# 24

# Online Laboratories in Engineering Education Research and Practice

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## 1 Introduction

Over the last decades, technology development and the Internet have shaped how we play and work. Among other innovations, these advances have made their way into education and have led to the development of online laboratories. The advent of those new forms of technology-enhanced instruction in the area of laboratory-based teaching and learning was briefly discussed in the first edition of this very handbook. Johri and Olds's (2014) one chapter discussed recent developments on the use of information technology in engineering education at that time (Madhavan & Lindsay, 2014). However, only one part of that chapter formed the discussion of remotely accessible experimentation technology, which was seen primarily to overcome the barrier of co-location during the learning process (Madhavan & Lindsay, 2014, p. 643).

The chapter in this new volume specifically builds on this prior discussion and examines online laboratories in more detail, considering broader educational research. On the one hand, online laboratories can be seen as just one other instructional tool out of the many options information technology offers for educational settings. In this chapter, on the other hand, we want to display and discuss the affordances and challenges online laboratories bring to the table for modern, innovative engineering education (Shor et al., 2011). We, therefore, dedicate this chapter to an in-depth reflection on the increased relevance of online laboratories for the engineering education landscape. This reflection also includes a discussion of the historical context of online laboratories, a reflection of the wider pedagogical considerations, and thoughts concerning the future trajectory of the field.

Writing this chapter following the COVID-19 disruption clearly offers the opportunity to go about online laboratories in instructional settings in two ways. Firstly, one could describe the specific impact COVID-19 had on the online learning community and, with that, on the perceived importance of instructional online laboratory solutions. Secondly, one could take a broader perspective and discuss online laboratories from a more holistic standpoint. We decided to mostly follow the second approach and add considerations in context with the pandemic disruption where applicable. By doing so, we hope to make this chapter helpful and interesting for a more diverse audience, including online laboratory experts and complete newcomers to this field. We also believe that many of the innovations and developments around online laboratories in the context of COVID-19 have not yet been sufficiently assessed outside of that unique situation due to the lack of time. Hence, the insights might not yet be of great value for the times after the pandemic. Nevertheless, we do

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foresee further research results coming out soon that show very practical and also more theoretical research outcomes based on scholarly activities during the last two years. Finally, we also refrain from going too much into detail in terms of the technical development of online laboratories. This would require a completely different approach and mostly address laboratory developers instead of the general engineering education community.

So far, we have used the term *online laboratories* very naturally and without going into greater detail. However, as is true for many other terminologies, it is essential to define what the authors intend when using specific terms. Hence, we want to provide a working definition of that very term before we move on with more detailed considerations.

## *1.1 Online Laboratories Defined*

> [Instructional] Laboratories allow the application and testing of theoretical knowledge in practical learning situations. Active working with experiments and problem solving does help learners to acquire applicable knowledge that can be used in practical situations. That is why courses in the sciences and engineering incorporate laboratory experimentation as an essential part of educating students.
>
> (Auer & Pester, 2007, p. 285)

Building on this broad understanding of the instructional laboratory itself, online laboratories are instructional laboratories in which students and equipment are not co-located in the same physical location or space. The opposite to that are traditional, hands-on laboratories, in which students use the equipment by manually operating it while being physically situated in front of or in close proximity to it. This broad understanding of online laboratories includes remote, virtually represented, fully simulated, and otherwise-emulated laboratories (Nickerson et al., 2007; Kennepohl & Moore, 2016; Auer et al., 2018; May, 2020). As for the instructional laboratory itself, the terminologies *online*, *virtual*, or *remote laboratory* can take on different meanings. These differences can be seen even when comparing international research communities or groups. In that context, several terms and expressions appeared over time, such as *cyberlab*, *web-based lab*, *weblab*, *web-accessible lab*, *online lab*, *virtual lab*, *iLab*, *remote-controlled laboratory* (RCL), and *remote access laboratory* (RAL), among others (Alves et al., 2007). Typically, differences in the use of the term *online laboratories* can be attributed to the specific technical setup in use, including gear and control interface.

The possibility to perform experiments remotely, in laboratories shared by different higher education institutions, was first proposed by Aburdene et al. (1991), the same year the first-ever web server was installed. Quoting Aburdene et al. (1991, p. 589), "sharing laboratories among universities is one possible solution . . . laboratory experiments can be operated remotely." The expression "remote laboratory" as an important subcategory of online laboratories was, however, later coined by Aktan et al. (1996) in an IEEE Transactions on Education article. On the same note, Froyd et al. (2012) wrote later:

> Remote laboratories, a method that can at least partially replace live experimentation, was first developed by Aktan et al. In a remote laboratory, students use a computer to control an actual experiment that is in a different physical space. . . . Remote laboratories allow institutions to share expensive equipment, and equipment downtime is reduced.
>
> *(Froyd et al., 2012, p. 1354)*

Research and development efforts for remote laboratories specifically have been the main driver for the international online laboratory community for a long time. However, the use of fully virtual laboratories and simulations also gained attention and led to a diversification of the field (Balamuralithara & Woods, 2009; de Jong et al., 2013; Potkonjak et al., 2016; Auer et al., 2018). Nowadays, there are many different types and subtypes of online laboratories: remote laboratories with live usage of real equipment (Reid et al., 2022), remote laboratories using pre-recorded experiment videos (KC et al., 2021), virtual desktop-based laboratories using simulated data (Makransky & Petersen, 2019), and even fully immersive virtual laboratories based on virtual reality technology (Franzluebbers et al., 2020; Kumar et al., 2021), to name just a few.

However, in many publications, the term "online laboratories" still refers to setups where physically existing equipment is controlled remotely via a web interface. Sometimes, such remote laboratories are even administered live and like traditional, hands-on laboratories with an instructor or laboratory assistant in the lab, students located off campus, and the equipment controlled remotely by students. This has been the case especially when remote access to laboratory equipment for students needed to be set up quickly without the necessary time to develop a fully functional remote laboratory (e.g., during the COVID-19 pandemic and its imposed social contact restrictions). Another permutation of this setup is the hybrid laboratory, where some students are in the laboratory and others are joining in via the Internet. However, HyFlex learning environments (Beatty, 2014) and pedagogical approaches mixing face-to-face experiences and online experimentation lie outside the scope of this chapter.

Nevertheless, discussing only remotely controlled laboratories in this chapter would not be sufficient to cover the current landscape of online laboratory technology and educational research. Fully virtual or partially simulated laboratories have gained attention as well. Even though these laboratories are technically very different from "classical" remote laboratories, we consider them conceptually close enough to be included without losing focus. Thus, for the sake of this chapter, *online laboratories* refer to both fully virtual or simulated laboratory equipment or experiences and to remotely accessible experimentation equipment for the purpose of laboratory-based instruction. This definition excludes technical solutions, like take-home lab kits that can be connected to a web server and augmented reality laboratory solutions. This exclusion is not intended to devalue those other solutions by any means. However, lab kits and augmented reality solutions typically co-locate the experimenter and the experiment. The inclusion of those laboratories in the discussion here would simply blur the focus of this chapter.

Similarly, to the terminology, various definitions and classifications for online laboratories have been proposed over the past two decades, for example, by Dormido-Bencomo (2004), Maiti et al. (2017). Specifically, Dormido-Bencomo (2004) proposed a simplified classification of laboratory environments based on two criteria: type of access to the laboratory resource (local, remote) and nature of the accessed resource (real, simulated). Table 24.1 is drawn based on the combination of these criteria and has been adopted by many authors. Although this represents a simplified and widely accepted classification, there are also examples of online laboratories that lie on the border between two environments, for example, laboratories that combine remote access to real equipment with the existence of simulated parts (Bruns & Erbe, 2004) and remote laboratories that return data recorded from real experiments, allowing simultaneous access by multiple users (Columbia-CTL, 2021; GOLC, 2021).

Another more recently published typology offered by May (2020) and Terkowsky et al. (2019) uses a framework categorizing online laboratory solutions along the three dimensions of "pedagogical approach," "degree of virtualization," and "laboratory distribution" (see Figure 24.1, based on Zutin et al. (2010) and Zutin (2018)). In this framework, the authors also include augmented reality laboratories as an intermediate stage of virtualization between real hands-on laboratories and fully remote laboratories, still measured along the degree of experiment virtualization. In other words, one can also distinguish instructional online laboratories along the continuum of physical reality (hands-on laboratories), augmented reality (augmented reality laboratories), mediated reality

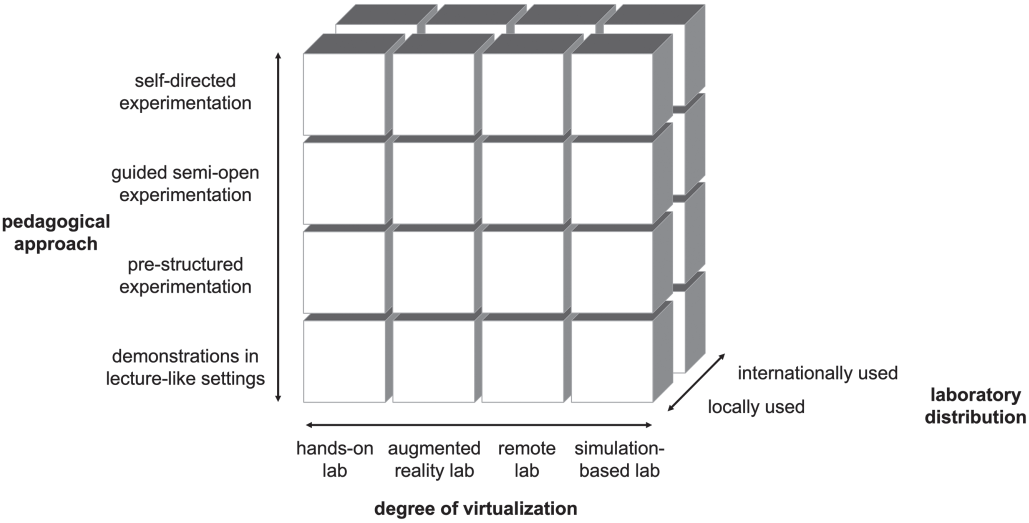

*Figure 24.1* Three-dimensional framework for online laboratories.
*Source:* May (2020).

*Table 24.1* Typology of Different (Online) Laboratory Environments

| | | *Nature of the Resource* | |
|---|---|---|---|
| | | *Real* | *Simulated* |
| **Access Type** | ***Local*** | Traditional hands-on laboratory | Virtual laboratory with local user access |
| | | Remote laboratory | Virtual laboratory with distributed user access |

Source: Adapted from Dormido-Bencomo (2004).

(remote laboratories), and simulated reality (simulation-based laboratories). The third dimension in this framework stems from the specific context of the author's work at that time, which examined laboratory usage distributed locally and internationally.

Most of the online laboratory classifications like the ones shown earlier include various dimensions, such as the location of the experiment versus the location of the user, multi-user versus single-user, hands-on versus mediated, face-to-face versus online, and simulated versus real, to just name a few. In everyday instructional practice, there are even combined forms of the aforementioned online laboratory types possible, which makes categorizing the different forms of online laboratories and their classroom application even more blurry at times. This is also the reason that we won't use any of the category systems later in this chapter to systemize existing online labs. We still believe that the brief discussion earlier will help the reader frame a conceptual understanding of different online laboratory typologies.

In summary, online laboratories as a concept can be described as a conceptual, instructional space in which students undertake a laboratory-like learning activity without requiring direct but somehow mediated access to real or virtual equipment (Kist et al., 2012). In the following, this chapter focuses on online laboratories as a general concept in the context of instructional laboratories in which students are either (1) not co-located with the experimental equipment during the laboratory experience but use online technology to control experimentation equipment remotely or (2) make use of fully virtual, simulated instruments for their laboratory experiences.

## 1.2 Chapter Overview

As mentioned earlier, early motivations for deploying online laboratories in general and remote laboratories particularly included providing more frequent access to experimental equipment and laboratory experiences, utilizing expensive equipment more efficiently, sharing equipment among institutions, broadening access to equipment, and allowing students who are not on campus access to laboratory-based instruction (Gustavsson, 2001; Madhavan & Lindsay, 2014). While remotely controlled experiments have been an active field of research for well over 20 years, more recent events, like the restrictions in context with the COVID-19 pandemic, have brought the affordances of online laboratory teaching to the forefront. Lockdowns and access restrictions have clearly triggered a leap in innovation and, in some cases, creative solutions.

As a starting point for our discussion, Section 2 in this chapter partly zooms out from the perspective on online laboratories only and unpacks why laboratories in general are used in engineering education and discusses the learning rationale for using such practical activities. However, offering learning activities in laboratory spaces is a resource-intensive endeavor for any educational institution. Naturally, laboratory spaces and specific equipment are required, and depending on student numbers, several copies of the same equipment are needed to offer enough seats in a laboratory course. Furthermore, both laboratory spaces and the equipment need to be maintained and supported by laboratory staff, faculty, supervisors, and tutors. It was no wonder that sharing laboratory equipment to provide affordable, flexible access was another early driver of online laboratory developments (Aburdene et al., 1991). Finally, it is also the goal of that section to display both the affordances and also the challenges for online laboratory–based instruction.

With this chapter, it is our intent to take a broader perspective on the overall online laboratory research landscape instead of focusing too much on very recent developments. Our main reason for this approach is the observation that online laboratories gained significant attention during the pandemic years, but much of it has been communicated as emergency remote teaching approaches instead of seeing the general affordances online laboratories can bring to the table (e.g., Fox et al., 2020; Sandi-Urena, 2020; Kruger et al., 2022). However, it is our strong belief that while displaying online laboratories as a fallback option in cases of emergency, the community would do a disservice to the great potential online laboratories have for the instructional landscape. Thus, Section 3 provides a broader perspective and a summary of educational research into online laboratories in the context of different types of instructional online laboratories. That section explores how the research has evolved and summarizes open research questions in the field.

Even today, many publications around online laboratory research focus on technical development and implementation details instead of instructional design, successful learning, and pedagogy, for example, in the form of educational research studies (Lindsay, 2005; Nickerson et al., 2007; Heradio et al., 2016; Post et al., 2019). However, instructional design considerations are at least as crucial as technical considerations for the successful design and delivery of online laboratories and are, therefore, discussed in Section 4 more broadly for laboratory-based instruction and for the specific context of online laboratories.

Given the close relationship between the scientific fields and the technical challenges in delivering online experiments, it is not surprising that many of the first online laboratories were proposed in the field of electrical engineering, information technology, and robotics, for example (Aktan et al., 1996). More recently, a wider range of examples has emerged in disciplines such as chemical engineering and bioengineering (Hossain et al., 2015; Faulconer & Gruss, 2018; Jones et al., 2021). Section 5 provides a timeline of the development of online laboratories and shares international examples of online laboratories and their respective working groups. Not all the laboratory examples are still active. That fact already illustrates a major challenge for the field: keeping online laboratories active and running independently from funded projects or even individual persons at the institutions.

We will come back to that discussion later in this chapter. Nevertheless, it is worth having a look at those examples as they display the diversity in online laboratory solutions and broaden the perspective to international projects. Section 6, finally, discusses future considerations for technology development and educational research around online laboratories based on the previous chapters and draws respective conclusions.

## 2 Rationale Behind Online Laboratories in Engineering Education

There are, of course, many reasons to require laboratory activities in engineering degree programs. Laboratory work can provide the opportunity for students to demonstrate achievement of such learning goals as engaging in experimentation, gathering and analyzing data, solving problems, and identifying the relationships between theoretical and applied knowledge (Feisel & Rosa, 2005). In addition to discipline-specific outcomes, laboratories can facilitate the so-called professional skills that transcend procedural skills and technical proficiency. These cross-disciplinary abilities, including written and verbal communication skills, teamwork, and creativity, for example, are particularly critical in the work environment. Professionals with both in-depth knowledge of their field and relevant professional skills are often considered "T-shaped" (Guest, 1991). This metaphor proposes that disciplinary knowledge forms the vertical stroke of the T, while cross-disciplinary skills form the horizontal bar at the top. This configuration enables engineers to collaborate with non-engineers, explain their thinking to others, and generate creative solutions to ill-defined challenges (Tranquillo, 2017).

The value of laboratory work can additionally be confirmed with a review of accreditation guidelines for engineering education. Both the Accreditation Board for Engineering and Technology (ABET) (ABET, 2020) and the European Accredited Engineer (EUR-ACE) label (ENAEE, 2021) criteria for engineering degree programs include outcomes that can be addressed with laboratory-based instruction. The question is what laboratories and, specifically, online laboratories bring to the table to develop this broad set of skills. Feisel and Rosa (2005, p. 121) noted that "[w]hile there seems to be general agreement that laboratories are necessary, little has been said about what they are expected to accomplish." Feisel and Rosa's list of intended learning objectives in the laboratory is, hence, particularly helpful beyond the accreditation criteria to gain an understanding of both the relevance of the instructional setting "laboratory" for the engineering domain as a whole and the high diversity of learning outcomes that can ideally be achieved through laboratory-based instruction (Feisel & Rosa, 2005, p. 127)

Having a closer look at Feisel and Rosa's list of learning objectives for the laboratory reveals that not all of them can be sufficiently represented in an online laboratory setting. Without discussing each of those outcomes in detail here, it is obvious that outcome 1, "instrumentation," can hardly be addressed in an online laboratory setting as the selection of applied sensors and instruments is mostly predefined in online laboratories. In contrast to that, outcome 2, "models," surely can be achieved in an online setting. A similar distinction can even be made in the context of only one learning objective. Outcome 3, "experiment," for example, includes aspects of the design of an experimental procedure (specify appropriate equipment and procedures) and the analysis of gathered data (interpret the resulting data). Whereas the first part is difficult to implement in online laboratories (only if designing the experimental setup is part of a simulation for example), data analysis and interpretation can be done in online laboratory settings too. Online laboratories may even be better suited in that sense, as they typically offer the opportunity to do more experiments and, with that, gather more data by mitigating practical constraints traditional, hands-on instructional laboratories typically entail.

At this point, it needs to be noted that back in 2005, the authors already pointed out suggestions for further inquiry and future research concerning online laboratories (Feisel & Rosa, 2005, p. 128).

They clearly stated that there is a need for assessing the effectiveness of remote laboratories, comparing the effectiveness of simulations vs. remote access of real equipment, and developing of laboratory simulations that include "noise" in terms of non-ideal parameters and data.

So far, this section has looked at the rationale for laboratory-based learning and the importance of laboratories in engineering education in general. The following sections unpack drivers for offering practical laboratory-based learning activities online. Advantages can be classified as educational drivers relating to students and operational drivers that link to institutional requirements. Following the discussion of advantages is a description of the challenges facing the incorporation of these nontraditional approaches.

## 2.1 Advantages of Online Laboratories for Student Learning

For student learning, online laboratories offer the potential for flexibility, more individual time on task, tightly coupled theoretical and practical learning activities, learning analytics, and access to remote resources. Online laboratories give students more flexibility to complete the exercises when and where they like, and in many cases, this freedom extends to allowing students to self-pace their learning. In an intriguing example of flexibility, Craifaleanu and Craifaleanu (2022) described their instructional co-creation, with students, of virtual laboratory activities, offering an innovative option they felt was optimal for the online environment. In-person laboratory access is often time-limited due to access and supervisory constraints. Online laboratory activities remove this constraint and allow students 24/7 access, although care must be taken to ensure that timely support is available for students when hitting roadblocks.

Online laboratories are generally accessible to students individually or in collaborative groups and are often available 24/7, whereas in-person laboratories are time-tabled and frequently must be completed in groups, due to resource constraints. This means that not all group members get time to interact with and to control the apparatuses. This limitation does not apply in the case of on-demand online laboratories, providing greater instructional design flexibility by enabling both individual and group activities. Rubim et al. (2019), in a review of 99 articles from 59 journals, summarized their findings by noting that "[t]he direction of research points to the use of remote laboratories as a means of inclusion, as an alternative for those whose access to experimentation is restricted" (p. 827), recognizing the value of remote or virtual experimentation beyond the traditional environment. Traditionally, laboratories are scheduled to loosely match the timing of the delivery of the theoretical curriculum. However, students may view theoretical background work and practical activities as only marginally related. Online laboratories allow embedding laboratory learning within the curriculum, tightly coupled with the delivery of theoretical content and practical skill acquisition. Achuthan et al. (2021), in their exploration of the effectiveness of a remote laboratory for mechanical engineering, found that students spent significantly more time interacting with equipment and made more experimental attempts than in the physical laboratory. Interestingly, this occurred even though the average time to complete the activity was notably shorter for students using the remote laboratories. The researchers also recorded more frequent interactions between students and instructors on topics related to theory.

This tighter integration and the fact that access to experiments is mediated by technology allows detailed, individual data collection, which in turn can enable and support learning analytics. Analytics can be done at an aggregated level to analyze how well an experiment operates and how users interact with the experiment. This can also be implemented at an individual level to understand better how individuals engage with the experiments, assess their limitations, and trigger support if they are stuck. Raman et al. (2021) found that within the online laboratory system, pages with theoretical content were viewed for a longer time than other pages, on average, and corresponding simulation pages often were viewed during the same session. This may indicate that students were familiarizing themselves with the conceptual material as a type of foundational preparation before attempting the activities.

Finally, some experiments are inherently risky and cannot be performed safely by students, and others are not possible because of where the activity is located. For example, using lasers may endanger students, and live observations of the southern night sky cannot be done from the Northern Hemisphere. In these cases, a virtual laboratory can allow students to use resources they should not or could not otherwise access, which in turn also offers operational advantages.

### *2.2 Advantages of Online Laboratories for Operational Considerations*

Operational drivers to use online laboratories include cost benefits through reduced staffing and space requirements, higher equipment utilizations, and safety considerations. Laboratory spaces with student access are typically staffed by technical and learning support staff, but this is not required in most remotely controlled environments. While support staff is still required to maintain the equipment, it is not coupled with when students use the experiments. In a discussion of factors influencing a move to instructional online laboratories in higher education, Radhamani et al. (2021) described cost-effectiveness as a situational (i.e., "mooring") effect driving the adoption of remote laboratories. Although online laboratory activities might be considered more passive than in-person experimentation, these researchers listed the potential for increased interaction within the laboratory activities as one of the factors attracting programs to these online systems.

Engineering and specialized equipment can be expensive to purchase, have specific space requirements, and might not be readily available at all institutions. At the same time, laboratory spaces and equipment are often underutilized. Online laboratories provide an opportunity to decrease space requirements and significantly increase equipment utilization. This can lead to significant operational cost savings. In addition to that, the equipment may have specific safe operating procedures that do not allow students to control the experiment in person. For safety reasons or to avoid damage to the rig, some equipment is controlled by an instructor. Operational limits can be implemented in an online setting, and boundaries can be enforced. This allows the design of inherently dangerous experiments to be operated by students within safe limits. Equipment with online access operated as part of an online laboratory management system can be shared between institutions across international borders.

In the case of distance education coursework, students are not located on campus and do not have ready access to laboratory spaces. With the increasing availability of online degree programs, this will apply across a more significant proportion of the sector. While not all learning outcomes can be addressed through online laboratories, they certainly will reduce the time distance students must be on campus. In many industries, the practice has shifted toward remote control and online operation. Using remote laboratories offers an opportunity to upskill students and prepare them for their future workplace.

### *2.3 Challenges for Online Laboratory–Based Instruction*

While online laboratories have significant benefits, they also present challenges. As discussed previously, online laboratories can address similar, but not always identical, learning outcomes to those of face-to-face laboratories. They require a more careful and purposeful pedagogical design than traditional laboratory activities in which a group of students completes most practical activities (Zacharia & De Jong, 2018). Besides addressing the intended learning outcomes regarding collaboration and teamwork, this practice also has the advantage that students can support each other when completing the practice activities. This is not the case for most online laboratories. It is therefore essential to provide on-demand support when individual students struggle and recognize these limitations when the learning activities are designed. As two example limitations, in their SWOT analysis of the VISIR remote lab, Alves et al. (2022) identified the need for specialized support as a weakness and teachers' resistance as a threat. Likewise, professional development for staff is necessary to use the affordances of remote laboratories effectively. Traditional laboratory manuals may have gaps readily filled in by the instructor during face-to-face sessions. However, in an online environment, missing steps can throw students off and lead to significant frustration.

Not all skills can be embedded in an online laboratory experiment, such as hands-on tactile experiences, as noted by Deniz et al. (2022), Rubim et al. (2019), and pedagogical conversations about why these skills are essential may offer alternative activities that students can undertake to acquire similar skills. There is also some expectation management required with faculty and students. Learners may perceive online laboratories as inauthentic and low stakes. If the activities are perceived as games, students may not apply the same effort and rigor that they typically would in a physical space where actual equipment is at stake and academic and peer pressure is applied.

While it's easy to assume that online learning and other technology-facilitated options are widely accepted, many instructors still consider remote or simulated lab options a poor substitute (at best). As recently as 2021, Keller argued that "[s]cience, one of the most difficult courses to teach remotely, has spawned a plethora of fake labs, also known as virtual lab simulations" (Keller, 2021). His op-ed was, in fact, a solid argument for well-designed science simulations, whether he intended it to be or not. Unfortunately, not all readers will see beyond the headline claiming that "[v]irtual lab simulations don't teach science." The challenge to adopt nontraditional labs across a department or beyond an occasional assignment can be exacerbated significantly as a result.

Initial capital investment in designing and building online laboratories is often significant, and there are also substantial costs involved in taking research projects to the operational state. In the past, many online laboratories evolved from personal interest and from research projects funded for a limited time (see examples later in this chapter). However, supporting laboratories in an ongoing fashion cannot be done at zero cost. This can be particularly difficult when academics are not rewarded for continuing support and maintenance but for innovation (Alves et al., 2022). To share laboratory resources beyond research projects requires service agreements and payment plans between organizations. Supporting cutting-edge web technologies over the long term can be difficult when the environment is in constant flux. Changes in technology can make existing implementations obsolete, as seen in the case of Adobe Flash Player–based solutions.

Another challenge can be the integration with existing university systems for authentication and learning management system support, for example. ICT systems and remote laboratories are inherently complex. Supporting these within a corporate network with tight security and regular updates can be challenging when production systems have significant ongoing service and support needs.

## 3 Educational Research on Online Laboratories

Over the last three decades, technical research papers and pilot studies, educational case studies, and educational research work covering online laboratories have been published across a variety of scholarly outlets. The referenced publications and research in the following subsections yet give an overview on specific online lab developments (see, for example, Nickerson et al., 2007; Brinson, 2015; Heradio et al., 2016; Potkonjak et al., 2016; Nikolic et al., 2021). As discussed earlier in this chapter, the early years of research were much dominated by the technical perspective and the attempt to effectively bring instructional hands-on laboratory work online and make it accessible remotely (De Jong & Van Joolingen, 1998). These technical research efforts and discussions are still present in the worldwide online laboratory research community. However, the focus has widened significantly in recent years. Starting around the beginning of this century, many researchers shifted their attention from technical considerations of online experimentation to education and instructional design.

In a bibliometric analysis paper, Heradio et al. (2016) examined and summarized the literature on virtual and remote laboratories from its beginnings to the year 2015, identifying the most influential publications, the most researched topics, and how the interest in those topics had evolved along the way. To do so, bibliographical data was gathered from ISI Web of Science, Scopus, and GRC2014 (Zappatore et al., 2015). Based on their work, the authors identified five main areas of research into which the most influential work could be organized: general overview work on online laboratories (i.e., remote and virtual laboratories); approaches to build, manage, and share online laboratories; descriptions of particular online laboratories; collaborative learning with online laboratories; and assessing the educational effectiveness of online laboratories. The latter two categories focus on the educational research perspective and serve as the nexus for this section.

### *3.1 20 Years of Online Laboratory Research*

The results from much of the research currently available serve to reinforce the long-standing argument, initiated by Clark (1983, 1994), that technologies do not directly influence learning achievement. Rather, they provide instructional designers an array of affordances that enable teaching and learning strategies that do make a difference in educational outcomes. These affordances can be thought of as the possibilities offered by a device or application, such as the ability to use remote equipment for more long-term experimentation than might be possible otherwise. Decades of research has shown that simply substituting a technological option for a traditional approach, without any change in the learning strategy, produces a "no significant difference" result in learning achievement (NRCDETA, 2019). A classic example is that students using paper flashcards for memorization remember just as much as students using an online flash card app in the same way (e.g., Sage et al., 2020). In other words, it's not the technology (online laboratories) that makes a difference; it's what students are doing as learners that can and does. Nevertheless, studies comparing the learning gains attributed to a technological solution versus a non-technological one are still being conducted and will be discussed in the following because they represent the majority of scholarly discussion in this field.

Ma and Nickerson (2006) compiled one of the first literature review papers in the context of online laboratories and discussed research on hands-on, simulated, and remote laboratories. The authors drew several conclusions with regard to the research state-of-the-art at that time. For example, the authors recognized that hands-on laboratory advocates emphasized design skills, while remote laboratory advocates focused on conceptual thinking and understanding. Ma and Nickerson made clear that students learn not only from the interaction with equipment but also from interaction with peers and teachers. Recognizing that technology would be implemented in laboratories even more in the following years, they made clear that it was of focal importance that teamwork and peer interaction needed to remain part of the instructional experience in online laboratory settings, as in hands-on laboratories. In their conclusion, the authors reflected on how students don't need only conceptual understanding but also cognitive immersion to maximize the learning potential in the laboratory environment and that the psychology of presence during an experiment may be as important as the technology itself. The authors furthermore summarized that the boundaries among the three laboratory types (remote, virtual, and hands-on) started to blur in the sense that most laboratories were already mediated by information technology and that combinations of hands-on and remote or virtual experiences in one and the same course setting were tested.

In a large-scale, multi-year, randomized study, Corter et al. (2011) compared learning activities and outcomes for hands-on, remotely operated, and simulation-based educational laboratories in an undergraduate engineering course in which the students typically worked in teams. Study data in this work showed that in the hands-on laboratory format, higher learning outcomes were achieved when the students collected experiment data as a group instead of individually. In contrast, remote laboratories seemed to work better in terms of learning outcome achievement when the students worked individually (although learner collaboration is easily facilitated with online laboratory activities). The pattern of time spent with the laboratory activity also suggested that working with real instead of simulated data (e.g., when comparing a remote laboratory with an entirely simulated lab) may induce higher levels of student motivation. Subsequently, the specific way new technologies in lab-based education were used for instructional purposes – in terms of instructional context, course requirements, and student interaction levels – largely determined their effectiveness, according to the authors.

Two further examples of such comparison studies include Brinson (2015) and Faulconer and Gruss (2018). The former synthesized a large number of empirical studies that focused on directly comparing learning outcome achievement when using traditional (in-person, hand-on) laboratories and nontraditional (remote or virtual) laboratories. This review summarized post-2005 research results in terms of student learning outcome achievement, learning outcome assessment, and respective assessment tools to evaluate student learning outcome achievement. Overall, findings suggested that student learning outcome achievement was at least equal or higher in nontraditional versus traditional laboratories across all learning outcome areas. However, outcomes and assessment tools were not consistent across all studies, and the majority of studies focused on learning outcomes related to content knowledge instead of conceptual understanding by using quizzes and tests as the most common assessment instrument.

Faulconer and Gruss (2018) also compared the effectiveness of traditional hands-on, face-to-face laboratories versus nontraditional, online, remote, or distance laboratories. Their article laid out the existing benefits and drawbacks of the different instructional laboratory modes using existing literature. Their review supported Brinson's work and found that a well-designed, nontraditional laboratory can be just as effective as a traditional, face-to-face laboratory experience when measuring either content knowledge acquisition or student opinions as the metric for equivalence. This is very much in line with works discussed by authors beyond Brinson (2017). Furthermore, these authors noted that there is little to no evidence to suggest that traditional laboratories are better at developing practical skills in comparison to nontraditional laboratories. However, nontraditional laboratories have the advantage in cost, accessibility, and safety, but traditional laboratories have the advantage in future safety concerns and group work. In other words, studies indicate that nontraditional laboratories can provide as many benefits as traditional laboratories.

### 3.2 Knowing What We Do Not Yet Know

Even though the previously discussed reviews seem to conclude very much in favor of online experimentation versus traditional laboratories, there is a constant critique in the research community of a significant lack of empirically comparable and scalable research results. In a recently published review by Nikolic et al. (2021), the authors examined assessment implementations to measure student achievement or learning by comparing published work on remote, simulation, and traditional teaching laboratories, with a particular focus on engineering. It was observed by the authors that empirical evidence around online laboratories so far is built primarily around students' subjective perceptions of their learning (e.g., Corter et al., 2011) or experiences collected via superficial post-intervention surveys, which only in some cases are complemented with more-advanced and validated quantitative assessment instruments. With the laboratory as a multifaceted, multi-domain learning environment also covering the psychomotor and affective domains, such observations suggest that the empirical data being collected and published so far is providing only an incomplete analysis. Based on their review, Nikolic et al. (2021) argued that in many studies, the research assessment was focused on the cognitive domain from the students' potentially subjective perspective, underselling the learning actually being achieved by the learners.

Nikolic et al. (2021), in some sense, also provided a superb example for the take-away message many other review papers offer in their conclusions (see also for example, Potkonjak et al., 2016; Post et al., 2019): the empirical bases of knowledge and in-depth educational research results are still somewhat weak and lacking general and replicable research results. Results are, in some cases, even contradictory, though the general direction of research shows that online laboratories offer great potential for engineering instruction. However, a general and broad assessment about online laboratories simply to compare them with hands-on laboratories is not helpful in the long run because of the diversity of online laboratory solutions, application settings, and possible learning outcomes.

At this point, before we zoom in on certain online laboratory examples in Section 5, we first want to zoom out even a bit more and shed a light on instructional design considerations for traditional, hands-on, and online laboratories. This seems to be important, as the instructional design, following Clark (1983) again, remains to be the cornerstone for a successful design and introduction for online laboratories and, hence, is needed to discuss the whole picture.

## 4 Instructional Design of Online Laboratories

The typical scenario for engineering instructors is to complete their own academic work, possibly up to a terminal degree, engage in nonacademic professional activity (maybe), then enter a teaching role. It is unlikely that these new faculty members have studied teaching and learning, coming into their new position with only their own student experiences to guide them. Therefore, it is unsurprising that laboratory work, online or in-person, has an inconsistent record of success when it comes to engaging students in higher-order thinking or linking theory and practice. Duderstadt (2008, p. 33) argued that highly structured laboratory courses did little to teach "the most important technical skills of engineering: the integration of knowledge, synthesis, design, and innovation." An intriguing result was found for example by Jones (2018) and Hamadani et al. (2022), however. Students who used Labster (a commercial provider for virtual laboratories in science education) during his biochemistry course scored highly on test questions that required higher-order thinking and the application of learned ideas but poorly on their recall of facts and definitions. Clearly, more research is needed to delve into this phenomenon, although it begs the question of the value of simple recall to begin with. While consistent use of validated instructional design models is recommended for all laboratory work, it is especially critical for the online environment, where students may have limited access to an instructor, TA, or course peers who could provide motivation, address their questions, or clarify instructions.

For this section, a framework based loosely on Gagne (1977) and his classic "nine events of instruction" model is proposed. His work expanded on instructional design models that focused on determining desired outcomes, planning instructional "interventions" to enable students to achieve the outcomes, and creating assessment instruments to measure student progress toward or mastery of the outcomes. The specificity of Gagne's model has been broadened and subsumed in the four categories of the MOST framework: *motivation, objectives, strategies, and tools and resources* (Zvacek, 2021). As noted by Clark (1983, 1994), the specific technologies used for the implementation of instruction are less significant than the instructional components. This model, therefore, can be applied to any type of laboratory-based instruction, with its relevance to remote and virtual activities addressed in each section.

### *4.1 Motivation*

The constant refrain, "My students aren't motivated," echoes through the halls of academia the world over. This condition can be alleviated, however, by relying on what psychological research has to say about what motivation consists of and how to facilitate it. One of the key reasons humans persist in a difficult activity is that they recognize its relevance to their long-term goals (e.g., "Learning how to calculate angle of repose will help me learn how to design bridges") (Albrecht & Karabenick, 2018). Hand in hand with relevance is confidence, or self-efficacy (Keller, 2016). The student may see the relevance of the assignment but have little confidence they can successfully complete it. Moderately challenging tasks encourage confidence ("I can do this if I work hard"), but assignments that are too easy ("This is just busywork") or too difficult ("I won't get this no matter how hard I try") erode the student's willingness to invest effort in the task (Ryan & Deci, 2020). Two additional variables, context and transfer, position motivation within a larger perspective, beyond the assignment (context) and beyond the course (transfer) (Blume et al., 2010). A laboratory assignment needs to fit into a meaningful sequence of activities that facilitates linking new learning to already-acquired knowledge and skills while simultaneously setting the stage for more advanced content and tasks to come. Laboratory work that occurs in isolation from other learning reduces motivation and inhibits the development of robust cognitive networks. Similarly, a critical element of motivation for laboratories is the expectation that one can transfer the new skills to challenges that may be encountered in the professional workplace, thus increasing task relevance as well. Each of these components (relevance, confidence, context, and transfer) contributes to motivation and can improve the motivational capacity of laboratory work.

How are these variables related to remote or virtual laboratories? First, as noted by Peck et al. (2018), motivation remains one of the most challenging aspects of online learning for many students. They may feel isolated from their peers, especially if laboratory work that was traditionally completed in groups now is done individually. Many students lack time management skills, which becomes obvious when online coursework requires a high degree of self-regulation, reducing their confidence and, consequently, their motivation. In addition, many students are surprised when they discover that online coursework is not easier than in-person learning. This demotivating realization can inhibit effort and even lead to students dropping the course. Addressing motivational variables up front is an essential part of designing online laboratories.

### *4.2 Objectives*

There is little argument concerning the value of identifying desired outcomes for an instructional lesson or unit. Objectives help students know what is expected and help teachers keep instruction focused on the course's most important concepts. Accreditation criteria or lists of intended learning outcomes for the laboratory (Feisel & Rosa, 2005), as noted earlier, can provide broad guidance for those outcomes, such as experimentation, design, and problem-solving. The difficulty comes when there is a mismatch between our own big-picture goals and the more specific breakdown of tasks that lead to that outcome. If you're looking for higher-order thinking in your students, do your objectives reflect that? More importantly, do your assessment activities require students to exhibit those skills or simply respond to easy-to-measure basic knowledge questions? Additionally, are your objectives explained directly in assignments, or hidden away in the syllabus, which may or may not be read by students?

This is important for any type of instruction, but especially pertinent for online teaching (Simonson et al., 2019). Students who don't have the luxury of catching the instructor in the hall or after class to get clarification on course expectations may find themselves guessing what constitutes a successful demonstration of knowledge and skills for a particular assignment or activity. Along these lines, the PhET Interactive Simulations Project was designed intentionally to "[optimize] understanding by giving students a lightly guided system to explore" (Perkins, K. in Jones, 2018) and was noted by Borish et al. (2022), who found that students overwhelmingly rated clear expectations and guidance from instructors as critical to their success with virtual laboratory work.

### 4.3 Strategies

There are a variety of educational approaches and frameworks that can be used to structure learning activities for laboratory assignments (Zvacek, 2015). For example, a problem-based approach presents a challenge that students might address with data gathering and analysis, design, or collaboration. A cognitive apprenticeship framework emphasizes the development of student autonomy by scaffolding the learning activities from high levels of guidance to independent decision-making (Clark & Mahboobin, 2018; Collins et al., 1987; Dennen & Burner, 2007; Frank et al., 2017; Pinto & Zvacek, 2022). It is important to remember that strategies are what students are doing to learn the content and skills that enable them to achieve the objectives, not what instructors are doing to teach.

The types of strategies most effective with online laboratories are those that involve practice and feedback. Many times, the strategy incorporates an instructional wrapper around the use of the remote or simulated equipment. For example, students may be required to do a pre-laboratory activity where they predict the results of their experimentation. Feedback would occur when comparing their prediction to the actual results that were obtained, followed by an opportunity to revise their work based on the feedback. Feedback may be as simple as activities in which students calculate how randomly assigned variables will influence performance and then confirm (or not) their calculations based on the resulting data. These types of before-and-after wrappings can position the manipulation of equipment or materials as part of a broader context from which students draw conclusions.

Some strategies may rely on students working with others to solve problems or apply specific design principles. Working with peers can develop skills of consensus building, communication, and negotiation. Peers can also provide feedback on one another's work as part of a learning strategy that benefits both participants. Borish et al. (2022), for example, noted that students who worked in a group as part of their virtual laboratory activities reported a greater sense of community within the course. An especially effective strategy for laboratory work is to require students to explain their decision-making process or problem solution to a peer who then shares their work, followed by a discussion of how and why they agreed or disagreed. Such explanations could be written, spoken, or expressed as images or concept maps (Zvacek et al., 2013). The practice of explaining their thinking requires that students know the content well enough to articulate it clearly to someone else, while acting as a potential peer teaching activity. A bonus is the strengthening of communication skills that are necessary for collaborating with others.

Formative assessment and instructor feedback strategies were noted by Van den Beemt et al. (2022) as a crucial element for students in a systems and control engineering course. Students reported that their follow-up progress meetings with instructors after completing remote laboratory activities on their own or in groups were a valuable part of their course success. Another assessment strategy, screen-captured videos, takes advantage of online tools to measure progress toward or mastery of laboratory objectives. Such videos, in which students conduct experiments and gather data as part of the online activity, can be uploaded to the learning management system (or other repository) and viewed by an instructor at a later time. For synchronous assessments, the ubiquity of videoconferencing systems can make presentations, demonstrations, or real-time data analysis by students readily accessible and convenient, whether for individuals or collaborative groups (Simonson et al., 2019). In general, online laboratories provide most of the same assessment opportunities as their face-to-face counterparts while addressing the challenges of space, time, equipment access, and cost.

### 4.4 Tools and Resources

The final component of the MOST framework asks, "What must be available to facilitate motivation, help students achieve the desired learning outcomes, and implement the strategies?" Four types of the necessary elements include content objects, materials and equipment, expertise/time, and tech support.

*Content objects* are the media that provide declarative, conceptual, and procedural knowledge within an organizational structure that facilitates comprehension and application of that knowledge. The most typical forms of content are books, articles, videos, and images, as well as students' notes taken during lectures or demonstrations. As with learning strategies, it is crucial to choose content resources that enable students to complete the laboratory tasks successfully and that are accessible to all learners (see, for example, Costa et al., 2015; Mourão & Netto, 2019). Resources that appear irrelevant or lack connection to the assignments may end up ignored or (maybe worse) encourage students to disregard other course resources as well. It may fall to the instructor to ensure that content objects are presented with guidance on what to do with them or why they're important.

It may be necessary to provide raw materials, if any, that will be used for the laboratory tasks. For virtual or remote laboratories, however, there may not be any materials required, or those materials may be accessed remotely, along with the equipment. For the purposes of this discussion, *equipment* includes the devices that students manipulate during the activity and the means of accessing the devices, such as a robust and reliable Internet connection. Bernhard (2018) argued that instructional strategies and purposes must be considered when choosing laboratory equipment. The affordances offered by specific experimental technologies "may shape students' experience of focal phenomena . . . and this mediating role is often neglected" (p. 819). In addition, it is crucial that instructional designers or instructors recognize that while remote activities can facilitate learning for students who find traveling to campus a challenge, not all students have easy access from their home to remote equipment, and that provisions for such barriers be addressed ahead of time.

A type of resource that is easily taken for granted is expertise, especially with a traditional in-person, hands-on laboratory configuration. When using remote or virtual laboratories, however, instructional designers or instructors might not have the technical skills necessary to establish the required connections, program a simulation, or create a virtual environment (Khan & Abid, 2021). Even if they do, it may take a significant block of time for which they should be compensated. Neither instructors nor instructional designers are expected to write course textbooks without additional remuneration, and the labor-intensive task of creating remote or virtual laboratories is no different. Instructors must also determine how student support for the learning activity will be provided. Although the equipment may be available 24/7, virtual office hours represent another consumer of faculty time to consider as a necessary resource.

Finally, tech support must be considered a student and instructor resource. Although the upfront design of a remote or virtual laboratory may involve specialized expertise, provisions for ongoing technical assistance are also required. Issues related to equipment access, operation, and troubleshooting must be considered, with a support plan in place before implementing the laboratory activities. Determining whose responsibility it is to ensure ongoing availability and operability of equipment, as well as how (or if) they will be compensated, may ultimately need to be addressed by upper administration.

## 5 International Examples of Online Laboratories

This section will provide an overview of the historical genesis and growth of online laboratories over time and share different strands of developments and use cases across the globe. In that light, we will display international examples of multi-institutional projects and respective research groups in the field of online laboratories. It is necessary mentioning at this point that those exemplary use cases are not on the level of individual online laboratory solutions but represent collaborative efforts (in some cases, even internationally) to either collect and curate many online laboratory solutions for an overarching portal, or combine different online laboratories at one institution to a wider set of experiments, or connect multiple institutions through a specific shared online laboratory that can be used across those institutions.

Currently, 26 years after the seminal article by Aktan et al. (1996), there are examples of remote and virtual laboratories in practically all disciplines (or sub-areas) of science, technology, engineering, and mathematics (STEM). In an early work, Zutin et al. (2010), described a repository (called "Lab2Go") of aggregated, searchable information about remote and virtual laboratory resources available in open or restricted format or pending prior request. This work does not list specific laboratories but marks an early endeavor to develop a space, through which multiple online laboratories can be shared. In another work, Endean and Braithwaite (2012) listed about 160 remote and virtual experiments offered by a single institution, in areas ranging from chemical engineering to materials science to electrical circuits. A later, more extensive work (Gröber et al., 2013) documented at least 335 remote laboratories, the majority in the field of engineering ($n$ = 64%), with the remainder in the field of physics ($n$ = 36%). Brinson (2017) classified the nontraditional laboratories presented in Ma and Nickerson (2006) and in Brinson (2015) according to the area of use (distinguishing engineering and natural sciences). According to Brinson (2017), there was an evolution from 2006 reporting a total of 60 nontraditional laboratories (NTLs) with a majority in the engineering area ($n$ = 39, 65%) and a minority in the area of natural sciences ($n$ = 13, 22%), to the 56 NTLs described in Brinson (2015) in the area of natural sciences ($n$ = 46, 82 %) and a minority in the field of engineering or computer science ($n$ = 9, 16%). Although Brinson (2017) noted that most remote and virtual laboratories are not accessible in an open or commercially available format, the trend has been toward open access, due not only to public funding for the development of online educational resources but also to the recent COVID-19 pandemic. This trend was also reported in Esposito et al. (2021), which presented a review of 40 NTLs and Lab Network Initiatives (or "federated laboratories"). In a very recent book on the use of remote laboratories in STEM education, García-Zubía (2021) described 15 remote laboratories in areas ranging from control and automation to mechanics.

Being virtually impossible to present all the previously referred remote and virtual laboratories in detail, at this point we would like to refer to the previously referenced overview and review articles (also see Section 3.1) and point out that those manuscripts provide excellent lists of the examined labs. In the following, we will display another set of exemplary online laboratories. The selection was made based on a recent publication by Raman et al. (2022) and is based on the overall relevance and impact by the online laboratories themselves, the connected research group, or the underlying research project for the international community.

### 5.1 Online Laboratory Research Groups and Solutions Around the Globe

The following subsections present an initial set of four exemplary use cases across the globe that have received public funding, represent multi-institutional working groups (Go-Lab, Next-Lab, LabShare, and Virtual Labs), or have been able to spread internationally beyond their region of origin. Building on that, an additional set of six specific online laboratories (GOLDi, NCSLab, RexLab, UNILabs, VISIR, and WebLab-Deusto) extends the global coverage. Raman's (2022) work provides a historical and bibliometric analysis of the past three decades of online laboratories development. The publication includes an overview with the top 18 contributing institutions, based on the total publications. The overview also displays the top 15 authors, based on total publications, total citations, and total publications with attention.

The two sets of exemplary use cases presented here cover half of the top contributing institutions and all major authors assessed by total publications. The exemplary use cases also provide a global overview in terms of the geographical and timely distribution of online laboratory developments and research activities. Furthermore, the majority (6 out of 10) of the presented examples are also part of the 40 Lab Network Initiatives (LTI) presented in Esposito et al. (2021). For each example of the first set of major use cases, a brief description and the URL are provided. The six examples forming the second set are briefly described and summarized in a graphic (Figure 24.2). This graphic also maps the respective home institutions and relevant authors (Raman et al., 2022).

## *5.1.1 Multi-Institutional Working Groups*

### 5.1.1.1 EUROPE (GO-LAB, NEXT-LAB, AND GO-GA)

The Go-Lab portal (www.golabz.eu) was developed in the context of the Go-Lab project (2012–2016) and continued through the Next-Lab (2017–2019) and GO-GA projects (2018–2020), all funded by the European Commission and offering over 1,000 remote and virtual experiments. The entry page of this repository includes a menu, through which it is possible to check the number of experiments by subject domains, type (remote, virtual, dataset), target age group (<7, 7–8, 9–10, 11–12, 13–14, 15–16, >16 years), and language of presentation. Using the list of experiments by subject domains, it was possible at the time of this writing to verify that the vast majority ($n$ = 700, 64%) were in physics, in the topics of electricity and magnetism ($n$ = 131, 12%) and forces and motion ($n$ = 323, 29%).

In Go-Lab, the online laboratories are part of Inquiry Learning Spaces (ILS), where students learn about a STEM concept from an investigative perspective divided into five phases: contextualization, conceptualization, experimentation, conclusion, and discussion. The ILS concept is grounded in work developed by Ton de Jong, who coordinated both projects (De Jong & Van Joolingen, 1998; Pedaste et al., 2015). Those European projects clearly mark one of the largest and longest-lasting endeavors to collect a high number of online laborites of any type and collectively offer them for usage for instruction. However, some of those online laboratories are not working anymore, which clearly shows a not-yet-solved challenge in the development of online laboratories: securing long-term support and further development of online laboratories independently from individuals and project-based funding. We will touch on this aspect in our final section, but letting online laboratories mature from their initial support is clearly one of the major, so far unsolved, tasks in the community.

### 5.1.1.2 AUSTRALIA (LABSHARE)

LabShare was an Australian government–funded project (2008–2011) that aimed to create a national network of shared remotely accessible laboratories. It was led by David Lowe, then affiliated with the University of Technology Sydney, who published several papers about the project (Lowe et al., 2009a, 2009b). The project website (www.labshare.edu.au) is no longer active, although still visible through the Internet Archive Wayback Machine. Although not pertaining to the original project consortium, the University of Sydney has also installed the Remote Laboratory Management System (RLMS) developed in the context of the LabShare project at https://labshare.sydney.edu.au.

This project marks an example of a project-based online laboratory development which did not survive after both project support and funding ended, even though the project was set up as a nation-wide endeavor. One would think that the inclusion of several institutions mitigates the risk of project results, such as developed laboratory setups being lost after the project period, but this specific case proves that, if online laboratory infrastructure is not made part of the universities' general laboratory infrastructure, it is difficult to maintain long-term support for it. However, it is still worth mentioning LabShare in this context here because this project was one of the drivers for remote laboratory developments back in those days.

#### 5.1.1.3 INDIA (VIRTUAL LABS)

Virtual Labs is an Indian nationwide initiative which is supported by the Ministry of Human Resources in India. The Virtual Labs initiative (2008–2011) brought together 11 engineering education institutions, with a predominance of Indian Institutes of Technology (IIT). Under Virtual Labs, over 100 online laboratories consisting of approximately 700+ web-enabled experiments were designed for remote operation and viewing. As per the homepage information itself, the Virtual Labs initiative has registered more than four million experiments as of 2021.

Virtual Labs displays the potential relevance and power online laboratories can play for an education sector in a specific country or region. Connecting several institutions over long distances by sharing infrastructure can be of mutual benefit to all participating partners. As of today, it still remains to be proven if this initiative solves funding and support challenges and stays active in the long run, though.

#### 5.1.1.4 UNITED STATES (ILAB MIT)

The iLab project (2001–2019) at the Massachusetts Institute of Technology (MIT) offered several online laboratories for instruction in electrical engineering and computer science, civil engineering, and chemical engineering. According to its coordinators, Del Alamo et al. (2002), some of these laboratories were shared with students from universities in North America, Europe, Asia, and Africa.

Although centered on a single institution, MIT, this network is probably one of the best-known cases of a federation of online laboratories, with installations reported in institutions like the Obafemi Awolowo University in Nigeria, the Makerere University in Uganda, the Carinthia University of Applied Sciences in Austria, or the University of Brasov in Romania (García-Zubía & Alves, 2011). One of the reasons for its success may come from the fact it was well supported by MIT and received generous funding from several sponsors, including Microsoft. Regarding the iLab (MIT) and the previously named LabShare projects, García-Zubía (2021) noted:

> iLAB and LabShare were excellent examples of remote laboratories directed by Judson Harward and David Lowe at MIT (USA) and UTS (Australia), respectively, and in their day were a world reference due to both the sophistication of their experiments and the quality of their RLMS, which permitted scalability, universality and federation from their core. However, both are more or less inactive, and neither can be used in class in a secure fashion.
>
> *(p. 74)*

### *5.1.2 Specific Online Laboratories*

The following six more specific examples represent online laboratories which have been developed and introduced for the first time at specific institutions (see Figure 24.2). However, some of them, like the VISIR lab, for example, have outgrown their local applications and are now used at several institutes across the globe. In that sense, VISIR is an outstanding example of one lab that is shared across institutions in the sense of shared infrastructure and even started international research collaborations and development efforts.

#### 5.1.2.1 VISIR

The Virtual Instrument Systems in Reality (VISIR) project started in 1999 at the Blekinge Institute of Technology (BTH), Sweden, under the leadership of Gustavsson (2001). VISIR is also an acronym for the associated remote laboratory that allows users to perform remote experiments with electrical and electronic circuits in less than a second, thus supporting the concurrent access

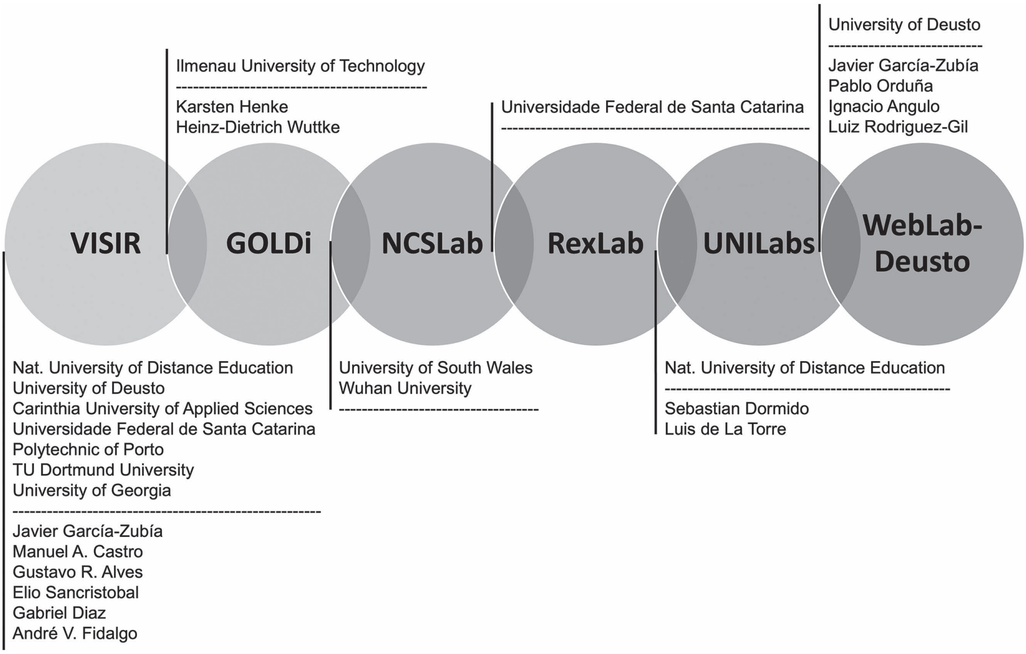

*Figure 24.2* Specific exemplary online laboratory use cases (GOLDi, NCSLab, RexLab, UNILabs, VISIR, and WebLab-Deusto).

of several users (http://openlabs.bth.se). Presently, the VISIR remote laboratory is installed in all five continents, specifically in Argentina, Austria, Australia, Brazil, Costa Rica, Georgia, Germany, India, Morocco, Portugal, Spain, Sweden, and the United States. García-Zubía (2021, p. 82) noted that "VISIR is perhaps the most powerful, spectacular and frequently used remote experiment in the world, and it has won various awards."

#### 5.1.2.2 A-ZUBGOLDI

The Grid of Online Laboratory Devices Ilmenau (GOLDi) was developed by Karsten Henke and Heinz-Dietrich Wuttke, based on work that can be traced back to 2003 (Henke et al., 2003). It uses a grid concept to implement a remote laboratory infrastructure based on the iLab architecture of MIT. As of 2022, GOLDi is still in operation (www.goldi-labs.net).

#### 5.1.2.3 NCSLAB

The Networked Control System Laboratory (NCSLab) is a remote laboratory that integrates various test rigs and experimental facilities of control systems around the world which was established in the University of South Wales, UK, in 2006. It is presently based at the University of Wuhan, China (www.powersim.whu.edu.cn/ncslab/), and is still quite active, with new developments regarding its user interface (Lei et al., 2021).

#### 5.1.2.4 REXLAB

The Remote Experimentation Laboratory (RexLab) was initially founded by João Bosco da Mota Alves in 1997 at the Federal University of Santa Catarina (UFSC), Brazil, as a result of the MSc thesis of Juarez Bento da Silva, who developed a remote debugger for the 8051 microcontroller. Presently, RexLab has expanded the number of remote experiments available through its site (http://relle.ufsc.br), which are publicly available to anyone wishing to use them. The list of available remote experiments includes electrical circuits, a development environment for programming in ARDUINO, an inclined plane for physics, and a pendulum, among many others.

#### 5.1.2.5 UNILABS

The University Network of Interactive Laboratories (UNILabs) was initially founded by Sebastian Dormido at the National Distance Education University (UNED), Spain, with a series of virtual laboratories for running experiments on automation and control theory (Dormido-Bencomo et al., 2000). Presently, it supports a number of remote and virtual experiments on those same areas (https://unilabs.dia.uned.es), being one of the most successful exemplary use cases.

#### 5.1.2.6 WEBLAB-DEUSTO

The foundations of WebLab-Deusto can be traced back to 2004, in a publication authored by Javier García-Zubía (García-Zubía, 2004). Presently, WebLab-Deusto offers a series of remote laboratories, mainly for supporting digital design, robot and ARDUINO programming, and remote experiments with electrical and electronic circuits (using its own VISIR node), among others (https://weblab.deusto.es/). LabsLand, a company that offers services based on remote laboratories, is a spin-off of WebLab-Deusto.

At this point, we want to halt displaying specific examples and again refer to the articles referenced at the beginning of this subsection and in Section 3. It needs to be stated that the research and development community working on online laboratories is still highly volatile. In addition to the online laboratories named up to this point, there are many more initiatives covering everything from very course-specific solutions to broader efforts across engineering curricula, and we personally expect even more case studies and online laboratory examples to be published based on work that happened during the COVID-19 interruption. It clearly may be too early to draw a conclusion on how the years 2020 and 2021 impacted the international online laboratory community. There was a sharp spike in online laboratory efforts detectable (see for example, Abumalloh et al., 2021; Mohammed et al., 2020; Vasiliadou, 2020; Vergara et al., 2022), but it is not yet clear to what extent this spike will lead to a fundamental change in the application and wider use of online laboratories in the broader engineering education landscape. In the following, we want to wrap up this chapter by pointing out future possible developments and challenges with regard to online laboratories.

## 6 Future Perspectives on Online Laboratories

Gravier et al. (2008) presented a review of the state-of-the-art of remote laboratories, covering an initial 10-year period (1997–2007) of developments, to then identify possible evolutions for the next generation of remote laboratories. Authors identified reusability, interoperability, opportunity to collaborate, and convergence with LMSs as four major issues for the leverage of remote laboratories. Many of these aspects were later addressed in the IEEE 1876–2019 Standard for Networked Smart Learning Objects for Online Laboratories (IEEE, 2019).

An article by Martins-Ferreira and Graven (2014), "Rise and Fall of Remote Labs: Or Perhaps Not?" presented a framework to delineate a plan of action for repositioning remote laboratories as technology-enhanced educational tools able to add value to teaching and learning processes. The plan of action specified four criteria defined by the authors: (1) "institutional networking" should be considered a priority for every institution active in this field; (2) "pedagogical value" represents an area where failure to improve may dictate the fall of remote laboratories; and (3) “availability” and (4) “accessibility” represent areas where successful research and development projects should generate relevant results to convert remote laboratories into a mainstream educational technology. These four criteria are met in projects like Go-Lab, Next-Lab, Virtual Labs, or VISIR, as already described in Section 5. In general terms, meeting these criteria has been a path to the successful evolution of online laboratories. In addition to that, long-term success for online laboratories needs to be seen in disconnecting the laboratories from both individual developers or researchers and extra-mural funding. It has been proven many times that no online laboratory can survive in the long run if it is not introduced into the institution’s general IT infrastructure and if financial as well as technical support is not coming from inside the institution. Otherwise, online laboratories remain “only” a temporarily finite project that dies after external funding ends or faculty move on to the next project. Actually, the switch from setting up online laboratories as part of a funded project to making them a long-term part of the curriculum is absolutely critical for success and has been a stumbling block for many, now-defunct laboratories.

Correia et al. (2021) proposed a graphical evolution model for remote and virtual laboratories that was validated against several existing and extinct online laboratories. A major aspect contributing to the endurance and evolution of online laboratories was the existence of several positive feedback loops, including a start-up. This was the case of WebLab-Deusto, which led to a start-up named LabsLand (2021). Some interesting aspects of LabsLand are that it uses the prosumer concept, where educational institutions may provide their own remote laboratories and/or use remote laboratories provided by other institutions (“institutional networking”); it provides additional didactical/pedagogical support, including integration with an LMS (Gravier et al., 2008) and “pedagogical value”; and it guarantees the “availability” and “accessibility” of all provided remote laboratories, complying with the third condition proposed by Martins-Ferreira and Graven (2014). These examples support the idea that, in some cases, it is possible to pinpoint specific aspects that can contribute to the positive evolution of online laboratories.

### 6.1 A(n) (Un)Certain Future?

The COVID-19 pandemic was a boost to many online educational solutions, including online laboratories, as part of several “emergency responses” described in recent literature. In the words of Pablo Orduña, co-founder and CEO of LabsLand:

> The usage of LabsLand remote laboratories has increased substantially since the beginning of the pandemic. In 2020, both the number of sessions and users was 7 times higher, and it is keeping the growing trend in 2021.
>
> *(Personal communication, November 5, 2021)*

This exponential growth was triggered by an unforeseen and exceptional reason; nevertheless, it supports the idea that if the conditions are favorable to the strengths of online laboratories (24/7 availability, online access, existence of supporting pedagogical materials, etc.), then its use will shift from being an option to being the option.

Any answer to “How will online laboratories impact the future of both face-to-face and online engineering education and how will they shape lab-based instruction as a whole?” faces the prime challenge associated with any prediction, that is, getting it right. In any case, recent emergency responses to the COVID-19 pandemic, in the engineering education sector, showed an unprecedented interest in and use of online laboratories, in parallel with alternative solutions, like visualized experiments or take-home laboratories, also called pocket laboratories. This justifies why the question is not “if online laboratories will impact the future of both face-to-face and online engineering education" but rather "how they will impact it." In a normal (i.e., non-emergency) situation, it's likely that the experience gained during the pandemic will not be lost, and many institutions/teachers/students will consider online laboratories a viable technology-enhanced tool able to support the acquisition of experimental skills and practical knowledge. Other emergency-proven solutions like pocket laboratories and visualized (or ultraconcurrent) laboratories are likely to be part of a sort of "laboratory palette," where each laboratory type may be used according to a set of conditions defined by the institution and/or the teachers. In any case, it will always be important to think first of what the intended learning outcomes are (see Feisel and Rosas's list), to then consider the overall instructional design (see the MOST framework), then investigate the available options and the characteristics (see the referenced SWOT analysis by Alves et al., 2022) of each option and proceed with a reasonable instructional approach. In other words, one must be aware of the ten commandments of remote experimentation proposed by García-Zubía (2021) that include, for example, "Think about the curriculum and you will succeed" and "The (remote) experiment should help, it should not in itself be a challenge." Recommendations from engineering education experts, such as Douglas (2020), are also relevant: "So, my recommendation is, the very first thing to think about is what were the learning objectives associated with that laboratory? What were the learning goals?" (0:23).

Exactly this mismatch between a more technology-driven development of online laboratories and the lack of in-depth pedagogical considerations may be one of the major reasons for the fact that online laboratories are still somewhat of a niche in the engineering education research community. So far, and this may change with the long-term impact of COVID-19, online laboratories have not yet gained a level of widespread attention in the instructional community, specifically in higher engineering education. It seems like there is still a dire need for further knowledge development that goes beyond the sheer technical development of individual labs and their somewhat-superficial, student perception–based evaluation. Further in-depth educational research is still needed to develop results that scholarly underpin and guide both the development and application of online laboratories.

## 6.2 Concluding Remarks

In summary, many research findings suggest that online laboratories can serve as an effective instructional tool for engineering education. Drawing on the advantages offered by online laboratories may help solve existing shortcomings of traditional curricula and hands-on laboratories, such as safety or capacity issues. However, review studies also underscore that comparative evaluations of different online laboratory technologies are difficult and may be of little use unless educationally relevant variables, such as student ability, time on task, and cooperative work patterns, are measured and controlled. Unfortunately, studies focused on the use of specific learning strategies with online laboratories and research examining metacognitive effects, time on task, teamwork skills, universal design, and learner self-efficacy (to name just a few examples) are not well represented in the literature. Variables related to the use of online laboratories also could include return on investment, efficiency, or instructor perceptions of usability. On that note, it is interesting that students typically rate remotely operated laboratories as less effective than simulated laboratories, even when learning achievement favors the former. Nevertheless, online laboratories have advantages in availability, cost–benefit, and sometimes learner inclusivity, which explains the underlying satisfaction ratings in many studies.

This chapter explored the value and challenges of online laboratories for engineering education. While some of the challenges may be mitigated with advances in learning technologies, the need for technologically savvy instructors and collaboration-minded institutions will remain. However, the benefits associated with learning and operational considerations are likely to outweigh, in the long term, inherent limitations that may dissuade potential adopters. In addition, online laboratories present an opportunity for institutions that have not initiated online degree programs because addressing the need for laboratories was deemed an insuperable hurdle. This alone has significant implications for sweeping change in academia. The future of engineering education will require flexibility, access, rigor, and creativity. Online laboratories will accommodate and complement those goals.

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