Practical science at home in a pandemic world

There are plenty of online resources to ensure that learning can continue for students who cannot access universities during a pandemic, but what options are there for practical aspects of science courses? ***Daren J. Caruana, Christoph Salzmann*** *and* ***Andrea Sella*** *offer a manifesto for home-based experiments.*

How do you run a first-year undergraduate teaching lab to keep students physically distanced during the COVID-19 pandemic? This question that academics across the world are wrestling with as we wonder how classes will resume in the autumn. There has been much talk of giving students datasets to analyze and of using one of the new virtual laboratory simulators. But none of this addresses the problem of how we can get students to experience hands-on science procedures without the need for a fully stocked and supported teaching lab. It was while mulling this over that we began to wonder whether students could do their practicals at home. We began to imagine sending each student a kit, a seed for a home science lab; in essence, a chemistry set for the 21st century.

The chemistry set sparks strong emotions. Among people of a certain age, mention of the chemistry set often brings on misty-eyed and elegiac reminiscences about the 'old days' when dangerous chemicals could simply be obtained from the local pharmacy ('the chemist') and startling experiments could be conducted with chemicals today considered beyond the pale. But is the impact of the chemistry set real? Whenever the subject comes up, a little probing invariably reveals that at least as important was the impact of a mentor — a relative (an 'Uncle Tungsten')[1], a neighbour or a teacher who helped to encourage and channel the activities.

One of us, (A.S.) was given a chemistry set around age 10 and after running out of pH paper and the bicarbonate the kit was shelved. Anecdotally this is what we have heard from lots of students and parents: that chemistry sets are bought with good intentions but are among the presents that, for most children, are among the fastest to lose their appeal. This may also be related to their marketing. Chemistry sets are always sold with the promise of 'Danger', the bottles elaborately labelled with 'WARNING' signs. It doesn't take long for the budding chemist to discover that they are unlikely to be able to burn holes through tables with 'molecular acid' or to set fire to their school or neighbourhood police station. This marketing strategy completely misrepresents what chemistry is about — this misrepresentation of chemistry, often by the chemistry community itself, is something that one of us (A.S.) tried to address[2] in the Michael Faraday lecture in 2015. More insidiously the focus on specific chemicals limits the scope of the kit to just those substances and little beyond. After all what distinguishes real science from "show and tell", or from what Ernest Rutherford dismissed as 'stamp collecting', is measurement.

We live in a golden age of easy-to access instrumentation thanks to the combination of smart phones and those vast online emporia where all manner of instruments can be bought for peanuts. Let us therefore imagine giving each student a toolbox, not just for chemistry, but for science. The kit would then set students on an individual journey to observe and measure many physical phenomena that they might have heard about, but perhaps never seen outside of an online video. What would this kit contain and where might this journey lead?

We start by asking students to bake a cake. Many chemists will resent the facile association of chemistry and cookery — Gatterman's famous textbook of laboratory instruction, used in Europe and North America for over 50 years, was sniffily dismissed as 'Gattermann's cookbook'.[3] Yet Imperial College here in London have recently introduced cooking sessions at the start of their course as a foundation step before moving into a chemistry lab. This is an inspired idea. Baking a cake has a playfulness that should set the tone for the entire programme of practicals, but that also provides a rigorous introduction to work in the lab. After all, any scientific protocol has parallels with a recipe. Ingredients/reagents must be assembled — and in the correct quantities. Digital scales, with a precision of ±1 g, need to be in the kit. Choosing a cake recipe based on the mass of the eggs used requires the student/cook to scale quantities appropriately, but also introduces the idea of the limiting reagent.

Beyond mass, cooking procedures require attention to temperature control and to mixing and heat transfer, especially if students are set the challenge of scaling up or down. Perhaps most importantly of all, recipes introduce the idea that any set of instructions have embedded in them preconceptions about a student's knowledge. There is scope here for discussion about one aspect of the 'reproducibility crisis' — the fact that experimental sections often omit crucial details (e.g. greasing the tin, what ‘grease’ and how much), not necessarily through the malice of the experimenters, but rather through their hidden assumptions and unconscious bias.

The next instrument in the box will be a digital thermometer. Thermocouples enable measurement of temperature from around –50 to 1000 ˚C, from the domestic freezer to a candle flame. Armed with a flexible thermocouple a student can be helped to start asking questions. For example, one of the more common reasons invoked for the notorious reproducibility crisis in cookbooks are differences in temperature between one oven and another. With a thermocouple a student can investigate this in exactly the same way that careful solid-state chemists verify the temperature profiles of their furnaces; the student can also establish a more precise criterion for when their cake is baked — when the internal temperature reaches a particular temperature — than the traditional, qualitative, wet-skewer test. Better cooking through chemistry.

The combination of a thermocouple and balance naturally leads to calorimetry. Students should conduct classic kettle calorimetry. Both the heat capacity of water and its enthalpy of vaporization (‘latent heat’) can be measured with surprising accuracy if the power consumption of the kettle is known. If one now considers that thermocouples can read with a precision of ± 0.5 ˚C, it becomes possible to measure the enthalpy of fusion of ice simply by mixing weighed quantities of ice and water. Two issues emerge here. First of all, directly seeing the orders of magnitude of these quantities is a great topic for discussion, relevant for the thermodynamics of matter and with enormous implications for future earth and climate scientists. Secondly these measurements have significant limitations. This is the perfect environment for error analysis. Does insulating the kettle make any difference to the measurement? How significant is the uncertainty in the kettle’s power rating. The point is that the very low-tech nature of these practicals can help us to teach students to embrace uncertainty — and error analysis in particular — as a tool for improving experimental protocols.

Weighing a bottle of mineral water allows a student to explore the solubility of carbon dioxide. One can get a reasonably good estimate of the distribution between the liquid and the gas phases (thanks to the moderately slow kinetics of bubble nucleation), simply by weighing the bottle. The importance of nucleation on the kinetics can also be explored through the addition of different solids and monitoring the weight as a function of time. And the ridiculous never lies far away thanks to the very messy Diet Coke/Mentos demonstration.[4]

Exploration of ice, salt and water takes us deep into the real mystery of colligative properties and, by including digital jewellers' scales (that can read to ±10 mg) in our toolbox, one can prepare standard solutions; we can verify Raoult's law, and do so with household ingredients like salt, sugar and baking soda. As a playful release from quantitative thermodynamics, the low temperatures achievable using salt enables students to supercool bottles of water or to make bespoke ice cream; thus classic demonstrations and children's-party-level activities are reinvented for more advanced students.

A pH meter is the next instrument in our toolbox. After an initial 'stamp collecting' approach of measuring things round the house ('What is the most alkaline household product?') or testing bodily fluids (just imagine the potential for engagement…) we can start on a serious study of acids and bases that are core material for the chemical, earth and life sciences. With the jewellers' scales one can make up a standard solution of NaOH (the first reagent to be included in the kit) and then titrate household vinegar in what is a classic strong base–weak acid titration to yield both concentration and pK_a. Although such titrations could be done using plastic volumetric pipettes rather than a burette, for an extra $35 one can include in the box a basic mechanical/Marburg pipette, the quintessential piece of apparatus that signals 'high-end scientist' and have time to develop real familiarity with its use.

Other subjects for titration include kettle descaler (lactic or citric acid) and cream of tartar (potassium hydrogen tartrate). Measurements of the pH of a bottle of mineral water can, with the earlier mass measurements, provide valuable environmental insights and open up important discussions of ocean acidification and other global challenges. Returning to simple acid–base reactions, these can be repeated on a preparative scale to provide bulk quantities of salts that can be repurposed for other things. Sodium acetate is, on the one hand, a classic chemical buffer, but is also a component of hand warmers and the subject of endless 'hot ice' demonstrations, with discussion of crystal nucleation not far away. With a little support a student could design a method to measure the enthalpy of solution of this salt. By contrast, potassium hydrogen tartrate yields Rochelle salt, $KNaC_4H_4O_6{\cdot}4H_2O$, that forms spectacular piezoelectric crystals. pH titrations can also be used to investigate colloid stability — adding acids to milk might help focus thinking on the electrostatic repulsions that hold fat globules apart. Students can later make paneer/fromage blanc for culinary study. But in an age where other ‘milks’ have now joined the mainstream, mammalian milks can be compared with each other, or with their oat, rice, nut or soya alternatives.

Next, the box contains a multimeter, a battery pack, a set of LEDs and some LEGO. Several teachers of chemistry have used these to build colorimeter/fluorimeters.[5] With a LEGO ‘spectrometer’ Beer–Lambert studies can be developed. If a UV LED and a few hundred milligrams of quinine sulfate are included in the box, a student can create calibration curves to determine the concentration of the alkaloid in tonic water and then go beyond to use Stern–Vollmer kinetics to study fluorescence quenching. If one wanted to be really playful, a student could taste their dilute quinine solutions (echoes of the famous Scoville test for capsaicin) and use the results to compare the sensitivity of the taste buds to that of the eye and the LED detector.

The use of thermocouples and LEDs suggests including a starter-level microprocessor kit into the toolbox. The LEDs of the colorimeter/fluorimeter can now be controlled and read with an Arduino or micro:bit, and the data transferred to a home computer.[6] Coding can now be introduced quite seamlessly into the educational programme, activities that open opportunities to dream up either citizen science projects or to collaborate with students from an art or architecture school to make environmentally responsive artworks. Thus a narrow undergraduate lab course can now be opened and become a starting point for other conversations, rather than an end in itself.

Soap making provides an entry into organic chemistry, but with a physical twist. The hydrolysis of animal or vegetable fat is a straightforward procedure that starts with NaOH and has to be done in careful quantitative fashion. The melting point can be determined using the thermocouple and a water/ice bath. The product can be tested for safety using the pH meter. In the absence of spectroscopic characterization one might take inspiration from Agnes Pockels[7] and Irving Langmuir to measure the molecular dimensions of the soap. A known mass can be laid on the surface of a baking tray sprinkled with talcum powder. The diameter of the resulting talcum-free circle can be measured with a ruler. Even with quite simplistic assumptions about molecular mass and density one can establish that the molecules are several times longer than their diameter across the surface of the water.

The availability of a homemade soap leads naturally to beautiful experiments with surface tension: floating and propelling objects on liquids, blowing bubbles, looking at foams between microscope slides, using coat hanger frames to visualize minimum energy surfaces. Measuring and manipulating contact angles of liquids with surfaces leads to discussion of hydrophilicity and hydrophobicity. The identification of suitable hydrophobic surfaces can lead to microscale inorganic chemistry in drops[8], which in turn yields diffusion constants for ions. What is more, with mobile phones, and their ever more sophisticated cameras (think slo-mo), such experiments can become hugely engaging and shareable.

A laser pointer included in the kit lets students play with optics. They can measure refractive indices for liquids — addition of drops of milk to water makes beams visible, allowing the position of the laser pointer and the beam to be photographed. The photograph can then be analyzed either with digital tools or with a protractor. But the monochromatic nature of the laser means that with a diffraction grating the wavelength of light can be measured and the information used to estimate the thickness of soap films. The laser pointer itself can be used to image microorganisms (e.g. tardigrades) in drops of pond water and, if the camera is equipped with a cheap microscope attachment (e.g. Foldscope),[9] the laser can be used as a light source for a cheap Zsygmondy ultramicroscope with which Brownian motion can be observed.

Finally, with blotting paper and crayons, wax-channel microfluidics can be used to go beyond simple paper chromatography and devise microscale assays. For example, by including copper chloride in the kit together with the NaOH and Rochelle salt, one might imagine using the Biuret test to detect amino acids/proteins and begin to discuss modern diagnostic tools.

The above list only begins to capture the myriad directions in which this approach can be taken. Crystal growing, sugar-glass making, piezoelectricity, polarization, optical rotation and birefringence, elasticity, electrophoresis, birefringence, magnetism and magnetic alignment can all be incorporated into these activities. What makes this framework different is that it places measurement at the very centre, with the 'chemicals' playing an almost incidental role. Where chemical compounds are used, the same ones are repurposed over and over to highlight different areas of science: if you measure and study one chemical, you can measure them all.

None of the ideas presented here are new. Indeed, science education journals, popular science books and science popularization sites[10] contain myriad ideas that can be adapted for such experiential learning. But there is one critical caveat. While the programme must be underpinned by a variety of text and video-based resources, for students this project will only really bloom with significant, dedicated mentoring and support. Just as with the recent debates about the 'One Laptop per Child' initiative,[11] simply sending students an instrument does little to enhance their learning. It is the mentoring aspect that is critical. A drop-in online helpdesk has to be available for face-to-face support, inspiration and guidance. There must also be deadlines for submission of notes, plots, measurements, photographs, videos and so on; the project has ample fodder for blogging which will provide much-needed practice in science writing and for developing an e-portfolio. And, perhaps most importantly, there need to be meetings with mentors/tutors at the end of each week to chew over and digest (sometimes literally) what has been done and then to prepare for the next stage in the practical sequence. We are currently developing a home laboratory manual to accompany this experiential learning toolbox.

Far from being childish, an instrument-drive approach to 'kitchen' science strongly reinforces the idea that structured thinking and simple tools are the gateway to learning about the world (often called 'the scientific method'). The difficulties of having to set up a measurement almost from scratch, without technicians to prepare equipment and solutions, could help inculcate a spirit of improvisation; the absence of rigid laboratory timetables also gives students more time and reason to footle about with these tools, building their own home lab and working collaboratively to try things out. The COVID crisis has created many problems; let's see if it can be harnessed as an opportunity for deep changes to our approach to practical education that will align our teaching laboratories with those where we conduct our research.

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Acknowledgments

Many co-conspirators contributed to this set of ideas, among them in no particular order Alom Shaha, Michael Depodesta, Carole Kenrick, Steve Price, Dewi Lewis, Emre Sener, Anna Roffey, Patrick Thompson, Mark Miodownik, Stefan Gates, Bob Worley, Chris Howard, Stephen Potts, Tom Miller, Helen Czerski, Sarah-Jayne Blakemore, Paul McMillan and many others.

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Figures

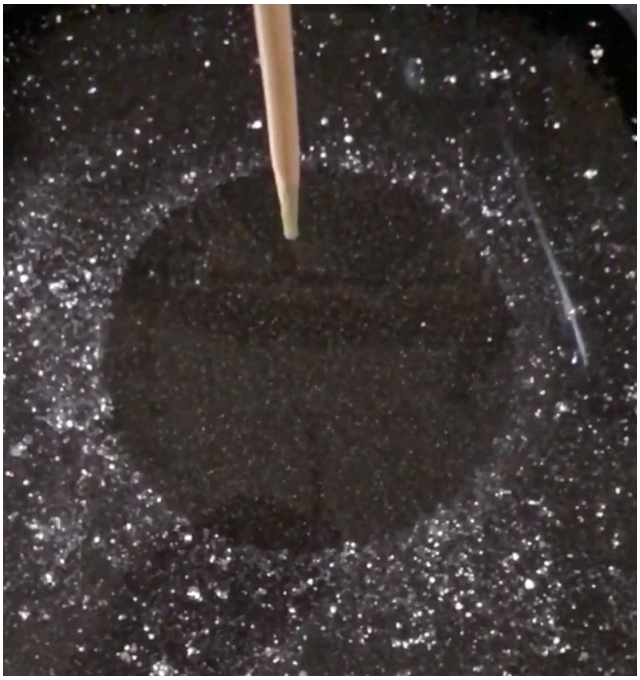

Figure 1 | Soap on water. A simple way to measure molecular dimensions, inspired by Irving Langmuir, using talcum powder sprinkled on water.

Box

Possible contents of the basic toolbox (Budget ~GBP60-100)

A notebook

Plastic ruler and protractor

A smartphone with a camera

A clip-on microscope

A digital thermometer

Kitchen scales (Up to 3 kg, precision: ± 1 g)

Jewellers' scales (Up to 100 g, precision: ± 10 mg)

A laser pointer (any colour)

Some plastic graduated pipettes (3 ml) OR a mechanical pipette (0.3 – 5 ml)

A handheld pH meter

A digital multimeter

Safety spectacles

A selection of LEDs of various colours (including 1 UV LED) and resistors

A battery pack

A box of LEGO with a base and some pieces with holes in them

Wires with crocodile clips

A square of polarising film

A square of plastic diffraction grating