A laboratory for multi-century science

Charles Cockell and colleagues consider what it takes to establish and maintain an experiment that lasts for decades – or even for centuries.

Scientific questions do not always fit into neat three-year grant cycles. How long can a microbe live for? How long does it take plastic to decompose? How long does it take for a fern leaf to transform into a fossil? What happens during these processes? Indeed, there are an impressive array of fascinating questions about the universe whose answers can only be brought into view by observing phenomena over century or longer timescales. We are addressing these sorts of questions with the design of a new Laboratory for Multi-Century Science.

Five years ago, we began a scientific experiment to study how quickly microbes lose viability over long time periods (Cockell 2014, Cockell *et al.* 2015, Ulrich *et al.* 2018). The 500-year microbiology experiment is a simple investigation to study the survival, decay and death of two species of desiccated microbes (*Chroococcidiopsis sp.* and *Bacillus subtilis* spores) and to test hypotheses about how microbes lose viability in a desiccated state over long time periods. The experiment is duplicated in Edinburgh and the Natural History Museum, London. Its third time point is in 2020. The implementation of this experiment led to conversations with numerous scientists about other scientific questions that cannot be answered over the short timescales associated with grants and human lifespans.

Experimental heritage

Long-term scientific experiments actually have an impressive heritage. William Beal, an American botanist, filled 20 bottles with seeds in 1879 and buried them. His intention was to study how long seeds could retain their viability. Originally intended to be unearthed every five years, the Beal Germination Experiment was later extended to every 10 and then every 20 years (Beal 1905, Darlington 1941, Kivilaan & Bandurski 1981, Telewski & Zeevaart 2002). The study will end in 2100. From the most recent bottle to be retrieved from its burial ground at Michigan State University, only two of the 21 plant species germinated. One downside of the experiment is the lack of replicates, for example replicate bottles or a replicate experiment somewhere else, and a clear understanding of the original viability of the seeds when the experiment began. Such limitations have plagued these types of experiments and were a motive for the proposal described here.

"Long-term scientific experiments actually have an impressive heritage"

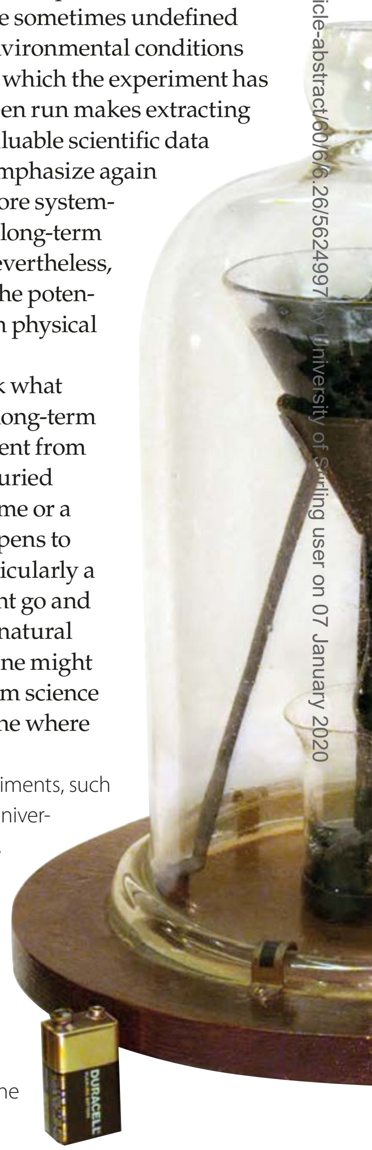
Beal's legacy continues at Michigan with Richard Lenski's long-term microbial evolution experiment, a study that has been tracking the genetic changes in 12 initially identical populations of *Escherichia coli* (e.g. Lenski & Travisano 1995, Barrick *et al.* 2009, Blount *et al.* 2012). The experiment was begun in 1988 and the populations reached the milestone of 66 000 generations in 2016.

At Rothamsted, UK, the Park Grass Experiment has been run since 1856 (Laws & Gilbert 1859, Silvertown *et al.* 2006). Originally designed to study the effects of fertilizers and manures on hay yields, its plots have yielded many new insights into biodiversity and evolutionary changes in plants. It is one of the most impressive long-term ecological research experiments to have been started.

Most famous are the pitch-drop experiments. In these experiments, a funnel containing a highly viscous fluid such as bitumen is prepared, allowing the material to flow, drop-by-drop, through the funnel into a beaker. An early demonstration example was set up in 1902 at the workshop of the Royal Scottish Museum in Edinburgh, which has dropped at least twice, although without precise observation. Rather, the Guinness World Record for the longest running laboratory experiment is held by the pitch-drop apparatus set up in 1927 by Thomas Parnell at the University of Queensland, Australia (figure 1). The ninth drop occurred in 2014. Similar experiments were started at Trinity College Dublin, Ireland, in 1944 (the first to capture a falling drop on camera) and at Aberystwyth University, Wales. In the latter case, the experiment, begun in 1914, used a very viscous pitch that has yet to produce its first drop.

These experiments are mainly educational. Although they have allowed for viscosity measurements to be made on the materials used, none of them have been set up in replicated form and the sometimes undefined environmental conditions in which the experiment has been run makes extracting valuable scientific data difficult. They emphasize again the need for a more systematic approach to long-term experiments. Nevertheless, they also show the potential for long-term physical experiments.

One might ask what distinguishes a long-term science experiment from a time capsule buried for a specified time or a sample that happens to be very old, particularly a sample one might go and collect from the natural environment? One might define a long-term science experiment as one where

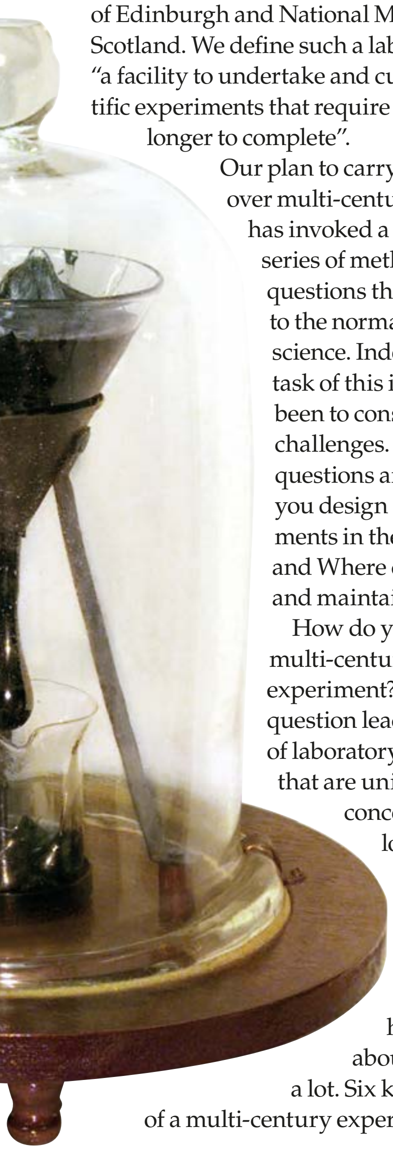


1 Pitch-drop experiments, such as this one at the University of Queensland, are well-known long-term experiments. They raise important questions about how such experiments should be ideally designed. The battery is for scale.

the experiment is deliberately designed to be run over timescales exceeding grant income or human lifespans. For example, although microorganisms from herbarium specimens have been studied that are well over 100 years old (Shirkey *et al*. 2003), the long-term experiment has a defined start and end point, adequate sampling time points (as opposed to a time capsule), multiple samples if necessary per time point, and appropriate controls, as well as other in-built experimental designs to address statistical considerations and the testing of the hypothesis. Intentionality and data collection are key: it is a *bona fide* preconceived experiment that runs for a long time.

A Laboratory for Multi-Century Science

Following the implementation of our 500-year microbiology experiment, we developed the idea of putting together a "laboratory" that is focused on initiating and caring for other experiments that require a century or longer to accomplish. We are currently developing plans for a Laboratory for Multi-Century Science as a collaboration between the University of Edinburgh and National Museums Scotland. We define such a laboratory as "a facility to undertake and curate scientific experiments that require a century or longer to complete".



Our plan to carry out science over multi-century timescales has invoked a fascinating series of methodological questions that are alien to the normal practice of science. Indeed, the first task of this initiative has been to consider these challenges. Two of these questions are: How do you design such experiments in the first place? and Where do you store and maintain them?

How do you design a multi-century science experiment? This single question leads to a series of laboratory challenges that are unique to the concept of very-long-term science experiments and hypothesis testing. We have thought about this rather a lot. Six key attributes of a multi-century experiment that we can identify are:

- (1) It must involve the minimum number of moving parts (preferably none) and the minimum total number of parts to reduce servicing requirements, energetic requirements and the chances of technical failure.
- (2) It must be robust against changes in environmental conditions or energetic requirement to mitigate the need for continuous highly controlled conditions.
- (3) It must not take up too much space so it can be curated over century time scales without becoming an encumbrance.
- (4) It must be easy for the samples to be taken and the sample procedure and method of analysis to be undertaken against a backdrop of century-long technological changes and cultural shifts or the collapse of civilizations, to make the results from each time point comparable to the others.
- (5) The scientific question must have a broad and, as far as possible, a long-lasting appeal.
- (6) Clear instructions and protocols on how to perform the experiment need to be available for posterity.

"Experimental methods and protocols must be recorded on media that will endure"

Simplicity is key to these experiments. Some of these attributes cannot be easily addressed objectively (for example no. 5), but nevertheless they provide a basis to advance a discussion on the design of particular experiments.

We can also learn a great deal from previous long-term experiments about experimental design. Although requirements such as replication, controls and a clear starting point in whatever is being quantified seem obvious design criteria for a scientific experiment, they have often been lacking in existing long-term experiments. Designing these requirements into an experiment at the beginning is not trivial. For example, triplicate samples at time points running over centuries can lead to a substantial number of samples. How are sampling time points to be reduced to a manageable number, while still ensuring that valuable scientific data can be obtained and that the period between each time point is not so long as to make it likely that the experiment will be forgotten? These are questions that have to be addressed for each individual experiment, yet they are important if the experiment is not to end up becoming a one-off time-capsule-like statement of posterity; this is fun, but potentially scientifically limited or even valueless.

Where could such experiments be housed? Museums seem ideal candidates, given their culture of careful documentation, the capacity to store objects under controlled environmental conditions, long institutional memory, and their mission to preserve for the long term (Lindsay 2005). National Museums Scotland, successor of the Royal Scottish Museum, has a shared pedigree and a long history of collaboration with the University of Edinburgh. Like other national collections, it is charged by law to care for objects for posterity – in this case the National Heritage (Scotland) Act 1985. We are considering the possibility of depositing the projects involved in a Laboratory for Multi-Century Science with National Museums Scotland, where they would be cared for at the National Museums Collections Centre north of Edinburgh, with potential for display at the main museum site in the centre of the city. This would be firmly in keeping with the institution's mission to "preserve, interpret, share and make [the natural world] accessible for all".

The prospect of curating such long-term experiments raises interesting museological questions. Curators generally prefer to acquire inert material and the notion of collecting a "live" experiment may seem problematic – until we consider that compared to any natural science specimen, any multi-century experiment must by definition be very stable. But is it problematic that during this accessioning process, title (ownership) would be transferred to the museum, as well as the intellectual property rights? How are time points to be obtained decades and centuries after the start?

Challenges

We have identified two particular challenges. First, experimental methods and protocols must be recorded on media that will endure or they must be regularly updated on new media. The 500-year microbiology experiment stipulates that at each time point, the data and methods are newly recorded on paper. But what is the best way to ensure a high reliability of the transmission of information over time? What language(s) should be used?

Secondly, curators must themselves have instructions. Centuries after the start of an experiment, when the originators are no longer around, the curator must know what type of scientist is required to implement a time point. There must be experimental protocols, but also curatorial protocols. Digital collection management systems are designed to endure, but they have only been in existence for a few decades. Our approach to this, and to the other issues around preservation and other museum practices on which the experiment will rely, is that at every time point curators need to ensure that the records, data and instructions will survive until the next time point. They will be passing the baton in a long-term relay.

Types of experiments

One of the fascinating outcomes of proposing a laboratory focused on long-term science experiments is the number of such experiments that have come to light and the stimulation it provides for conceiving such experiments. Many of our tea breaks have revolved around such discussions.

Concepts for new experiments include further long-term microbiology experiments designed to address questions on the longevity of desiccation-resistant microbes and molecular changes incurred over long time periods. Following on from the ESA BioRock space experiment (Loudon *et al.* 2018) is a Multi-Century BioRock experiment. It will explore the multi-century longevity and survival of biofilms formed by a single organism on surfaces (*Sphingomonas desiccabilis*, one of the microbes used on the International Space Station), as compared to a microbial community. Different types of rock, natural and artificial substrates will be tested.

Experiments are planned to investigate the intersection of biology and geology. We are constructing the Million Year Entombment Experiment, which involves investigating the longevity of bacterial spores and vegetative cells entombed in salt crystals. Time points at 1, 5, 10, 100, 1000, 10 000, 100 000 years and at the million year mark will allow for a quantitative assessment of the controversial question of how long microbes can survive in salt substrates. There have been claims of the recovery of 250-million-year-old spores entombed in salt (Vreeland *et al.* 2000), but the hypothesis remains highly controversial. Although the length of this experiment seems outlandish, it carries with it the entertaining distinction of being the first scientific experiment to bridge traditional biological and geological timescales – and it will no doubt attract the attention of museum audiences.

Other experiments will also have rich science engagement potential linked to their contemporary relevance. We often hear the refrain that some plastics take centuries to be degraded in the environment. It has been discovered recently that plastics are becoming part of natural rocks ("plasticrust") and that microplastics are polluting waters (Hammer *et al.* 2012, Gestoso *et al.* 2019). Although there is much data that supports the long timescales of destruction, artificial plastic was introduced into our lives only about 150 years ago, and museums have struggled to anticipate their behaviour (Shashoua 2008). The obvious way to address the question empirically is to do the long-term experiment. Pieces of plastic, metals, paper and other materials, perhaps chosen by school pupils, can be subjected to long-term burial in sediments and exposed to natural environmental conditions to study their rate of decline over multi-century timescales.

"Beyond biology and geology, chemistry can benefit from long-term experiments"

The fate of buried materials is also central to fossilization. The processes in the early stages of fossilization that determine whether a buried leaf, for example, is broken down and strewn asunder or whether it leaves an imprint in the rock record are poorly known. Multi-century experiments in fossilization might well allow scientists to understand better the early processes in how fossils are formed.

Many fundamental geological processes occur over multi-century time spans and these too might lend themselves to experiments. For example, the study of the rate of erosion of different types of rock as water passes across them might be studied in long-period experiments. Samples of well-defined rock types can be exposed to the natural environment and their behaviour and weathering rates examined over century timescales. Yet another experiment we have considered is the study of the release of hydrogen from mafic rocks in the process of serpentinization, whereby olivine minerals in the rocks react with water to produce hydrogen which can potentially fuel a deep subsurface biosphere. How much hydrogen is produced over century timescales at low temperatures from this process? The answer to this question will be useful to understand the subsurface habitability of Mars and other planets.

Beyond biology and geology, chemistry can benefit from long-term experiments. The study of chemical reactions over century timescales, for example interactions of organic materials with mineral surfaces or low-temperature behaviour of organic materials, might offer opportunities for investigations in fields such as the chemistry of the origin of life. The study of "use-by" dates on drugs, generally not tested over very long time periods, could be a further avenue of chemical studies.

Astronomy could provide additional experiments. Following from preliminary discussions with Andrew Lawrence (University of Edinburgh), potential scientific interest in changes over hundreds of years is significant, ranging from brightness variations of the most distant quasars, to motions of solar system bodies. The sky does the experiments for us, and data collection is likely to be by large multi-organization projects. Like other fields, the key issues are long-term data preservation, curation and documentation.

STEM engagement

The concept of multi-century experiments has enormous potential for engaging different audiences, and especially young people, with science, technology, engineering and mathematics (STEM). Museums are keen to collect material relating to contemporary – and in this case, future – science (Alberti *et al.* 2018), and audiences respond well to the presentation of the scientific process and ongoing and unfinished work (Hine & Medvecky 2015). When we commandeered the help of undergraduates in preparing the vials for the 500-year microbiology experiment in 2014, we noticed the enthusiasm they had for the hands-on practicalities of making the experiment. The idea that the vials they were sealing over a Bunsen flame might next be opened in the 26th century exerted a powerful grip on their imagination.

We might capitalize on the appeal of this project. For example, one approach would be to hold a schools competition to design a multi-century experiment; the winning design could join the existing experiments. This would engage students in scientific experimental design and give them an opportunity to contribute towards a scientific programme of work; most of all, it would encourage young people to construct scientific questions. The experiments themselves might enrich both pupil and adult visits to the museum. We like the idea of enthusiastic children devising their own scientific experiment, carrying it out for an entire lifespan and then eventually passing it on to posterity. ●

AUTHORS

Charles S Cockell (c.s.cockell@ed.ac.uk) is professor of astrobiology at UK Centre for Astrobiology (UKCA), University of Edinburgh; **Rosa Santomartino**, **Sean McMahon** and **Philippe Reekie**, UKCA; **Samuel J M M Alberti**, National Museums Scotland, Edinburgh (NMS) and Centre for Environment, Heritage and Policy, University of Stirling, UK; **Tacye Phillipson**, NMS; **Sara Russell**, Natural History Museum, London, UK.

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