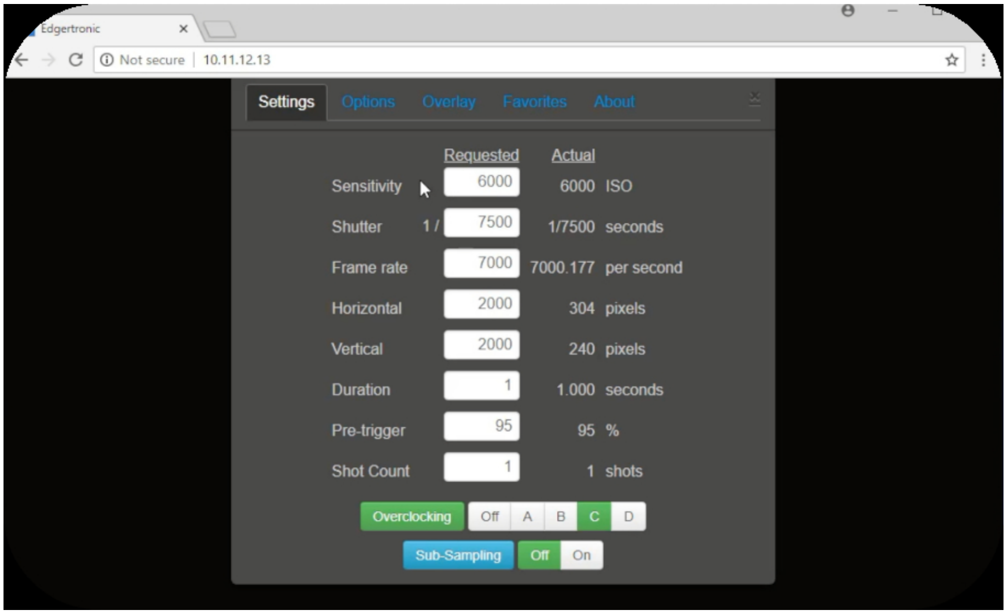


Fig. 2. Slow Motion Chamber (SMC).



	Requested	Actual
Sensitivity	6000	6000 ISO
Shutter	1 / 7500	1/7500 seconds
Frame rate	7000	7000.177 per second
Horizontal	2000	304 pixels
Vertical	2000	240 pixels
Duration	1	1.000 seconds
Pre-trigger	95	95 %
Shot Count	1	1 shots

Overclocking: Off A B [✓ C] D

Sub-Sampling: [✓ Off] On

Fig. 3. Configuration software for running the Edgertronic camera.

Fig. 4. The Shattering wine glass demonstration. (a) Experimental set-up; (b-d) Consequent frames of the vibrating wine glass until it breaks.

Fig. 4. The Shattering wine glass demonstration. (a) Experimental set-up; (b-d) Consequent frames of the vibrating wine glass until it breaks.

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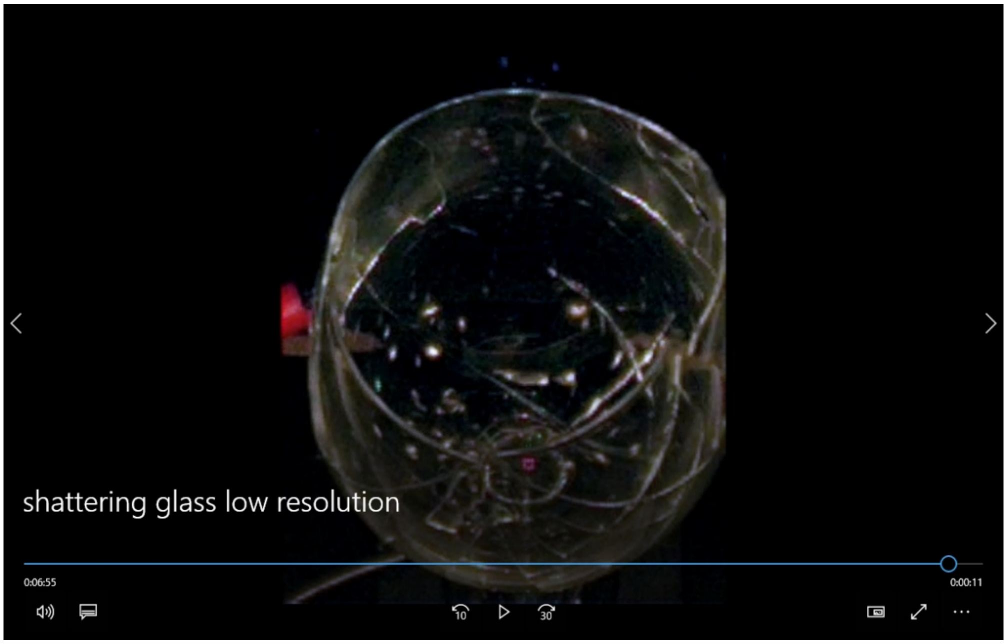


Fig. 4. The Shattering wine glass demonstration. (a) Experimental set-up; (b-d) Consequent frames of the vibrating wine glass until it breaks.

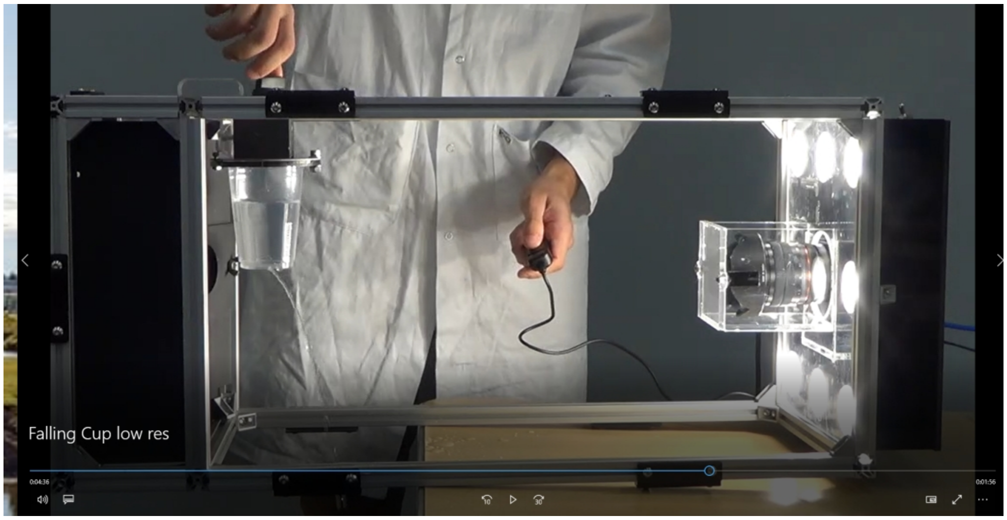


Fig. 5. The Falling cup demonstration. (a) Experimental set-up; (b-d) consequent frames of the free falling water cup; (b) The water is flowing right before the cup was dropped; (c) At the beginning of the fall, the water was still flowing due to inertia; (d) During the fall the water stops flowing.

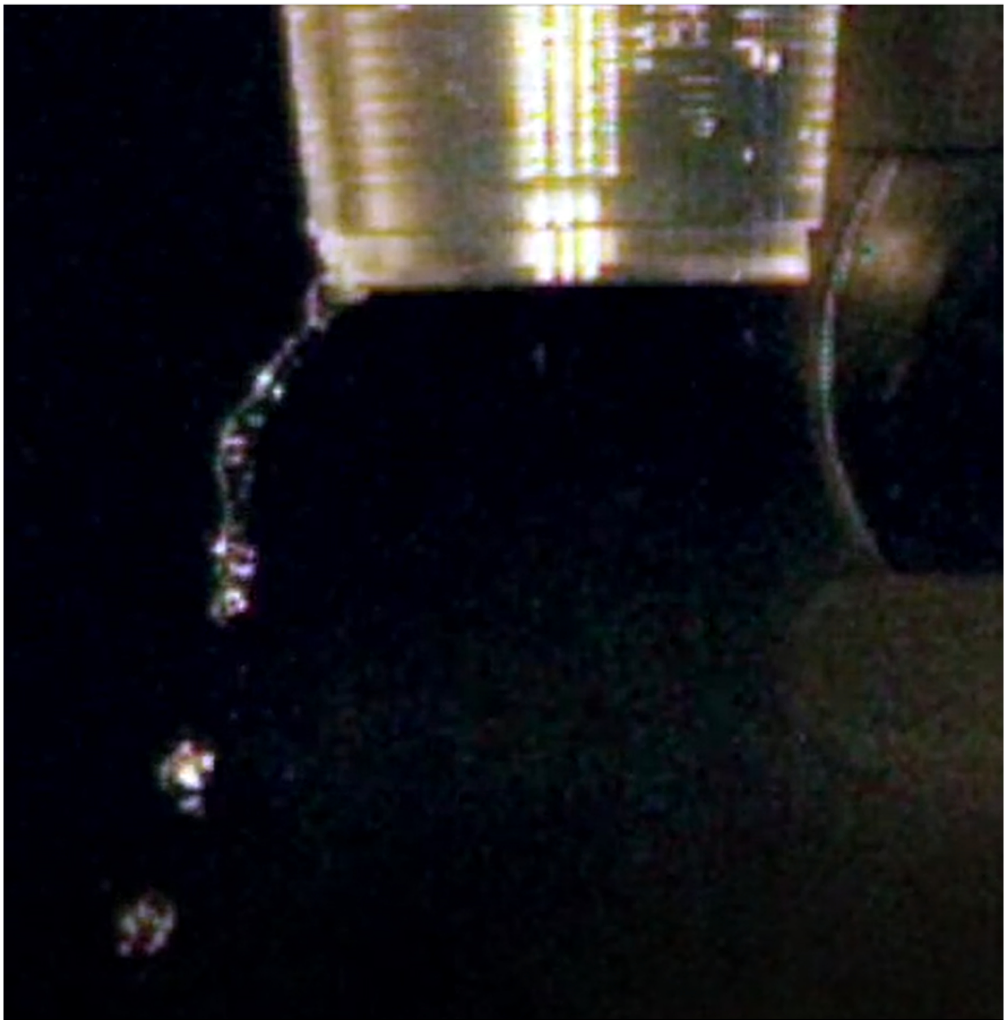
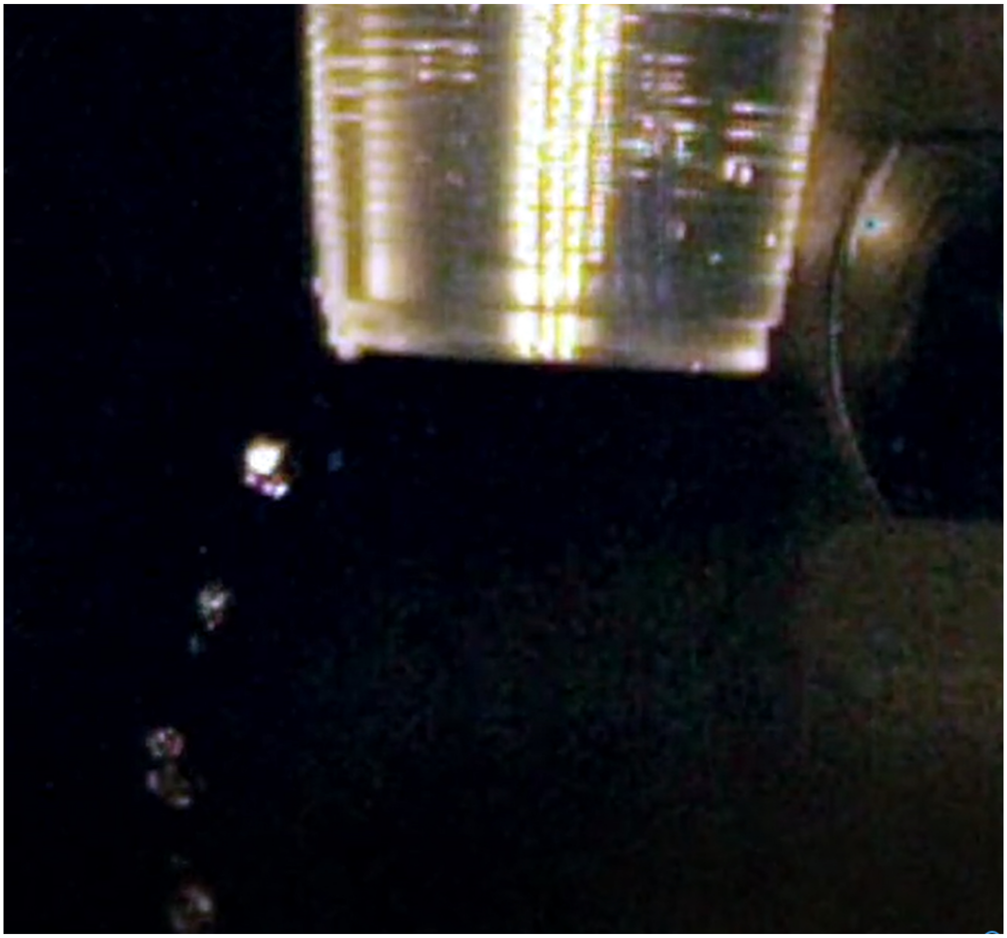


Fig. 5. The Falling cup demonstration. (a) Experimental set-up; (b-d) consequent frames of the free falling water cup; (b) The water is flowing right before the cup was dropped; (c) At the beginning of the fall, the water was still flowing due to inertia; (d) During the fall the water stops flowing.



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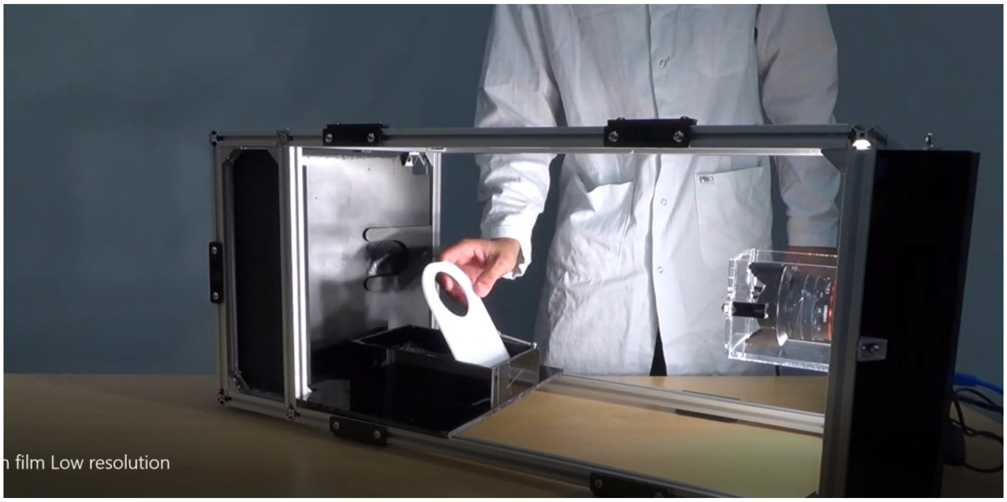
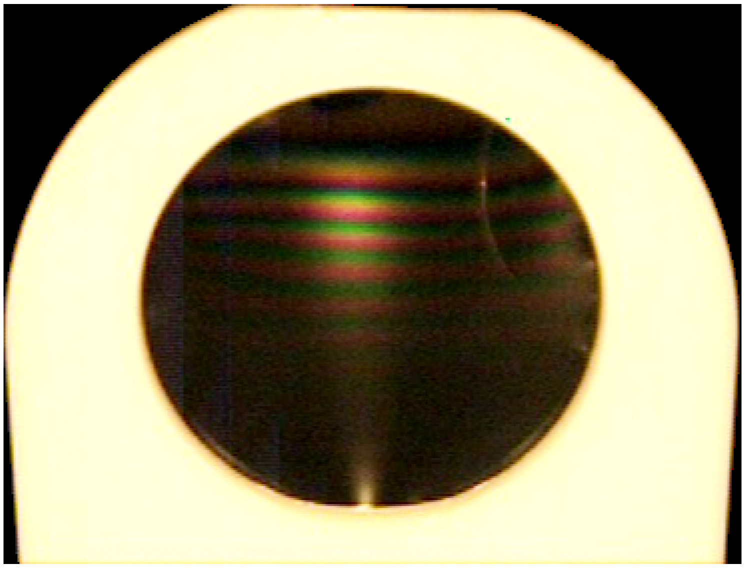


Fig. 6. The Popping thin film demonstration. (a) Experimental set-up; (b, c) Consequent frames of the thin film before and after its spontaneous collapse.



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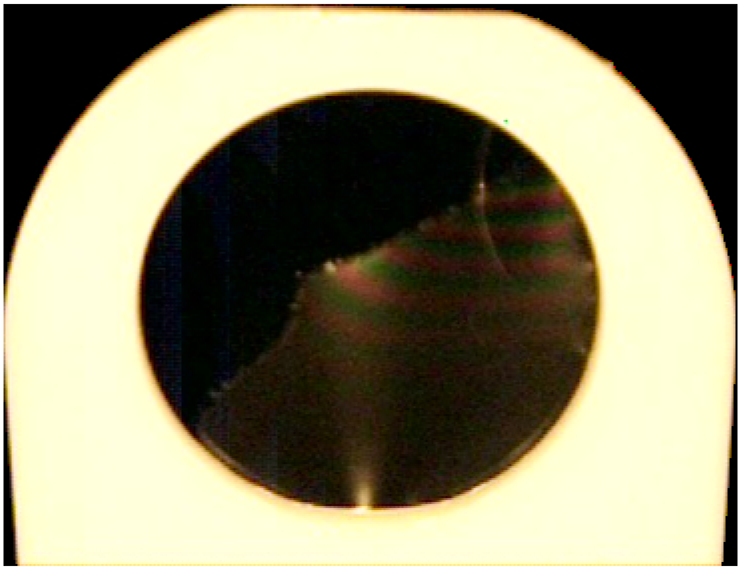

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