Remote Teaching and Assessment of Professional Science Laboratory Skills

Sashi Jeffries, Wiremu S. Demchick, Magdalena Bereza, and Paul H. Demchick

***Abstract*—An approach and system for remote teaching and assessment of a range of science laboratory skills including use of pipettes, micropipettes, dispensing solids by mass and aseptic manipulations is described. This approach assures that students have a range of job-ready practical skills before undertaking a training placement in a commercial laboratory. The system allows two-way audio and video between the student and the educator, allows the educator to remotely know the reading on a digital laboratory balance and allows student and educator to view each other's inputs in real time on a mock Laboratory Information Management System (simulating those used in professional laboratories).**

***Index Terms*—Science laboratory skills, pipetting, weighing, distance learning, distance assessment.**

I. Introduction

COVID-19 has forced many educational providers to consider ways to do science laboratory teaching and assessment remotely [1]-[6]. Even before COVID-19, there were interesting approaches to remote delivery of science laboratory education [7]. However, our reason for laboratory teaching is different from many, as is our motivation for laboratory teaching and assessment. Since our needs have been more long-term, our developed approach is further along the refinement path than some. This article describes an approach that allows the teaching and assessment of selected key laboratory skills.

There are various reasons for including laboratory work in science education, including increasing student interest, reinforcing concepts, allowing practice with experimental design and others. There are various approaches to accomplishing some of those in distance learning. For example, there are "dry labs" in which students are given mock experimental data to analyze. Also, there are online systems that allow the user to do simulated laboratory work online.

However, our undergraduate programs have needs that were not met by previously existing approaches. Our undergraduate programs prepare people with no significant laboratory experience for roles in industrial laboratories. During the course of the program, they need to develop the sort of speed and accuracy that is expected in a professional laboratory. The early part of our undergraduate program involves online video lessons and learning of key practical skills. The later part of the undergraduate program includes a training placement in a high-quality commercial laboratory, in which the students receive training on a wider range of laboratory work. It is important for making good use of the placement time that students arrive well prepared on the key skills. The fact that they will have that level of skill is part of our promise to the commercial laboratories with whom we partner for the placements. Therefore, the focus of our undergraduate program is the acquisition of basic practical laboratory skills, rather than things like experimental design.

The reason remote delivery and assessment of the learning is particular to our situation, but our situation is not unique. New Zealand's population and laboratories are sufficiently geographically dispersed, that it would be impractical to have in-person laboratory skills training available to most New Zealanders. Therefore, we developed approaches and systems to allow high-quality teaching and assessment of key practical skills, remotely. Another motivation for allowing learning remotely was to allow each participant all of the practice time they needed. Learning the basics of performing selected practical tasks correctly (i.e., doing all the right steps), takes most students a few hours. However, to develop the level of proficiency (e.g., reliability, accuracy, pace) we require typically takes students many more hours of practice. Sufficient assessment to assure that each student has achieved that level of proficiency is also time-consuming. In an in-person setting, allocating enough time would require a laboratory to be available for practice during more hours than would usually be available.

Given these requirements, particularly that the laboratory work in our undergraduate program is for the purpose of practical skills building, none of the existing approaches for remote laboratories we assessed were suitable.

Recently, a team at University of Illinois described [8] a remotely delivered exercise that involved micropipetting, one of the key skills we remotely teach and assess. Their approach is appropriately reflective of the learning objectives they list, which do not include the sort of pace, reliability and accuracy we need our participants to obtain. Although the hands-on use of a micropipette was similar to some of the teaching and assessment we describe here, their approach gives no way to judge pace, and little way to judge other aspects of proficiency, especially if a student is willing to report data that are better than those they actually get. However, again, proficiency development was not key for them and the approach they described was an innovative way to deliver an experience that is similar to what students would typically experience in an in-person educational laboratory.

There was also a recent report of remote teaching and assessing selected surgical skills [9]. Although not identical

Manuscript received September 24, 2021; revised December 24, 2021. This work was supported in part by the Tertiary Education Commission (New Zealand).

The authors are with New Zealand Laboratory Education (Real World Education Ltd), Palmerston North, New Zealand (e-mail: pdemchick@real.ac.nz).

doi: 10.18178/ijiet.2022.12.5.1633

to the approach reported here, the two-way use of video (albeit, asynchronous in their case) is similar as is their observations of some of the advantages the approach gave, which is why they report intensions to use the approach after the COVID-19-related motivations to use the approach fade.

The systems and approaches we describe here can be used for laboratory skills teaching, but could certainly be adapted to teaching other practical skills. The ready availability of two way video and audio communications was a good start, but the augmentation of other aspects of the system greatly improved the teaching and assessment.

II. The Specific Skills Practiced and Assessed

The laboratory skills practiced and assessed had to be things that could be done safely at home. They needed to be things widely used in laboratories. They needed to be things that significant time is required to gain proficiency (e.g., fast, reliable, accurate) with; things that can be mastered quickly can be learned at the commercial laboratory. The set of key skills we selected was use of a graduated pipette, use of a micropipette, dispensing materials by mass to various tolerances, and basic aseptic manipulations. In each case, we needed to have a way to know if the work was being done correctly. For all except the aseptic work, the way we judge the accuracy is the use of a balance. That directly allows the determination of the mass for dispensing by mass. It also allows determination of the accuracy of the volumes delivered by using the graduated pipette or micropipette. This is done by dispensing water, and weighing the water dispensed. Based on the density of the water and the mass, the volume can be determined. This is an approach commonly used in laboratories to check that equipment is correctly (accurately and precisely) dispensing liquid, since laboratories almost always have more accurate and precise ways to determine mass than volume.

Students are sent a case of supplies and equipment to practice and to be assessed on these key laboratory skills. Equipment includes a top-loading balance with a 200 gram capacity that reads to 0.001 gram, a laptop, a micropipette, graduated pipettes and a pipette aid.

One assessment requires students to deliver a specific volume of water repeatedly using the micropipette. Another assessment requires students to deliver various specified volumes of water using a micropipette. A third assessment requires students to deliver a specific volume of water repeatedly using a graduated pipette. A fourth assessment requires students to deliver various specified volumes of water using a graduated pipette. For each of these, the tolerance on the mass dispensed and the time allowed are based on the accuracy and pace required in a commercial laboratory. There is also a series of assessments in which students need to dispense solids with various textures to a variety of specific masses to various specified tolerances. This requires students to make appropriate judgments about how finicky to be with each weighing because some have a tight tolerance and some do not. If students do not make good judgments, they cannot both stay within the tolerance specified, and finish the assessments in the required time. Again, the time selected requires students to be doing good work at a commercially appropriate pace. The practical assessments listed above make use of all of the aspects of the system. There are others (e.g. aseptic transfers) which require only parts of the system.

III. System Overview

We designed, implemented, and deployed a full-featured software suite to assist with assessing laboratory skills long-distance. This suite of software consists of a video meeting system; an assessment workflow engine; an integrated mock Laboratory Information Management System (LIMS); and a telemetry system for use with the balances. All components, with the exception of the video meeting system, are tightly integrated from a user's perspective. The video meeting system may be more fully integrated in the future.

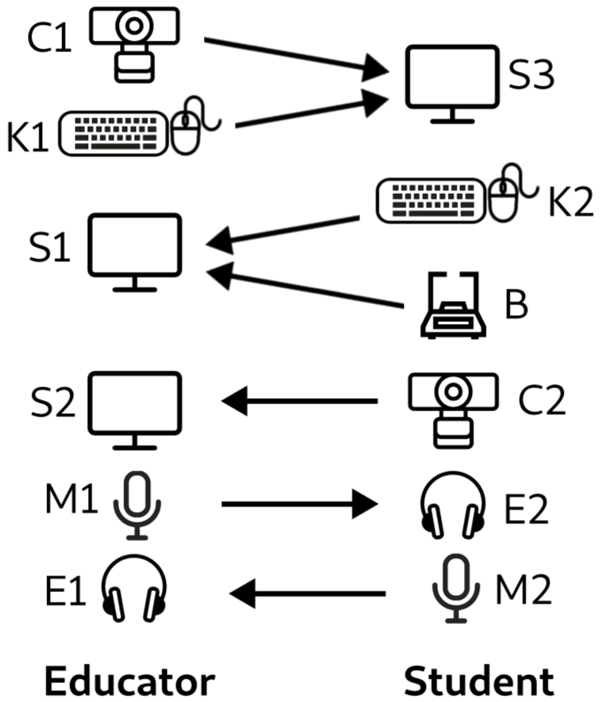

Fig. 1. Simplified diagram of the information flow between input devices and output devises. Intermediate components and systems are omitted.

All of these components were selected to facilitate real-time situational awareness for both the student and the educator. Generally, actions performed by the student or educator are visible to the other party in well under a second. This allows for a responsive learning environment. As represented in Fig. 1, the educator can hear the student (M2 to E1) and the student can hear the educator (M1 to E2). The student typically has one screen (S3) on which they can see the educator (C1) and the display of the mock-LIMS (detailed below). The educator has two screens. On one (S1), the educator can see the display of the mock-LIMS and the information from telemetry (in this case, the balance, B). On the other (S2), the educator can see the student (C2). Both the student (K2) and the educator (K1) can input information into the system. However, there is certain information that only the student can enter (e.g. mass data) and certain information only the educator can enter (e.g. controlling the flow of the assessment, as described below).

The system was designed with reliability in mind, and experience has demonstrated that this goal was met. Besides the need to engineer reliable software, the greatest challenge was the heterogeneous technological environment that often characterizes distance learning. In order to improve the reliability of the assessments, each of the students is provided with a laptop with a fresh install of the software required to use the assessment system. We have a system which allows for this fresh installation to be performed automatically, which makes this a practical approach.

Almost all elements of the system can be accessed through any modern web browser, including Google Chrome and Mozilla Firefox. The system utilizes technologies such as WebSocket in order to avoid reachability issues encountered on some networks [10].

All third-party software used in the system was freely-licensed and open-source. That has likely allowed for greater flexibility, better security, higher reliability, and lower costs than relying on closed-source software would.

IV. Video Meeting System

A key element of the assessment system is the video meeting system. During an assessment, the video meeting system allows the student and educator to chat freely, and the educator is able to see what the student is doing through the video feed. BigBlueButton [11] was selected as the video meeting system. Using a turn-key solution for this proved to be the correct choice, as it saved considerable development effort and has proved reliable.

While many distance learning providers use proprietary video chat services like Zoom or Skype, we opted for a self-hosted open-source solution for a variety of reasons. Running our own video meeting server has allowed us to allocate enough technological resources to provide a service that consistently performs well. The server is located geographically near where our educators work, which has allowed for very low latencies; this is important, because the communication delays caused by high latencies would be disruptive.

We utilize the recording feature of BigBlueButton to keep the video of the session for our quality assurance processes.

V. Assessment Workflow Engine

An important goal in our approach to assessment is to ensure that the student learns how to perform practical skills consistently well. To that end, we have designed the assessments to require that the student meet a certain standard of accuracy and pace several times in a row. Manual record keeping would be time consuming and error-prone. Therefore, automatic record keeping and an orderly workflow were key design requirements. Given the requirement of a number of consecutive satisfactory results, students might have difficulty keeping track of their progress. Therefore, it was desired that the system assist educator and student in being informed about the progress.

The system gives great flexibility in defining assessment types. Assessment types define a number of aspects of the assessment, and can be thought of as a template for the assessments.

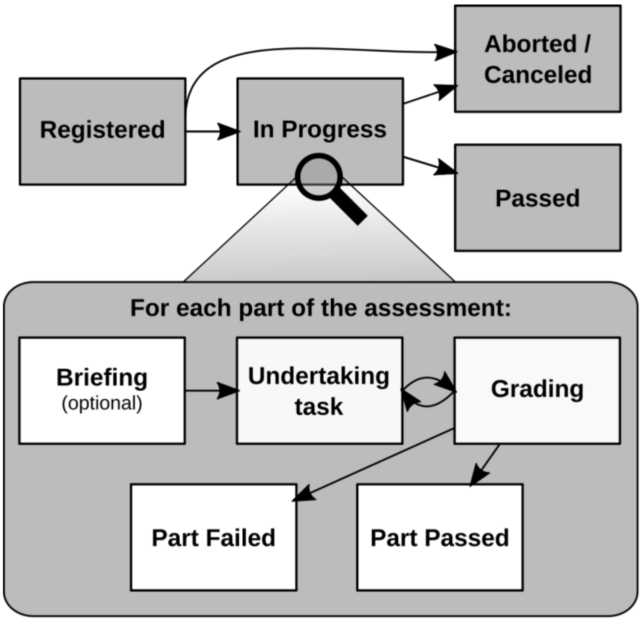

Fig. 2. Simplified pattern of assessment flow.

Referring to Fig. 2, educators can register students for particular assessments. The characteristics of an assessment are determined at registration time by specifying an assessment type. A registration remains active in the system until the registration is aborted/canceled by explicit action of an educator or the full assessment (including all required repetitions) is passed. All active registrations are available for all educators, so a student can do different repetitions of assessment parts with any educator. After each assessment part (repetition), the educator can indicate that the part was passed or failed. If failed, the number of consecutive passes is re-set to zero. If the required number of consecutive passes is achieved, the workflow engine progresses to full completion of that assessment type.

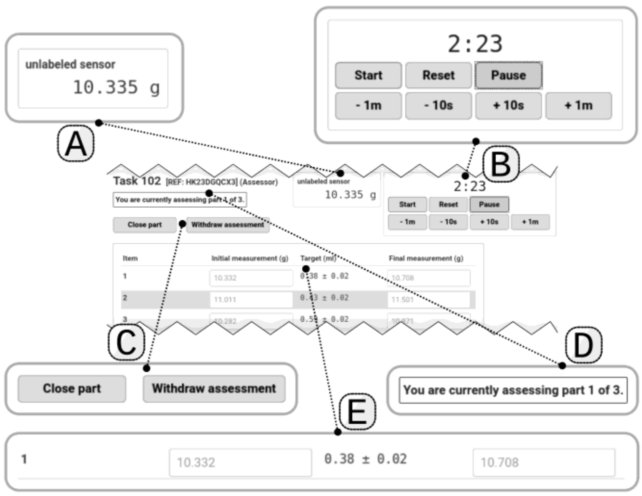

Fig. 3. Educator view during assessment.

Fig. 3 includes a portion of the educator's screen that is not the one with video of the student, and details of selected portions of that central view. D shows details of the part that indicates to the educator the progress on the assessment. C shows the flow controls currently available to the educator.

The "withdraw assessment" option is for the rare situation that an assessment it ended without a pass or fail. For example, equipment malfunction which is not caused by a student error would be a situation in which "withdraw assessment" would be used. After selection of "close part" the educator is prompted to indicate whether the attempt was passed or failed. The assessments are started by educators using controls in that section of the display.

Fig. 4 shows a portion of the student display (at top). As shown, the student is shown the task they are being assessed on, and a reference code, which uniquely identifies the assessment registration. The display also indicates to the student their progress. Various other messages are displayed to the student at key points throughout the workflow of the assessment. Examples are in Fig. 4.

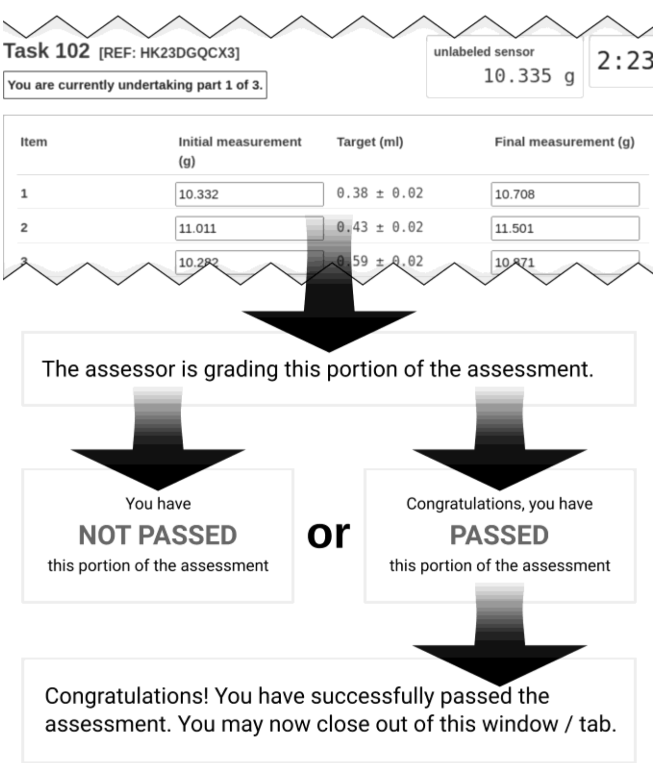

Fig. 4. Student view during assessment.

Fig. 5. Assessment logbook.

The system also has a timer controllable by the educator (Fig. 3, B) and viewable by the student (Fig. 4, upper right). These are used to keep track of the pace of the student as they perform a task.

The workflow engine automatically keeps a detailed record of workflow events, avoiding the mistakes and wasted time associated with manual recordkeeping. Fig. 5 (personally-identifiable information blurred) is an example of a portion of the log that the workflow engine keeps. Actions visible in the log include actions taken by the educator, as well as the data entered by the student. The educator can also enter notes where they wish to record further details. This provides a high level of transparency. Such a record would be impractical to create manually.

VI. Mock LIMS

Many laboratories utilize a type of software called a Laboratory Information Management System (LIMS). A principal feature of such a system is the ability for technicians to enter the results of laboratory analyses for storage. Taking this cue from industry, a mock LIMS was developed for integration into the system for students to enter results they produce during their assessments. As the student enters the data (Fig. 4), it is viewable by the educator in real-time, in a way similar to Google Docs or Etherpad. (Fig. 3, E)

As the student enters data into the mock LIMS, the system automatically checks each measurement for whether it is within specifications, and displays this to the educator.

VII. Telemetry

In order to further increase the ability of the educator to properly assess what the student is performing, a telemetry system was created, which allows for measurements from the balance used by the student to be displayed to the educator in real-time (Fig. 3, A). This allows for the educator to check that the student has entered the correct results into the LIMS. This telemetry system has also proven useful in troubleshooting issues with the balance that have occasionally occurred.

Fig. 6. Sensor listing.

The student connects their balance to their laptop using a cable. Software installed on the laptop then automatically connects to a server, and begins transmitting the data. No additional steps are required for the data feed to be setup.

Each remote telemetry station (which is currently implemented on the laptops) is automatically assigned a unique identifier, in the form of an ed25519 keypair [12]. All transmitted data is cryptographically signed using the assigned private key. This identification method allows each telemetry station to be reliably matched to a given student from a simple sensor management page, (Fig. 6, personally-identifiable information blurred) where the current status of each balance can also be viewed. The matching is only performed once for each student; after that, the balance display automatically appears in the LIMS interface for all assessments for that student. Normally, this matching is performed on the laptop before it is sent to the student, providing a simple workflow which does not require matching at assessment time.

Currently, the only sensor type we use is a balance, but the system was designed to allow the use of other remote sensors.

VIII. Discussion

Students have indicated that our program seems more face-to-face than many "face-to-face" programs. We have taken that as a complement and challenge. The goal is to make the student experience be more human, personalized and interactive than if they were sitting in the room in a class. This approach to the teaching and assessing of practical skills meets that standard. It does consume significant educator time, but that time is well spent doing personalized teaching and doing careful assessment. The system allows the vast majority of educator time to be focused on teaching and assessing with very little time consumed with administrative tasks related to that teaching and assessing.

When students have problems with equipment, the system also allows for effective and efficient remote troubleshooting. Although not a planned part of the learning, being in a session with an experienced laboratory expert troubleshooting almost certainly has incidental educational benefits.

Care was taken in selecting items that allow good skills development and a generally good user experience while not getting overly expensive. The entire case and contents cost approximately US$300. This includes the laptops which were acquired as used equipment in excellent condition. The cost could have been further reduced by having students install the appropriate software on their own computers instead of sending them a laptop. However, for our purposes, we decided that supplying the laptops was preferable for the increased convenience, increased reliability and to avoid any student misattributing any future problems with their computer to the software we provided. The vast majority of the items that are sent are returned in good condition and, after checking, are again sent to students.

Feedback from laboratories that host placements after the basic skills are learned indicate a very high level of satisfaction with the practical skills taught and assessed by the remote manner described. We have frequently received feedback that specifically indicates that our graduate prepared and assessed remotely are better prepared in these skills than people the laboratories hire or have on placement who are graduates of longer, face-to-face programmes.

The information recorded by the system, including audio and video, assessment logs, etc., give a far richer record of the assessment than is often available from a practical assessment. Therefore, review to assure consistency in the administration of assessments is more effective. That has allowed the detection of minor inconsistencies that have since been rectified. That rich record also is a ready-made training resource for any educator who is preparing to administer a practical assessment that that educator has not previously given. The clear notifications to the student given by the system greatly reduce the chance of misunderstanding or differing opinions about assessments. However, the rich record is available for review should differing opinions or recollections occur.

The authenticity of any assessment can be a concern, but this can be especially problematic for remote assessments. The approach described here leaves little doubt that a practical assessment passed was passed authentically.

The general features of the system could be readily adapted to other sorts of practical assessment including in other fields. The sensor for telemetry is a balance in the use-case described here, but could be another type of sensor for laboratory purposes or for another field. Similarly, the software could be easily modified to allow different information to be recorded by the student, data that would be appropriate to other assessments.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The whole project was very much a group collaboration with WD doing almost all of the computer systems engineering, and the others, especially SJ and MB being mostly involved in designing and refining the assessments. The initial suggestion to use two way video for this was by SJ. The initial suggestion to include telemetry was by PD. The majority of the writing was by WD and PD. All authors had approved the final version.

Acknowledgment

The authors thank Rebecca Stadtwald-Demchick for her review of the manuscript and helpful suggestions.

References

[1] N. Pather, P. Blyth, J. A. Chapman, M. R. Dayal, N. A. M. S. Flack, Q. A. Fogg, R. A. Green, A. K. Hulme, I. P. Johnson, A. J. Meyer, J. W. Morley, P. J. Shortland, G. Štrkalj, M. Štrkalj, K. Valter, A. L. Webb, S. J. Woodley, and M. D. Lazarus. "Forced disruption of anatomy education in Australia and New Zealand: An acute response to the covid-19 pandemic," *Anatomical Sciences Education*, vol. 13 no. 3, pp. 284-300, May 2020.

[2] S. M. Sherrer, "A virtual laboratory module exploring photosynthesis during COVID-19," *Biochemistry and Molecular Biology Education*, vol. 48 no. 6, pp. 659-661, November 2020.

[3] M. Costabile, "Using online simulations to teach biochemistry laboratory content during COVID-19," *Biochemistry and Molecular Biology Education*, vol. 48 no. 5, pp. 509–510, September 2020.

[4] H. Yoo, D. Kim, Y. M. Lee, and I. J. Rhyu. "Adaptations in anatomy education during COVID-19," *Journal of Korean Medical Science*, vol. 36, no. 1, January 2021.

[5] S. Sandi-Urena, "Experimentation skills away from the chemistry laboratory: Emergency remote teaching of multimodal laboratories," *Journal of Chemical Education*, vol. 97, no. 9, pp. 3011-3017, August 2020.

[6] R. Soong, A. Jenne, D. H. Lysak, R. Ghosh Biswas, A. Adamo, K. S. Kim, and A. Simpson, "Titrate over the Internet: An open-source remote-control titration unit for all students," *Journal of Chemical Education*, vol. 98, no. 3, pp. 1037–1042, January 2021.

[7] D. Kennepohl, J. Baran, and R. Currie. "Remote instrumentation for the teaching laboratory," *Journal of Chemical Education*, vol. 81, no. 12, pp. 1814-1816, December 2004.

[8] M. N. Jawad, A. Bhattacharjee, R. Lehmann, A. Busza, P. Perez-Pinera, and K. Jensen, "Remote laboratory exercise to develop micropipetting skills," *Journal of Microbiology and Biology Education*, vol. 22, no. 1, pp. 1-4 March 2021.

[9] C. Bachmann 1, A. L. P. Hernandez, S. Müller, S. Khalatbarizamanpoor, T. Tschiesche, F. Reißmann, L. Kiesow, D. Ebbert, W. Smirnow, A. Wilken, and U. Dahmen, "Digital teaching and learning of surgical skills (not only) during the pandemic: a report on a blended learning project," *GMS Journal of Medical Education*, vol. 37, no. 7, pp. 1-6, December 2020.

[10] IETF RFC6455, "The WebSocket protocol," Section 1.1.

[11] H. Suga, "A comparison of bandwidth consumption between proprietary web conference services and BigBlueButton, an open source webinar system," Bioresource Science Reports (a publication of Prefectural University of Hiroshima), vol. 1, no. 1, March 2021.

[12] D. J. Bernstein, N. Duif, T. Lange, P. Schwabe, and B. Yang, "High-speed high-security signatures," *Journal of Cryptographic Engineering*, vol. 2, no. 2, September 2012.

Sashi Jeffries earned a diploma in science and technology from the Waikato Institute of Technology (WinTec), Hamilton, New Zealand.

She has held a variety of senior roles in commercial testing laboratories. These roles included training of other laboratory personnel. Her leadership roles have been in chemistry and microbiology laboratories, including testing of water, wastewater, soils and foods. Her career has included use of a wide range of techniques and instruments. She has been a Report Signatory for timber testing, an Administrator for a laboratory information management system and Authorize Representative to International Accreditation New Zealand (laboratory accreditation body). Her current role is Science Laboratory Educator with New Zealand Laboratory Education (Real World Education, Ltd.)

Wiremu S. Demchick earned Te Tohu Pōkaitahi a te Rumaki Reo mō te Kōrero Māori (certificate in Māori language fluency) from Te Wānanga Takiura o Ngā Kura Kaupapa Māori, Auckland, New Zealand.

He has been a software engineer, system administrator, and technical consultant for many organizations spanning a diverse range of sectors, including medical, education, media, and hospitality, as well as a wide-range of non-profit organizations. He has specialized in implementing, maintaining, and supporting mission-critical software applications in UNIX environments, building on top of freely-licensed third-party software. He has in-depth experience writing software in a wide variety of programming languages, including Python, C, Haskell, PHP, and Perl. His interests include proactive computer security and software correctness.

Magdalena Bereza earned a bachelor of science degree in biology from Warsaw University, Poland, where her thesis was entitled 'Taxonomy verification of selected groups of *Phacus* species based on partial analysis of 18S rRNA genes'. She then earned a master of science in biology from Warsaw University where her thesis was entitled 'Estimation of phylogeny of selected *Phacus orbicularis* subspecies based on analysis of 16S and 18S rRNA genes' She then earned a PhD in biochemistry from Friedrich Schiller University, Germany where her dissertation was entitled 'Assessment of β-amyloid structural diversity with genetically engineered antibody fragments.'

In addition to research positions she has held senior positions in commercial testing laboratories, which included heading a microbiology laboratory. She was also responsible for supervision of PhD students. Most of her publications explained biochemical, immunological and molecular aspects of Alzheimer's disease. She has also published about molecular phylogeny of algae of the genus *Phacus* and of *Mycobacterium smegmatis*. Her current role is Science Laboratory Educator with New Zealand Laboratory Education (Real World Education, Ltd).

Paul H. Demchick earned a bachelor of science degree in chemistry from Drexel University, Philadelphia'. He then earned a master of science in biology from Indiana University, Bloomington where his thesis was entitled 'Possible role of prodigiosin in *Serratia marcescens* in low phosphate' He then earned a PhD in microbiology (biochemistry minor) from Indiana University where his dissertation was entitled 'Molecular sieving by the cell walls of *Escherichia coli* and *Bacillus subtilis*.

He held a research role with the United States Department of Agriculture. His academic appointments have included Lecturer, Senior Lecture, Professor and Academic Leader for Science at a variety of tertiary educational institutions. He has done a variety of scientific consulting. He was admitted to the bar to practice in matters before the United States Patent and Trademark Office. He has dozens of journal publications, meeting presentations and patents. Most of them have been at the interface between microbiology and chemistry, but some have been education related. He has been a visiting scientist in industry. His current role is Director of New Zealand Laboratory Education (Real World Education, Ltd).