Higher Education Pedagogies

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rhep20

Opinion piece: non-traditional practical work for traditional campuses

Timothy D. Drysdale , Simon Kelley , Anne-Marie Scott , Victoria Dishon , Andrew Weightman , Richard James Lewis & Stephen Watts

To cite this article: Timothy D. Drysdale , Simon Kelley , Anne-Marie Scott , Victoria Dishon , Andrew Weightman , Richard James Lewis & Stephen Watts (2020) Opinion piece: non-traditional practical work for traditional campuses, Higher Education Pedagogies, 5:1, 210-222, DOI: 10.1080/23752696.2020.1816845

To link to this article: https://doi.org/10.1080/23752696.2020.1816845

Published online: 14 Sep 2020.

HIGHER EDUCATION PEDAGOGIES
2020, VOL. 5, NO. 1, 210–222
https://doi.org/10.1080/23752696.2020.1816845

Taylor & Francis
Taylor & Francis Group

ARTICLE

OPEN ACCESS Check for updates

Opinion piece: non-traditional practical work for traditional campuses

Timothy D. Drysdale [a], Simon Kelley [b], Anne-Marie Scott [c], Victoria Dishon [d], Andrew Weightman [e], Richard James Lewis [f] and Stephen Watts [g]

[a]School of Engineering, The University of Edinburgh, Edinburgh, United Kingdom of Great Britain and Northern Ireland; [b]School of Geosciences, The University of Edinburgh, Edinburgh, United Kingdom of Great Britain and Northern Ireland; [c]Office of the Deputy Provost, Athabasca University, Athabasca, Alberta, Canada; [d]College of Science and Engineering, The University of Edinburgh, Edinburgh, United Kingdom of Great Britain and Northern Ireland; [e]Mechanical and Aeronautical Engineering Division, The University of Manchester, Manchester, United Kingdom of Great Britain and Northern Ireland; [f]Physics and Astronomy, Cardiff University, Cardiff, United Kingdom of Great Britain and Northern Ireland; [g]Electronic and Electrical Engineering, University of Bath, Bath, United Kingdom of Great Britain and Northern Ireland

ABSTRACT

Traditional practical work for higher education in STEM subjects is under pressure from rising student numbers and adesired increase in active learning. Investing in more buildings and staff is financially challenging, while stretching existing resources affects outcomes, health, and participation. A more pragmatic approach is to embrace a less instrumentalist view of practical work in physical spaces and instead adopt a critical post-humanist approach which mixes both humanity and technology to achieve a sum greater than the parts, not bound by the limits of either. We share the experiences of leading UK exponents of non-traditional laboratories in the four main categories of simulation, virtual laboratories, real-asynchronous, and real-synchronous activities, as well as experts in scaling digital education initiatives for university-wide adoption. We foreshadow opportunities, challenges and potential solutions to increasing the opportunity for active learning by students studying at traditional campuses, via the complementary addition of non-traditional practical work.

ARTICLE HISTORY
Received 29 July 2019
Revised 6 February 2020
Accepted 12 May 2020

KEYWORDS
Laboratories; practical work; experiments; simulations; remote laboratories; virtual laboratories; blended learning; pooling; automation

1. Introduction

There is a widespread perception that STEM educators need to turn out graduates better able to meet societal and industry needs, and to do so at scale in order to satisfy demand. See, for example, Graham (2018) in the case of Engineering or Manduca et al. (2017) for Geosciences. To meet this challenge, it is often suggested to use active learning in its various forms such as problem-based learning (PBL), design-based learning (DBL) or project-based learning (PJL). However, these approaches are typically confined to small cohorts with high per-capita budgets and often championed by individuals even in the face of significant under-resourcing according to Graham and Crawley (2010). While the educational appropriateness of these methods is broadly

CONTACT Timothy D. Drysdale Timothy.Drysdale@ed.ac.uk School of Engineering, The University of Edinburgh, Edinburgh EH9 3FG, United Kingdom of Great Britain and Northern Ireland

accepted (Perrenet, Bouhuijs, & Smits, 2000), it is simply not possible to envisage operating them at scale in most campuses due to physical laboratory, timetabling, and staffing constraints.

On the other hand, STEM education can meet this overarching challenge, and alleviate existing constraints, through significant adoption of non-traditional practical work (NTPW). NTPW is an umbrella term to describe digital and online alternatives to traditional practical work. NTPW includes virtual and remote laboratories, augmented and virtual reality, and simulations. Delivery can be online, on demand, on- or off-campus, with automated feedback and evaluation, and available 24/7. Staff are no longer to be present for activities to proceed safely and meaningfully, and physical space is reclaimed in previously under- or unused locations that are not suitable for face-to-face interactions. NTPW presents an attractive value proposition due to the reduced space it requires per activity, increased laboratory availability, and attendant environmental sustainability benefits.

NTPW is not simply a low-cost alternative to traditional laboratories, as it offers equal or better outcomes than traditional practical work, across all educational categories (Brinson, 2015). Benefits accrue in part because NTPW offers affordances not possible in traditional laboratories e.g. visualising hidden fields such as stress, or flow (Nolen & Koretsky, 2018). However, we argue that traditional laboratories must also be retained so students can benefit from a mixture of the approaches, which has been shown to be better than either approach alone (see, for example, Brinson, 2015 and Herodotou et al., 2018). The pedagogical case for using NTPW will continue to develop as community experience in the sector grows, with near-future growth likely to come from recognising that the risk of exploring pedagogical opportunities is at least offset by the immediacy of the scaling benefits (if implemented well). The nature of the implementation and the institutional support available directly affects aspects of the pedagogy such as staff agency to contextualise NTPW to their local conditions so as to support student diversity and inclusivity. In section two, we will illustrate examples connected with our experience of existing NTPW activities across the spectrum, from simulations to remote laboratories with real equipment, with our view on how these areas can or should progress. Then, in section three, we outline a future-looking view of the challenges and opportunities in what we see as the next generation of NTPW development.

2. NTPW illustrations

We now illustrate an aspect of each of the following main types of NTPW, to show how our opinion has developed:

- *Simulated* laboratories (mathematically-modelled data)
- *Virtual* laboratories (replay of data pre-recorded from real equipment)
- *Asynchronous real* laboratories (experiments performed automatically on remote equipment with the results sent back to the student afterwards)
- *Synchronous real* laboratories (experiments performed interactively on remote equipment with results streamed in real time)

2.1 Simulated laboratories

2.1.1. Physics simulations for education

A broad range of purpose-built physics simulations for educational purposes is available from multiple providers. The typical educational level and target application contexts in this sector include:

(1) **Fundamental concepts**. The University of Colorado Boulder's Physics Education Technology (PhET) provides undergraduate level educational simulations and teaching materials for physical sciences and mathematics. PhET simulations are quite diagrammatic, but are highly optimised for usability and student exploration of fundamental concepts; see Adams, Paulson, and Wieman (2008). Similar resources include CK-12, myPhysicsLab, and Emanim.

(2) **Pre-/post-lab enhancement**. Learning Science and ChemCollective's virtual laboratories are designed as pre- or post-lab enhancement sessions for chemistry, physics, biology, and other disciplines. The UI experience is less abstract than PhET and much closer to a 'traditional' laboratory experience. A major benefit of pre-lab simulations is the enhancement of students' cognitive focus in the linked laboratory exercises; see Winberg and Berg (2007).

(3) **True virtual laboratories** such as Labster, PraxiLabs, and Virtlabs provide 3D and VR environments that mesh with sophisticated physical science and engineering simulations to provide a very convincing 'in the room' user experience close to that of a typical undergraduate laboratory. In contrast to the more abstract, diagrammatic representations of PhET and Learning Science, these virtual laboratories often have the stated aim of *replacing* real laboratories.

(4) **Playful, large-scale simulation software** such as Universe Sandbox 2 and Celestia and true video games such as Kerbal Space Program are examples of 3D simulations of environments that could not possibly be explored in the laboratory. Central to the user experience is the playful interaction with reasonably accurate simulations of physical and astrophysical phenomena.

The above examples are valuable educational tools within their own operational contexts, but none of them resemble physics *research* simulations in terms of scope, UI design, or operational context. A gap in the presentation of the 'realism of practice' therefore exists into which education-adapted research simulations could usefully sit.

2.1.2. Physics simulations for research

Simulations for use within physics research groups can be broadly divided into four categories: (1) fundamental 'single-physics' simulations, (2) multiphysics simulations, (3) instrumentation/system simulations, and (4) 'big physics' simulations.

(1) 'Single-physics' simulations are typically bespoke software written by a single scientist or research group for the purpose of high-fidelity simulation, usually involving physics from a single field. Such software is often open-source. There is often no attempt made to integrate with other code, beyond using well-established open-source numerical software and libraries.

(2) Multiphysics simulation suites allow the simulation of physical systems that involve coupled phenomena spanning several different fields. Such suites are central to system and component design, providing an invaluable baseline for comparison with experimentation. Multiphysics suites are mostly commercial, closed-source software, although they may interface with open-source libraries, e.g. differential equation solvers.
(3) Instrumentation/system simulations are typically bespoke packages written by a research group to support the design and test process. Such software is usually closed-source, often not disseminated beyond the research group that developed it, although more general-purpose, commercially-available instrument design software is available.
(4) ‘Big physics’ simulations, i.e. simulations which involve either very computationally-intensive algorithms and/or very large datasets (‘big data’) were once restricted to being carried out on large, expensive supercomputers. The past twenty years has seen a dramatic rise in the use of distributed computing, fast desktop PCs, and GPU cluster supercomputers, together with a sharp drop in the overall implementation and running costs for ‘big physics’-capable computation; see for example Fernández, Fernández, Miguel-Dávila, Conde, and Matellán (2019) and Xu, Chi, and Xiao (2016).

Physics research simulations types (1) to (3) and often (4) can be practically run on modern desktop PCs, exploiting parallelism in codes where available. In addition, many higher education institutions have access to an on-site supercomputer whose time can be partially allocated for educational purposes, especially in USA and UK (Dhawan, Gupta, & Gupta, 2018).

Adams et al. (2008) clearly demonstrated that significant work was necessary to optimise usability even for conceptually simple purpose-built educational simulations for inclusion in PhET. In order to adapt physics research simulations for educational use, a careful choice of the application context and a usability optimisation process will certainly be required.

2.1.3. The future of simulations for educational use in remote laboratories

The operational context of physics research simulations for educational use is typically restricted to small-scale implementations of the ‘single-physics’ type. Simulations in active learning contexts are very effective in supporting learning (Freeman et al., 2014), however the educational context has at least partially defined the form the simulations take; they are often virtual versions of simple undergraduate experiments; see for example Tong-on, Saphet, and Thepnurat (2017). There are exceptions; Nolen and Koretsky (2018) identify affordances of simulations as embedded in realistic project-based learning contexts. Instances exist where the boundary between physical and virtual laboratories is blurred; see for example Lindgren, Tscholl, Wang, and Johnson (2016).

In the context of ever-increasing student numbers in Higher Education, it is likely that the modality of teaching and learning will change. Remote access-simulated-resource-type remote laboratories (Heradio et al., 2016) would go a long way to easing pressures on institutional resources, while enhancing student learning and experience. The growing impact of and reduced barrier to entry of high-performance computing raises the additional issue of the challenges of introducing parallel computing into science curricula (Voevodin, Gergel, & Popova, 2015).

Potkonjak et al. (2016) acknowledged the infrastructural advantages of simulation for educational use, but criticised the typical lack of educationally useful 'bad' outcomes in 'safe' virtual environments. This could be partly addressed by adapting research-grade simulations for educational use in realistic project-based learning environments (Lewis & Drysdale, 2019). Such authentic simulations are also usable as training aids, addressing Potkonjak et al.'s authenticity criticism. Simulations which implement modularity, user interaction, adjustable complexity, and use of educational affordances in an appropriate way would be a valuable and flexible element in a mixture of traditional and remote laboratories.

2.2. Virtual laboratories

Virtual laboratories provide a genuine practical work experience by allowing students to explore authentic pre-gathered data, typically collected using research-grade equipment. Experiments with a finite set of parameters are preferred, so that sufficient data can be collected in advance. A good example of this is virtual microscopy, where the whole slide can be digitised into a large multi-resolution image file (hundreds of megabytes to tens of gigabytes), with elements of the image delivered on demand to the student in a browser window as required, as if the data were streaming from a real microscope. Virtual microscopy applies to many fields, ranging from geoscience, microbiology, health, veterinary medicine, medicine, dentistry and metallurgy. The concept of multi-resolution files delivered on demand applies equally well to telescopic observations, such as visible, infrared and radio astronomy.

To date, a number of courses have implemented virtual microscopy (e.g. Herodotou et al., 2018; Parker & Zimmerman, 2011). Most implementations have concentrated on offering features such as choice of slide, magnification level, and X-Y translation of the slide. Some have added Z-translation to simulate the need to focus (by deblurring the image). The UK Open University pioneered the inclusion of additional features such as hyperlinked text associated with specific locations (ensuring distance learners could discuss specific features on a given slide in confidence), and also rotations of the sample under polarised light – an important feature for geoscience, as shown in Figure 1. Due to the data required at the time, rotations were only available in selected locations and launched by clicking a 'hot spot' in the image.

An evaluation of the student experience of using virtual microscopes alone and in combination with physical microscopes was conducted by comparing the experience of usage of virtual microscopes with a distance learning only cohort and a conventional university cohort who had access to a virtual microscope (Herodotou et al., 2018). The main outcomes from the study were that students in blended learning conditions were most satisfied with their experience, and achieved the best learning outcomes, compared with students studying online only. Consistent with other studies (e.g. as reviewed in Brinson, 2015) there is emerging a consensus that the optimal pedagogical approach is to embed virtual microscopes *and* conventional microscopes in the course material and assessment rather than use them to augment conventional teaching or as 'homework.'

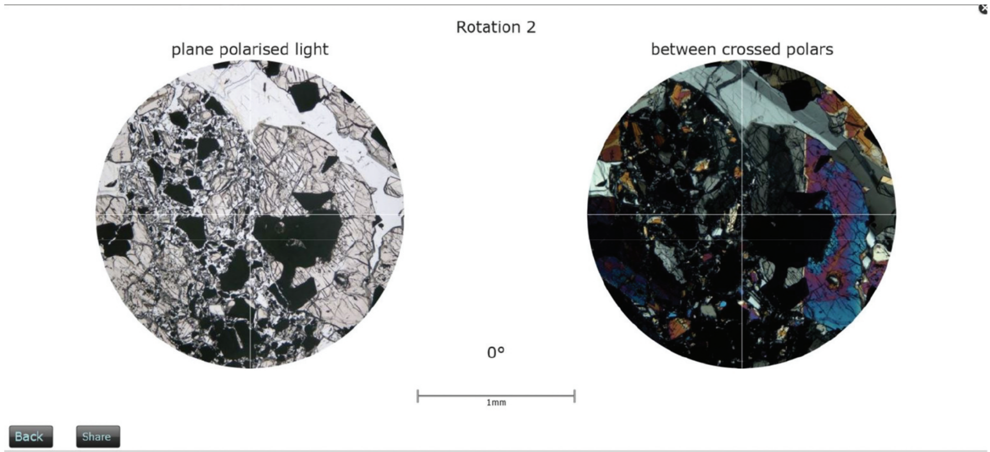

Figure 1. A picture of a virtual microscope interface from the Open University, showing the polarised light feature. Figure from https://virtualmicroscope.org reproduced under the Creative Commons Attribution-NonCommercial-ShareAlike 2.0 Licence.

2.2.1. Future of virtual laboratories

Looking to the future, there are several improvements that can be made on the technical and pedagogical aspects of virtual microscope use in Higher Education. For example, 3D samples are of increasing relevance, so require new developments in capturing, preparing and delivering the data on demand. Features such as sample rotation under polarised light ought to be extended to allow students to rotate any given sample. Consideration needs to be given to the effects of artificially introducing focal blur, and tensioning the efficiency of the data communications and latency in the user interface against authenticity in the representation. This applies also to transitioning between polarised light data captured at discrete angles, yet presented to students as a continuously rotatable sample. The capability to deliver a shared experience for group work involves significantly increased data bandwidth but is worthy of further investigation. Conflicting reports in the literature on student preferences for communication during activities reflect higher satisfaction with classroom-like environments. For student co-creation, and extension of the data sets available by course staff, the future must include prioritisation of systems and platforms to crowdsource images, as well as manage permissions for access to sensitive samples.

2.3. Asynchronous laboratories

Asynchronous laboratories are those in which a student does not interact with the experiment in real-time. For example, consider a student submitting experimental control parameters (forward path gain, feedback gain *etc*) for a position servomechanism, as shown in block diagram from in Figure 2, via a web page. The asynchronous experimental system will queue the request if it is one of many, acting on it in turn and sending experimental data back to be displayed in the webpage (Weightman, Culmer, Levesly, & Hansen, 2007,; Hanson et al., 2009).

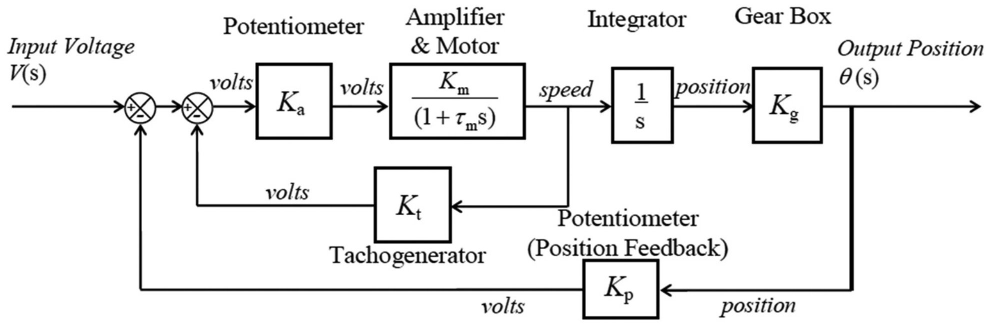

Figure 2. Block diagram for an experimental position servomechanism. Students undertake asynchronous experiments through a web page varying the gains K_a, K_t and K_p. Figure sourced from. Weightman et al. (2007)

In this manner the student can undertake the assignment set undertaking multiple measurements, analysis and submitting their results via the web interface. The asynchronous experimental system may create an online database of all results and present these back to the student as a visual illustration of the characterised system, enabling students to compare their results to those of their peers, see Figure 3. The visualisation can present both model (theoretical) and experimental results. A further learning outcome is an illustration of how experimental uncertainty creates small but noticeable differences with model solutions (Figure 3). If students are allowed to submit multiple times then this can provide an environment for risk-free experimentation enabling error correction before credit is assigned. This feedback contrasts against traditional laboratories, which are, time limited and do not provide students with an opportunity to redo experimental work or calculations, although there is a tension against providing feedback that only amounts to grade-polishing.

Large experimental classes in traditional laboratory settings can mean high expenditure is required on equipment, compromises are made on the quality of the equipment, or students are forced to work in large groups, which may hinder the learning of some

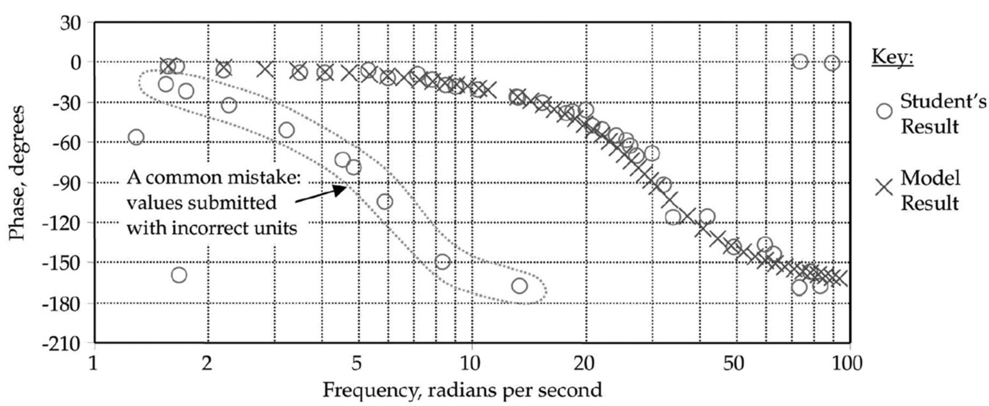

Figure 3. Results of multiple Individual student responses characterise a dynamic experimental system. Figure sourced from.Hanson et al. (2009)

within them. The alternative is to have smaller class and group sizes but this will inevitably increase utilisation of staff time and create timetabling challenges.

Asynchronous laboratories if used appropriately within the curriculum, can compliment traditional 'hands on' lab work, alleviate some of the challenges articulated above, and have some valuable educational advantages (Weightman et al., 2007,; Heradio et al., 2016):

- **Flexible access** – students can engage with laboratory work for a prolonged period of time (24–7);
- **Flexible learning model –** Flexible access enables students to engage in a manner, which suits their lifestyle;
- **Access to specialist equipment –** Single item and/or expensive cutting edge technology can be integrated into the curriculum;
- **Increased accessibility** – unlike traditional laboratories, students can repeat experiments to check/confirm results;
- **Personalisation of experiments** – Individual students within a group can have different experimental configurations, reducing the potential for academic malpractice and enabling characterisation of overall system performance e.g. see Figure 3;
- **Efficiency –** Experimental equipment is not as labour intensive for teaching staff when in use;
- **Immediate feedback –** Formative and summative;
- **Safety –** dangerous experimental work.

With careful design asynchronous laboratories can be used to promote differentiated learning, deeper learning (in more interested students), enhanced student control of their learning, a more inclusive, accessible, teaching environment and enhanced linking of practical and theoretical work. In order to provide exploratory opportunities with minimal delay between setting parameters and observing the results, it is necessary to move from an asynchronous to a synchronous remote laboratory.

2.4. Synchronous laboratories

Synchronous laboratories impose stringent technical conditions in order to create an emotionally engaging experience, otherwise, the frustration of expecting an instant response but finding delays can lead to negative outcomes such as disengagement. This constraint does not apply to asynchronous laboratories because there is no expectation of an immediate response. Humans are said to be able to associate cause and effect within a window of approximately 200 ms (Kahneman, 2012) without undue effort, whereas introducing a delay of 30 seconds in seeing the results of an activity is known to reduce the acquisition of the skill of that activity (Dyal, 1964). Fortunately, low-latency video feeds can be streamed using the W3C standard WebRTC, such as pioneered in the context of remote laboratories by the openEngineering Laboratory at the UK Open University (Drysdale & Braithwaite, 2018). Informal observation shows that achievable latencies in cross-city, cross-country and international usage are low enough to achieve emotional engagement wherever there is good internet service to the user's location.

Security considerations are necessary to protect the quality of experience. For example, per-session access control ensures sure that students can share their session with peers or staff, but afterwards they cannot accidentally use the history or back-button features of their browser to re-connect (thus avoiding conflict with subsequent users).

For students who have booked in advance, perhaps making care arrangements to free up their study time, it is unacceptable to fail to connect them to working equipment. A triple-pronged approach ensures that the equipment can run for weeks or months without requiring maintenance, that the equipment protects itself from damaging inputs from students, and that an automatic management system checks every experiment before connecting a student. Redundant experimental stations are provisioned so that technicians can schedule the repair of any non-working experiments into normal working hours without affecting the student experience out of hours. While equipment should not damage itself, experiments should still provide opportunities for failure in terms of the exercise, such as throwing up surprising (genuine) results to provoke further thought. Examples include range sensors that fail to detect triangular objects due to the returning wave being deflected away from sensor, or driven undamped pendulums that appear to have a resonant frequency when theoretically they should not.

2.4.1. Future of synchronous laboratories

The development of remote laboratory facilities with equipment at multiple sites offers the possibility for pooling to increase throughput at busy times during the term (assuming equipment usage patterns differ from site to site), or for enhancing the diversity of equipment available by allowing cross-institution access to specialised one-off experiments. Such an approach would allow the rapid intra- & inter-institutional dissemination of pedagogical approaches that are embodied in software, such as for automatic evaluation or feedback (e.g. Gal, Uzan, Belford, Karabinos & Yaron, 2015) based on the rich data stream flowing between NTPW activities and students; or for the connection of live data streams from experiments to live web dashboards or numerical analysis tools.

Blended laboratories would allow students to construct apparatus during the day, then access it remotely overnight, running experiments that are too long to be able to be run in traditional laboratory time, yet retaining the elements of experimental design and construction traditionally associated with hands-on activity.

3. Future teaching and delivery

Each of the illustrations refers to work (or reflective thought) that was developed (and delivered) in isolation, yet they echo common themes of instrumental motivation relating to resource pressure, and excitement in the opportunity to explore new pedagogical approaches. We propose that through using both physical and NTPW experiments in teaching, we can offer the advantages of tactile learning in traditional laboratory settings, and the less conspicuous opportunities of unbound digital experimentation (Gourlay, 2015). In doing so we can provide a more playful and risk-less space to aid (often unobserved) consolidative leaps of understanding by students. At present students working in traditional labs are often time limited and where there is pressure to complete the experiment with the correct result, failure is not easily accommodated. Traditional labs can be seen as a performance, with students learning the 'lines' to reproduce a change or effect as demonstrated by an expert. Students may leave the laboratory having learned the mechanics of the experiment, but has each student had the opportunity to explore to the extent that they individually require? Do they understand the purpose of the experiment? Did they achieve the learning outcome as designed by the teacher, or did they only learn how to repeat the steps to achieve success?

NTPW activities can present students with the opportunity to learn in a less restricted environment, and to take some risks with their learning. NTPW could even be used to facilitate flipped laboratory teaching, where students use NTPW experiments to explore in advance of physical laboratory sessions, enabling more inquiry-led learning in earlier years (Sharples et al., 2015).

Furthermore, we argue that viewing NTPW activities through a post-humanist lens (Braidotti, 2018) provides fruitful ground for appreciating significant new potential in this space. Critical post-humanist approaches emphasise that technology should not attempt to replace humans but instead be valued on its own terms (Bayne, 2015). In her work on a chatbot for a digital humanities course, Bayne has motivated the aspect of our work that sees NTPW activities as potential collaborative partners with their own agency, and that NTPW activities could have some inherent capability to fulfil teacher-like functions, such as hinting, prompting, guiding, or even questioning and challenging the student. In NTPW activities students are bounded to a relevant scope of enquiry by the hardware and user interface designs, provoked to think by results which may be surprising, and can explore multiple variations of the parameters. The NTPW experiment itself communicates the values of a malleable intelligence and should not be combined with a procedural lab sheet. Layering additional responsive prompts, such as introducing tasks or goals to complete, or adding artificial-intelligence communication abilities is also a possibility, but there is already great potential in the guidance that can be achieved through the design and interactivity of the user interface.

It would be naive to suggest that the path to achieving this lies simply in the introduction of a new technology however. The key to success will lie in appropriate academic development support combined with programme-led curriculum design, especially where the role of the demonstrator or the teacher might be being reconceptualised (Cendon, 2018). Scaffolding student use of NTPW activities across the breadth of a programme of study requires careful design, fully considered by an experienced team with a background in experimental teaching. These individuals would craft a framework of activities that present incremental challenges, building up layers of fundamental concepts to deliver a cumulative effect. Over a sustained period of study, students in early years would gradually transition from highly structured problem based learning and tutor guided activity, through to senior years where they can confidently and successfully approach open-ended project based learning as the ultimate goal (Riley et al, 2017). A further benefit comes in using the inherent timetabling flexibility offered by NTPW activities to open new opportunities for within-programme cross-year, and inter-programme (interdisciplinary) project working.

3.1. Future delivery

As each of the illustrations highlight, NTPW activities are an area where the commercial educational technology market does not provide, and where the sector is building significant expertise for itself. In order to leverage the benefits of this expertise, to accommodate a sector of mixed capacity and resource, and to ensure best practices in areas such as accessibility are easily scaled, we believe that the next generation of NTPW activities should be delivered through pooling and sharing arrangements. In this model institutions would make available spare capacity to other institutions, lowering the total costs of ownership for all. Sharing equipment and expertise across institutions would also support rapid dissemination and remixing of best practice in NTPW activities.

The ideal scenario would be one where NTPW experiments from a sector pool could be easily accessed by teachers from with institutional Virtual Learning Environments (VLEs). We suggest that with the release of the IMS LTI 1.3 specification the required integration standards are now mature enough. If NTPW activities from many institutions were integrated with a centralised management infrastructure then, using LTI, deep links to specific experiments could be embedded into courses from an 'app store' like interface, and authentication and authorization for course cohorts to access experiments easily handled. Work is required to ensure that any management infrastructure is robust and not a single point of failure, and there would be data protection considerations to address within any shared service model. Thought is also required in a commons of NTPW activities as to how ensure that one institution's learning technology doesn't become another's 'black box', by facilitating some opportunity for remixing experiments locally. Going further, engaging students directly with co-creation or remixing/refactoring NTPW experiments arguably offers a myriad of rich new pedagogical opportunities.

Building out a commons of NTPW activities, owned and operated by a community of educational institutions requires an additional level of institutional investment. We argue that in order to scale up provision across STEM teaching, a new role, analogous to the current technician role is required. We have a long history of technicians fabricating physical artefacts for in-person lab work, and it is not a huge conceptual leap to assume that we need a similar role now to create digital artefacts for online lab work. Ideally this role would have an understanding of pedagogy as well as digital development skills, and so extending our current thinking around the learning technologist role towards a learning technology developer may be a useful place to begin. As many institutions increasingly move to SaaS based commercial educational technology providers, we argue that a failure to retain some in-house innovation capability is a potentially significant risk to realising the potential for NTPW activities within STEM teaching. We advocate that savings made in outsourcing core educational technology services such as the VLE could be reinvested in what we see as the next generation of educational technology for STEM learning. A further benefit of NTPW is that it can assist institutions in meeting their sustainable development goals by reducing the need for students to travel.

4. Conclusion

We argued that the challenge of scale and improving student capabilities in real-world professional practice can be met by sharing and pooling NTPW experiments across institutions and adopting a posthuman approach where NTPW activities are explicitly designed such that they have some teacher-like agency. We envisage a future where students and teachers work generatively in collaboration with a wide network of NTPW experiments, benefiting from human and technological interactions where each has its strengths.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Timothy D. Drysdale http://orcid.org/0000-0003-3068-2113
Richard James Lewis http://orcid.org/0000-0003-1859-0021

References

Gourlay, L. (2015). 'Student engagement' and the tyranny of participation. *Teaching in Higher Education*, *20*(4), 402–411. doi:10.1080/13562517.2015.1020784

Adams, W.K., Paulson, A., & Wieman, C.E. (2008). What levels of guidance promote engaged exploration with interactive simulations? *AIP Conference Proceedings*, *1064*, 59–62.

Bayne, S. (2015). Teacherbot: Interventions in automated teaching. *Teaching in Higher Education*, *20*(4), 455–467. doi:10.1080/13562517.2015.1020783

Braidotti, R. (2018). A theoretical framework for the critical posthumanities. *Theory, Culture & Society, 36*(6), 31–61.

Brinson, J.R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, *87*, 218–237. doi:10.1016/j.compedu.2015.07.003

Cendon, E. (2018). The role of teachers in professional studies and perspectives on networked learning. In M. Bajić, N.B. Dohn, M. de Laat, P. Jandrić, & T. Ryberg (Eds.), *Proceedings of the 11th International Conference on Networked Learning,* Zagreb, Croatia *2018.*

Dhawan, S.M., Gupta, B.M., & Gupta, R. (2018, July). Supercomputing: A scientometric assessment of global publications output during 2007–16. *COLLNET Journal of Scientometrics and Information Management*, *12*(2), 197–213. doi:10.1080/09737766.2018.1545395

Drysdale, T.D., & Braithwaite, N.S.-J. (2018). Practical engineering education through a web browser: An internet of engineering lab things. Retrieved from http://sine.ni.com/cs/app/doc/p/id/cs-17710

Dyal, J.A. (1964). Effects of delay of knowledge of results in a line-drawing task. *Perceptual and Motor Skills*, *19*(2), 433–434. doi:10.2466/pms.1964.19.2.433

Fernández, Á., Fernández, C., Miguel-Dávila, J.Á., Conde, M.Á., & Matellán, V. (2019, January). Supercomputers to improve the performance in higher education: A review of the literature. *Computers & Education*, *128*, 353–364. doi:10.1016/j.compedu.2018.10.004

Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014, June). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, *111*(23), 8410–8415. doi:10.1073/pnas.1319030111

Gal, Y., Uzan, O., Belford, R., Karabinos, M., and Yaron, D. (2015). Making sense of students' actions in an open-ended virtual laboratory environment. *Journal of Chemical Education, 92*(4), 610–616. doi:10.1021/ed500531a

Graham, R. (2018). *The global state of the art in engineering education*. Cambridge, MA, USA: New Engineering Education Transformation, MIT.

Graham, R., & Crawley, E. (2010). Making projects work: A review of transferable best practice approaches to engineering project-based learning in the UK. *Engineering Education*, *5*(2), 41–49. doi:10.11120/ened.2010.05020041

Hanson, B., Culmer, P., Gallagher, J., Page, K., Read, E., Weightman, A., & Levesley, M. (2009). ReLOAD: Real labs operated at a distance. *IEEE Transactions on Learning Technologies*, *2*(4), 331–341. doi:10.1109/TLT.2009.35

Heradio, R., De La Torre, L., Galan, D., Cabrerizo, F., Herrera-Viedma, E., & Dormido, S. (2016). Virtual and remote labs in education: A bibliometric analysis. *Computers & Education*, *98*, 14–38. doi:10.1016/j.compedu.2016.03.010

Herodotou, C., Muirhead, D.K., Aristeidou, M., Hole, M.J., Kelley, S., Scanlon, E., & Duffy, M. (2018). Blended and online learning: A comparative study of virtual microscopy in higher education. *Interactive Learning Environments*, 1–16. doi:10.1080/10494820.2018.1552874

Kahneman, D. (2012). *Thinking fast and slow*. London, England: Penguin Books.

Lewis, R.J., & Drysdale, T.D. (2019). Simulation of research-grade physics, chemistry, and engineering experiments in LabVIEW as a flexible template for remote laboratories. In *Proceedings of the SEFI 47th Annual Conference,* Budapest, Hungary, (pp. 710–725). 15–19 September.

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016, April). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers & Education*, *95*, 174–187. doi:10.1016/j.compedu.2016.01.001

Manduca, C.A., Iverson, E.R., Luxenberg, M., Macdonald, R.H., Mcconnell, D.A., Mogk, D.W., & Tewksbury, B.J. (2017). Improving undergraduate STEM education: The efficacy of discipline-based professional development. *Science Advances*, *3*(2), E1600193. doi:10.1126/sciadv.1600193

Nolen, S.B., & Koretsky, M.D. (2018). Affordances of virtual and physical laboratory projects for instructional design: Impacts on student engagement. *IEEE Transactions on Education*, *61*(3), 226–233. doi:10.1109/te.2018.2791445

Parker, N.T., & Zimmerman, L. (2011). Comparison of microbiological laboratory skills of students with online versus traditional preparatory laboratory experiences. In *Proceedings of the 18th Annual American Society for Microbiology Conference for Undergraduate Educators* (pp. 38–B). Baltimore, Maryland, USA: John Hopkins University.

Perrenet, J.C., Bouhuijs, A.J., & Smits, J.G.M.M. (2000). The suitability of problem-based learning for engineering education: Theory and practice. *Teaching in Higher Education*, *5*(3), 345–358. doi:10.1080/713699144

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V.M., & Jovanović, K. (2016, April). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, *95*, 309–327. doi:10.1016/j.compedu.2016.02.002

Riley, S., Pirie, I., & McCabe, G. (2017). Student-Led, Individually-Created Courses (SLICCs): Enabling students to gain academic credit for extra-curricular activities during the summer vacation and take ownership of their learning. In S. Elkington & C. Evans (Eds.), *Transforming assessment in higher education: A case study series* [Case Report 18] (pp. 104–108). York, UK: Higher Education Academy.

Sharples, M., Adams, A., Alozie, N., Ferguson, R., FitzGerald, E., & Yarnall, L. (2015). Innovating pedagogy. *The Open University Innovation Report 4*. Retrieved from http://open.ac.uk/innovating

Tong-on, A., Saphet, P., & Thepnurat, M. (2017, September). Simple harmonics motion experiment based on LabVIEW interface for Arduino. *Journal of Physics: Conference Series*, *901*(1), 012114.

Voevodin, V., Gergel, V., & Popova, N. (2015). Challenges of a systematic approach to parallel computing and supercomputing education. In *Euro-Par 2015: Parallel Processing Workshops* (pp. 90–101).

Weightman, A., Culmer, P., Levesly, M., & Hansen, B. (2007). An application of remotely controlled experiments to perform feed forward and feedback damping control of an electro mechanical servomechanism. In *Webist conference 2007*.

Winberg, T.M., & Berg, C.A.R. (2007). Students' cognitive focus during a chemistry laboratory exercise: Effects of a computer-simulated prelab. *Journal of Research in Science Teaching*, *44*, 1108–1133. doi:10.1002/tea.20217

Xu, Z., Chi, X., & Xiao, N. (2016, March). High-performance computing environment: A review of twenty years of experiments in China. *National Science Review*, *3*(1), 36–48. doi:10.1093/nsr/nww001