Physics in a Small Bedroom

Denis Weaire, Stefan Hutzler, Ali Irannezhad, and Kym Cox

1 Physics Teaching and Research in the Time of the Covid Pandemic

In 2020 the corona virus sent universities and schools into prolonged hibernation, forcing us to ask: how are we to adapt to our confinement? Available space for study might be restricted to a small bedroom. How were we to use it?

An obvious response has been to use remote teaching and learning, with online lectures and assignments. So far so good, and it will be very interesting to see what lasting effect this has on traditional teaching methods. One of us (DW) once wrote a humorous piece, "Rough World" [1], about the horrors of university life, including the torture of the ill-prepared lecturer confronted by a smart student . . . We have not always been honest with ourselves about the quality of our lecturing: we could well have adopted a better mix of online and personal teaching, long ago.

But in physics we insist on hands-on experimental work. In Trinity College Dublin this is imposed even on the theoretical physicists. Simulated experiments on a screen are hardly an adequate substitute for the real thing. So what could we do in such remote confinement?

Some of the best experiments in teaching and research are very simple and safe. They can be done at home, with materials that are readily at hand. Mostly they relate to classical mechanics or elementary properties of materials.

Many have argued that classical physics is the best training for rigorous thought. Even apparently trivial everyday phenomena can throw up teasing challenges to

D. Weaire · S. Hutzler (✉) · A. Irannezhad
School of Physics, Trinity College Dublin, Dublin, Ireland
e-mail: stefan.hutzler@tcd.ie

K. Cox
60 Spur Hill Ave, Poole, UK

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analysis. See, for example, the excellent work of Eric Mazur at Harvard [2]. Indeed, "Rough World" centred on a very elementary question that cropped up in a lecture: What happens if you modify the traditional "ladder-against-a-frictionless-wall" problem by allowing friction on the wall? [1]. This could indeed be a candidate for analysis in the bedroom.

What other experiments suggest themselves for this restricted space? Let us start with one that we have recently published in the *American Journal of Physics*: it made it on to the cover of the May 2020 issue [3].

2 Toying with Hard Spheres

Take any convenient number of ball bearings or similar hard spheres. (In what follows, you will find that it matters whether the number of spheres is odd or even, inviting thoughts and analysis on symmetry properties.) Place them in a tube with stoppers at both ends, lay it horizontally, and agitate slightly to encourage the system to come into equilibrium. (Immersion of the balls in oil will help.)

If sufficiently compressed by adjusting the stoppers, the chain of hard spheres buckles in a zig-zag pattern, as in Fig. 1. (Study problem: is this "Euler buckling"?) But the buckling is not uniform, as is evident from Fig. 1, and there are alternative sphere arrangements for higher values of compression. The phenomenon of localized buckling calls to mind the subject of "kinks" and "solitons" found in many nonlinear systems, so thoughts about nonlinearity in general are provoked.

The great John von Neumann said long ago that the computer (which he helped to invent) would release mathematics from the narrow confines of linear problems. So why not try to replicate your results by computer simulation?

There are much more sophisticated laboratory systems that are analogous to the humble set-up described above; they often demand the kind of expensive apparatus (e.g., for ion trapping) which we were determined to avoid. There are lots of possible variations without undue complication, for example, using soft bubbles instead of hard spheres.

Another hard-sphere experiment is associated with Isaac Newton, some of whose greatest achievements were made in seclusion: "All this was in the two plague years of 1665–1666. For in those days I was in the prime of my age for invention and minded Mathematicks and Philosophy more then than at any time since." (quoted in [5])

Newton's Cradle (Fig. 2), which appears to have been discussed first in 1662 by the mathematicians/natural philosophers John Wallis, Christiaan Huygens and Christopher Wren (the latter being also the architect of St. Paul's Cathedral in London), is a popular executive desk ornament, illustrating the principles of classical Newtonian mechanics. It is not hard to understand its obvious properties, but physicists always like to look more closely. John Hinch (one of many leading mathematicians who have followed in Newton's footsteps at Trinity College Cambridge) did so [6]. So have we [7], looking ever more closely: the experiment and

Fig. 1 One of the authors (AI) performing experiments in his bedroom in Tehran, Iran, during a Covid lock-down. His apparatus consists of a cylinder containing metal spheres. Pushing in the sides of the cylinder induces buckling of the initially linear chain. The effect becomes more and more localized as this compression is increased. In a variation of the experiment we study the position of the localisation peak as the cylinder is tilted, in order to determine the so-called Peierls-Nabarro potential [4]. This potential, originating in the theory of crystal dislocations, can tell us how the localized buckling moves when we tilt the apparatus (This is difficult to investigate with hard spheres, easier with bubbles)

its theoretical counterpart continue to be fascinating, with a never-ending pursuit of variations and complications [8].

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We recently spotted an attractive large scale Newton's Cradle in a local hospital, Fig. 2. Alas, its spheres were bolted together, so both art and science must have been frustrated by other considerations.

Fig. 2 In the standard textbook description of Newton's Cradle there is always only one sphere in motion. However, careful observation of the experiment shows that, already after the first impact of a displaced sphere on one side, the entire chain begins to break up, with all spheres in motion. Theory and computer simulations confirm this, and attribute it to the finite elastic modulus of the spheres [7]. The photograph shows the stainless-steel sculpture *For every action* ... by Fiona Mulholland (2005), permanently sited at Beacon Court South Quarter, Sandyford, Co Dublin. (Photo reproduced with kind permission by the artist)

3 Playing with Soft Bubbles

Soap bubbles can provide another homely source of inspiration, as they have done for centuries, in art, for which the definitive review is that of Emmer [9], and science, whose elementary aspects were described by Isenberg [10].

Staring into a foam with the naked eye, or with the help of a magnifying glass, will reveal local order amongst the randomness. Three soap films always meet in a line under an angle of 120°, and four such lines meet under the tetrahedral angle of 109.4°. The lines are called Plateau borders in honour of the Belgian scientist Joseph Plateau who was the first to describe them. His experiments were undertaken after he became blind (rashly staring at the sun, in the interests of science), so some of them may well have been performed in a domestic environment, with the help of his wife [11].

Rather than scooping up bubbles from the kitchen sink one may prefer to blow air through a straw into some soapy water. Blowing carefully (or using an aquarium pump borrowed from your fish) results in the generation of bubbles of equal size. These crystallize spontaneously to form a hexagonal pattern (triangular lattice) on top of the soap solution, with some defects, such as dislocations, amongst them (Fig. 3).

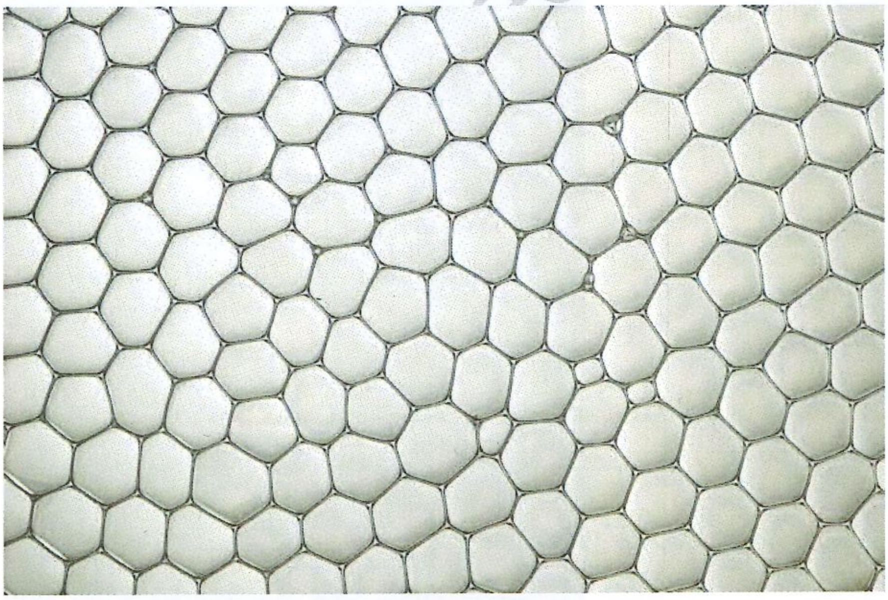

Fig. 3 Example of a (mostly) single layer of bubbles on top of a surfactant solution. The slight variation in size of the bubbles prevents the perfect crystallization seen in Bragg rafts of identical bubbles. ©Kym Cox

In 1947 Nobel Laureate William Bragg and John F. Nye studied such a 2d bubble raft as a source of inspiration for the study of crystalline defects [12]. Why did such prominent physicists experiment on such simple classical physics, working in the Cavendish Laboratory? Probable answer: there was no plague at the time but a World War must have left even Cambridge University impoverished.

Three-dimensional structures formed by monodisperse bubbles can provide more entertainment and questions for physics. Photographer and co-author Kym Cox recently brought them to great prominence via the *New Scientist* (Aug. 24, 2019) and even *The New York Times* (April 9, 2019). Figure 4 shows a particularly amusing example of her work. It was one of us (SH) who taught her the tricks of making such foams in her own kitchen.

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In turn, she surprised and challenged us by a further simplification of the experiment which was perfected by our Dublin research group: letting bubbles of equal size flow out of a cylinder is sufficient for generating a variety of regular bubble chains of various degrees of complexity, such as the one shown in Fig. 5.

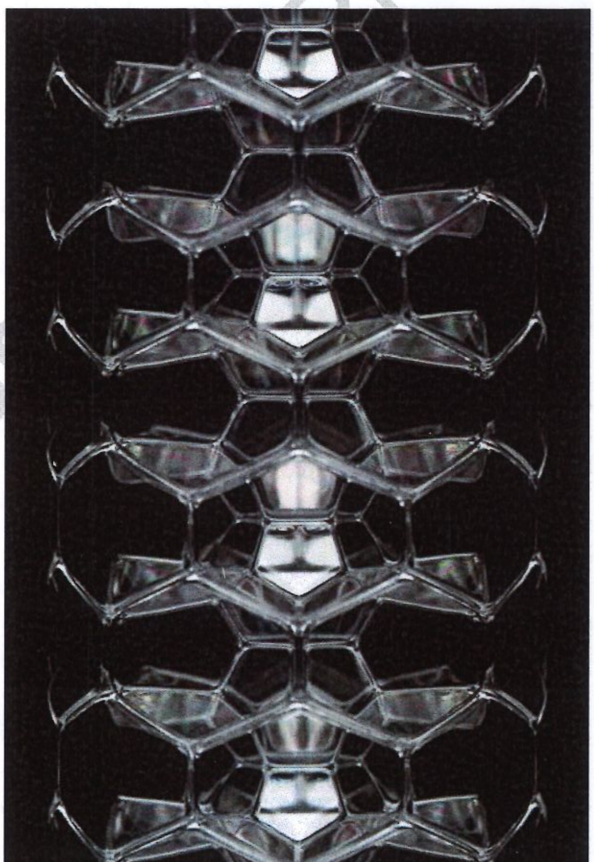

Fig. 4 "Columnar crystal" made of soap bubbles [13, 14], as observed by artist and photographer Kym Cox https://www.kymcox.com/©Kym Cox

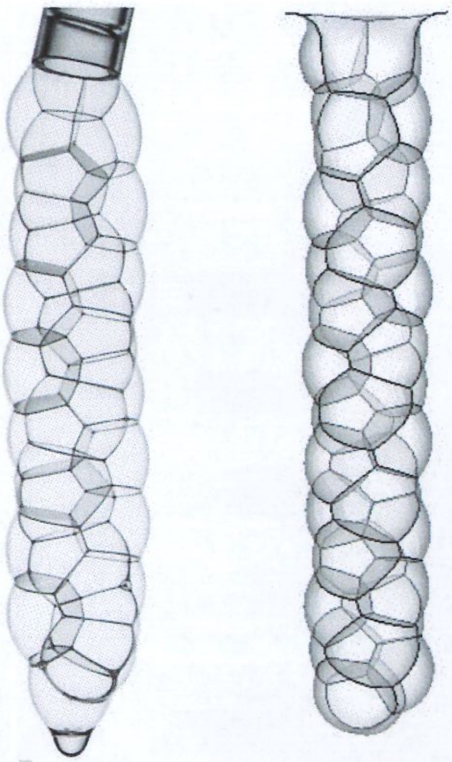

Fig. 5 Photograph of a freely hanging chain of soap bubbles (left, ©Kym Cox), recreated using computer simulations (right)[15]

The figure also shows our response: a computer simulation, which reproduces the key features of the structure.

4 Colours Brighten up a Dull Day

When soap films are viewed under appropriate optical conditions they display a rich spectacle of colours which fascinated both Robert Hooke and Isaac Newton. Figure 6 shows a sequence of four photographs of the interference patterns produced in a crystalline foam similar to the one shown in Fig. 4. As time progresses, the films thin as liquid drain away, leading to ever-changing interference patterns. Eventually, black spots appear on the film when viewed from reflection, as was already described by Hooke and Newton. This is due to destructive interference which occurs when the local film thickness is much less than the wave-length of light. (The phase shift of π due to reflection from the film is responsible for this.) Soap films may be as thin as 5 nm, making nanoscale effects visible to the naked eye!

Fig. 6 Four photographs in a time sequence (top left to bottom right) of draining soap films in a "crystalline foam", formed by soap bubbles, confined in a cylinder (©Kym Cox). The interference colours are indicative of the local thickness of the soap films. Since the foam structure is periodic in space, also the interference pattern seen in the films is repeated in each of the four photographs, with minor random fluctuations

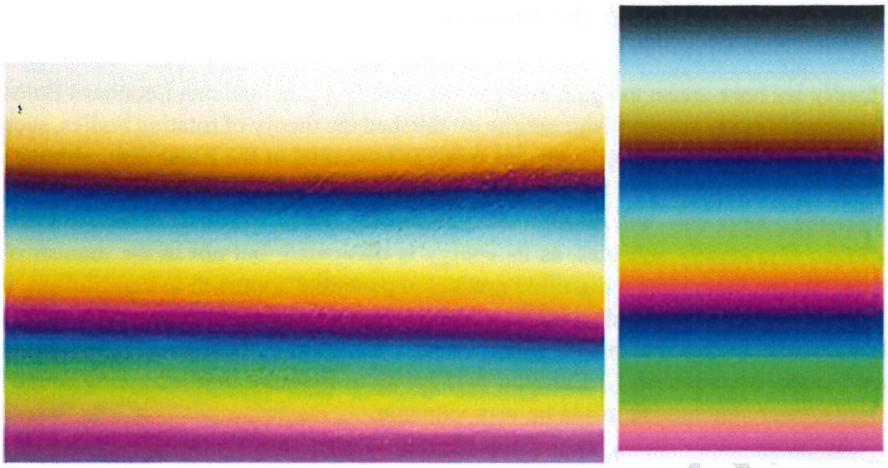

Fig. 7 Interference colours in a free-standing vertical film in photography (left, ©Kym Cox) and a computer simulation (final year TCD undergraduate project by Thomas Greg Corcoran, 2006)

The simple interference pattern of a single vertical wedge shaped soap film is readily computed and displayed using, for example, the Mathematica software. Figure 7 shows the result, together with a corresponding photograph of a real soap film.

Newton's experiments on the refraction of light, producing the colours of the rainbow by a prism, were either accomplished in his Cambridge college rooms or at his home in Woolthorpe Manor, using the light from his window. In our own College, Humphrey Lloyd performed another ground-breaking experiment on light in a similar way, demonstrating conical refraction [16]. Purpose-built and properly furnished physics laboratories are a relatively modern innovation, dating from the second half of the nineteenth century.

Nowadays, laser pointers are ideal for optics demonstrations, and the ever present smart phone offers apps for all kinds of data taking and analysis to conduct physics at home.

Artists have often painted bubbles to symbolize youthful joy, but also fragility and mortality [9], and many poets have done the same. In a further bedroom-type experiment we have measured the lifetime of thousands of soap films [17, 18]. The time variation of failure rates offers interpretations for both failure of technical devices and also human mortality.

We should not leave this wonderland of films and bubbles without reference to Cyril Stanley Smith [19]. Despite the great sophistications of many of his ideas, he rejoiced in the beauty of simple bubble structures and their significance. He directly encouraged one of us (DW) to find time to play with them.

5 Putting a Spin on the Lock-in

Finally we have cause to again bring in the prolific mathematician Leonhard Euler. Among his many accomplishments he established the theory of rotating bodies, such as the spinning top. Accordingly, his name is honoured in the Euler disk, although there is no evidence that he originated it. It is a flat disk, preferably a heavy one, although a large coin will do for a start. Search the house. When spun on a firm flat surface it gradually subsides, as its energy is dissipated, but not in the manner of most things. Instead of a dignified gradual exponential approach to equilibrium, it heads dramatically towards a crisis, emitting a sound of ever increasing frequency. It suddenly settles—not with a whimper but a bang. (In mathematical terms this is an "essential singularity".) Can you find a way to measure that intriguing sound? Again, your smartphone might be very valuable.

As for its explanation, enter Keith Moffatt, yet another Trinity Cambridge don (this kind of thing must be infectious ...). He has written with erudition on the subject [20]. A previous paper by Moffatt led one of the present authors (DW), while still an undergraduate, to throw eggs out of his second-storey student room on to an adjacent lawn. Moffatt claimed that they would not break, and he was (mostly) right!

Just one warning: if you do find a really heavy Euler disk (a manhole cover?), please try not to wake the neighbours!

6 Return to the Lab

At the time of writing we look forward to a return to our schools and laboratories. Truly remarkable (and very expensive) equipment awaits us. It is a pity that it consists largely of large grey boxes! We might bring back to the teaching and research laboratory an admiration of phenomena that have striking immediate visual or aural impact, and can be brought to your local Science Gallery, bridging science and art. They may look trivial but can still be challenging, teaching us to speculate and analyse until we get to the heart of the matter. And then, as so often in physics, we are tempted to go deeper still!

Note of Precaution Of course, safety is a paramount consideration. We trust that none of our suggestions will pose any significant hazards within the domestic environment, but caution is advised in every case.

Kym Cox is an artist and professional photographer. For a selection of her work see https://www.kymcox.com/.

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References

1. Weaire, D.: Rough World. Phys World **10**, 76 (1997)
2. Mazur, E.: Peer Instruction: A User's Manual. Pearson, London (1998)
3. Weaire, D., Irannezhad, A., Mughal, A., Hutzler, S.: A simple experimental system to illustrate the nonlinear properties of a linear chain under compression. Am. J. Phys. **88**, 347–352 (2020)
4. Mughal, A., Weaire, D., Hutzler, S.: Peierls–Nabarro potential for a confined chain of hard spheres under compression (2020, submitted)

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5. Westfall, R.S.: The Life of Isaac Newton. Cambridge University Press, Cambridge (1993/2015)
6. Hinch, E.J., Saint–Jean, S.: The fragmentation of line of balls by an impact. Proc. Royal Soc. Lond. A Math. Phys. Eng. Sci. **455**, 3201–3220 (1999)
7. Hutzler, S., Gary, D., Weaire, D., MacLeod, F.: Rocking Newton's cradle. Am. J. Phys. **72**, 1508–1516 (2004)
8. Cross, R.: The effect of very small ball gaps in Newton's cradle. Eur. J. Phys. **42**, 025004 (2021)
9. Emmer, M., Bolle di sapone. Tra arte e matematica, Bollati Boringhieri (2009)
10. Isenberg, C.: The Science of Soap Films and Soap Bubbles. Dover Publications, New York (1992)
11. Aste, T., Weaire, D.: The Pursuit of Perfect Packing, 2nd edn. CRC Press, Boca Raton (2019)
12. Bragg, L., Nye, J.F.: A Dynamical Model of a Crystal Structure. Proc. R. Soc. Lond. A Math. Phys. Sci. **190**, 474–481 (1947)
13. Saadatfar, M., Barry, J., Weaire, D., Hutzler, S.: Ordered cylindrical foam structures with internal bubbles. Philos. Mag. Lett. **88**, 661–668 (2008)
14. Tobin, S.T., Barry, J.D., Meagher, A.J., Bulfin, B., O'Rathaille, C.E., Hutzler, S.: Ordered polyhedral foams in tubes with circular, triangular and square cross-section. Colloids Surf. A Physicochem. Eng. Asp. **382**, 24–31 (2011)
15. Hutzler, S., Cox, K., Winkelmann, J., Ryan-Purcell, J., Kraynik, A.M. (in preparation)
16. Lunney, J.G., Weaire, D.: The ins and outs of conical refraction. Europhys. News **37**, 26–29 (2006)
17. Bois, A., Garcia-Roger, E., Hong, E., Hutzler, S., Irannezhad, A., Mannioui, A., Richmond, P., Roehner, B.M., Tronche, S.: Physical models of infant mortality. Implications for defects in biological systems. J. Biol. Phys. **46**, 371–394 (2020)
18. Richmond, P., Roehner, B.M., Irannezhad, A., Hutzler, S.: Mortality: a physics perspective. Phys. A **566**, 125660 (2021)
19. Smith, C.S.: A Search for Structure. MIT Press, Cambridge (1981)
20. Moffatt, H.K.: Euler's disk and its finite-time singularity. Nature **404**, 833–834 (2000)

AUTHOR QUERIES

AQ1. Please provide organization name for author “Kym Cox”.
AQ2. Please check the hierarchy of the section headings and correct if necessary.
AQ3. Please check if the word “then” can be removed from the sentence “All this was in the two plague....”
AQ4. Ref. “Fiona Mulholland (2005)” is cited in the figure caption but not provided in the reference list. Please provide it in the reference list or delete the citation from the text.
AQ5. Please provide revised artwork of Fig. 5, as the part of image is blurred.
AQ6. Please provide an update for Refs. [4] and [15].

AQ1; [Kym Cox has no "affiliation", she is a freelancing artist]

AQ2; hierarchy is ok

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AQ4; > have moved the date (2005) closer to the title of the artwork. This is NOT a standard citation.

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