Engaging Students in Distance Learning of Science With Remote Labs 2.0

Charles Xie, Chenglu Li, Shannon Sung, and Rundong Jiang

Abstract—**During the COVID-19 pandemic, many students lost opportunities to explore science in labs due to school closures. Remote labs provide a possible solution to mitigate this loss. However, most remote labs to date are based on a somehow centralized model in which experts design and conduct certain types of experiments in well-equipped facilities, with a few options of manipulation provided to remote users. In this paper, we propose a distributed framework, dubbed remote labs 2.0, that offers the flexibility needed to build an open platform to support educators to create, operate, and share their own remote labs. Similar to the transformation of the Web from 1.0 to 2.0, remote labs 2.0 can greatly enrich experimental science on the Internet by allowing users to choose and contribute their subjects and topics. As a reference implementation, we developed a platform branded as Telelab. In collaboration with a high school chemistry teacher, we conducted remote chemical reaction experiments on the Telelab platform with two online classes. Pre/posttest results showed that these high school students attained significant gains ($t(26) = 8.76$, $p < .00001$) in evidence-based reasoning abilities. Student surveys revealed three key affordances of Telelab: live experiments, scientific instruments, and social interactions. All 31 respondents were engaged by one or more of these affordances. Students' behaviors were characterized by analyzing their interaction data logged by the platform. These findings suggest that appropriate applications of remote labs 2.0 in distance education can, to some extent, reproduce critical effects of their local counterparts on promoting science learning.**

Index Terms—**COVID-19, Internet of Things, learning analytics, learning environments, online learning, remote laboratories, student experiments, thermal sensors.**

I. Introduction

DISTANCE learning has grown into an indispensable part of modern education systems. According to the National Center for Education Statistics [1], during the 2017–18 school year, about 21% of public K-12 schools in the United States offered at least one online course. During the COVID-19 pandemic, complete or partial distance learning became mandatory in many school districts. But there are problems with science education from a distance. While many teaching and learning activities can migrate online, laboratory experiments usually require physical presence of and close collaboration among students in schools. Given the reality of school closings and the requirement of social distancing, many teachers were forced to cut lab activities short or even give them up altogether. Although schools may be able to provide material and instructional supports for students to conduct some simple experiments at home as exemplified in [2], [3], sophisticated experiments that involve shared equipment and hazardous materials are out of the question due to the concerns about costs and issues related to sanitizing, distributing, and disposing lab supplies. This bottleneck limits the scope and depth of science investigations that students can carry out at home. Given the indisputable importance of laboratory exploration in science education [4], [5], new learning technologies need to be developed to provide students remote access to science labs so that the problem can be mitigated to some degree. Even for those who wonder about the usefulness of these technologies after the pandemic, the investments will likely pay off in the long run as they address an important missing piece about laboratory experiences in current distance education systems, which must be filled to fully accomplish the mission of online learning to promote equity in education [6]. After all, technologies that can provide students remote access to advanced labs from home during an epidemic can also be used at any time and from anywhere to benefit students in underresourced schools that are not privileged to be equipped with such labs or students whose schools have been severely damaged by natural disasters such as Hurricane Harvey [7]. The purpose of this paper is to introduce a new idea that can potentially make remote labs more accessible and effective.

II. Conceptualization

A. Alternatives to Laboratory Experiments

Before the COVID-19 pandemic, science educators have been exploring various methods for enabling scientific experimentation in online settings. For example, virtual labs have been proposed to supplement, even supplant, physical labs

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[8]–[11]. However, many educators have issues with using only virtual labs, as the lack of physical components in those activities may deprive students of opportunities to experiment with the material world in the same way scientists and engineers do in the workplace. As a testimonial, the American Chemical Society maintains a policy position that states “computer simulations that mimic laboratory procedures have the potential to be a useful supplement to student hands-on activities, but not a substitute for them” [12].

Another alternative to a physical lab is a remote lab that allows students to interact remotely with real experiments through the Web [13], [14]. As a concept, remote labs date back to a proposal by Aburdene, Mastascusa, and Massengale [15] at the dawn of the Internet era (in 1991). Compared with virtual labs, remote labs retain many key characteristics of physical labs, such as authenticity, complexity, uncertainty, errors, and psychology of presence [16]–[20]. In more than two decades of exploratory research, remote labs have provided students access to large apparatuses such as telescopes at observatories [21]–[23], expensive instruments such as atomic force microscopes and scanning electron microscopes [24]–[26], dangerous measurements such as using a Geiger counter to detect radioactivity [27], [28], biological interactions such as using biotic processing units to stimulate cells [29]–[31], and engineering shops that have special equipment [32]–[36]. Across the documented studies that compared remote and local labs in higher education, little to no differences have been found in students’ learning outcomes [37], thereby validating the use of remote labs as alternative learning environments in college. As remote labs promise to broaden participation in scientific experimentation by giving anyone, including those in underserved communities and those with physical disabilities, access to scarce laboratory or observatory resources, they represent an important direction and an exciting opportunity of research and development for formal and informal science education at precollege levels as well. This paper presents our exploratory work in advancing remote lab technology.

B. Next-Generation Remote Labs

Despite their remarkable successes, most remote labs in the reported studies were based on a somewhat centralized model in which the experiments were, for the most part, designed and operated by an expert provider at a well-equipped facility (typically a university lab). Students and teachers then worked

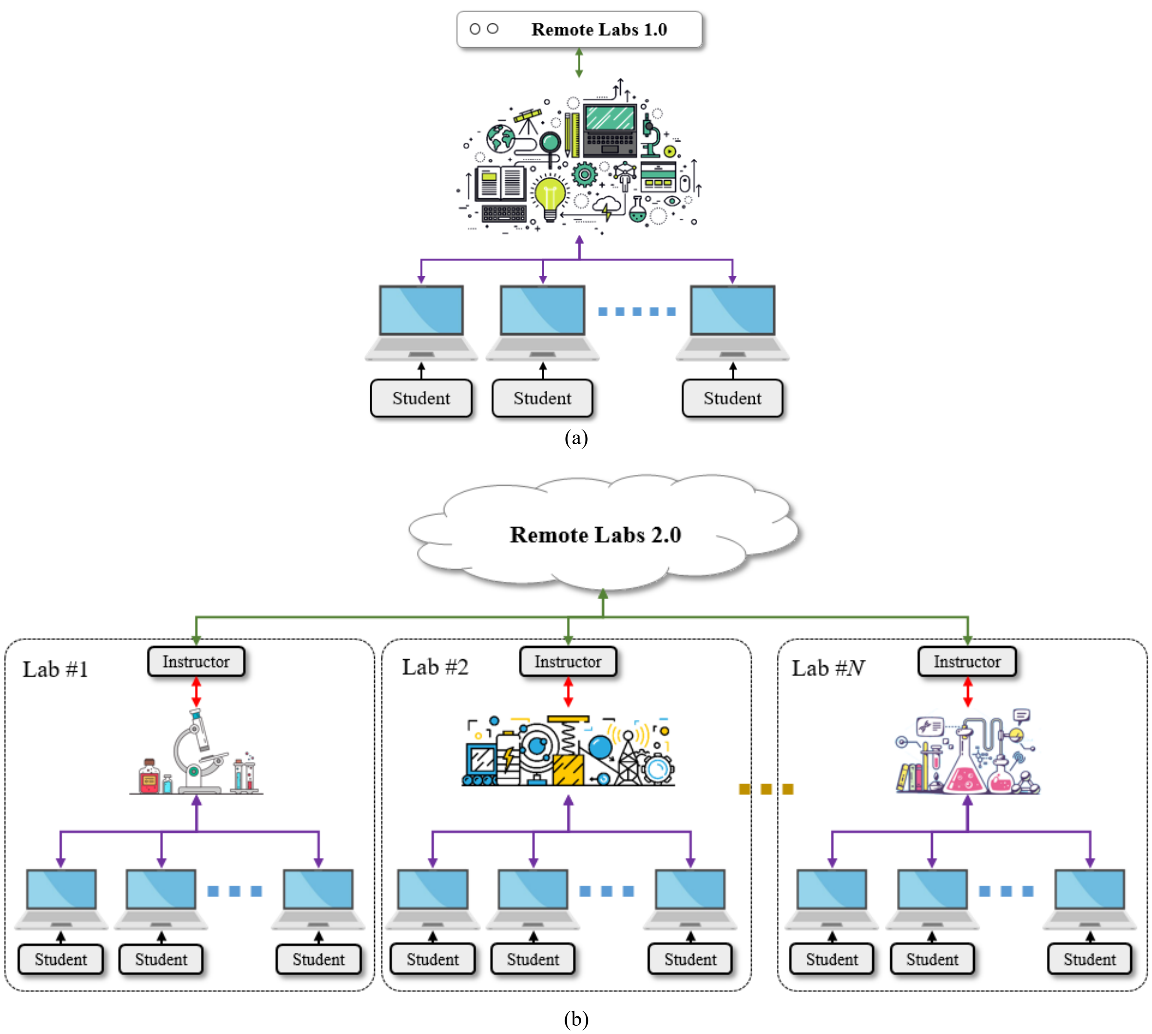


Fig. 1. A schematic illustration of the differences between the centralized model (a) and the distributed model (b) for remote labs, which we refer to as remote labs 1.0 and 2.0, respectively. The distributed model can be realized through a scalable cloud-based application that supports anyone to create, operate, and share their own remote labs on the Internet, similar to typical teleconferencing software that allow many people to use their own meeting rooms to converse with others.

with such remote experiments through the Internet using computer interfaces that controlled a set of parameters allowed by the designers. While this centralized model ensures the efficiency, reliability, and reproducibility of the experiments, it limits the ability of students and teachers to choose their own topics, subjects, and methods. This intellectual liberty is a hallmark of science exploration in open-ended, hands-on labs that is vitally important for cultivating students' spirit of independent inquiry. For remote labs to become a truly useful cyberinfrastructure that supports online experimentation at all levels on a large scale, they must meet teachers' needs to address diverse science content and student interest with desirable open-endedness, flexibility, and interactivity.

This calls for adding a distributed model that can accommodate many remote labs of different types provided in parallel by any number of instructors to their own students (Fig. 1), similar to the concept of "rooms" in virtual meetings that anyone can initiate and invite others to join while many others are convening in different such "rooms." A distributed model like this also solves the scalability problem that would overwhelm a central provider with too many requests for experimentation from numerous students at the same time if it were to serve a large number of schools on a regular basis. In a distributed model, teachers who possess their own remote labs only need to attend to the requests from their own students. At first glance, one may think setting up a remote lab on their own would be a daunting task for teachers. The task, however, can be significantly simplified with technology, as we demonstrate later in this paper. In practice, a straightforward way for teachers to create a remote lab is to convert an existing physical lab into a remote one. This requires the development, revision, or upgrade of laboratory technology that can support existing experiments commonly encountered in the science curriculum while being capable of communicating with a remote labs 2.0 server based on a data protocol mutually agreed on both sides to facilitate the flow of data back and forth. Once such technology is provided to teachers, initiating and running a remote lab require just a few trivial steps as the underlying software will automatically take care of the hard work.

To some extent, the main differences between the centralized model and the distributed model of remote labs are similar to those between Web 1.0 and 2.0. In the era of Web 1.0, it was primarily professional developers who built and ran Web sites that subsequently became the predominant sources of information on the Internet. In contrast, Web 2.0 technologies have enabled average users to generate and share their own content easily on the Internet, ushering in much larger and richer cyber-ecosystems that propel themselves to meet the diverse needs and interest of people dynamically. Because of this resemblance, it is proper to dub the centralized model remote labs 1.0 and the distributed model remote labs 2.0.

Thanks to the rapid advancement of information technology, we now have a tremendous collection of existing technologies, such as cyber-physical systems, Internet of Things (IoT), robotics, virtual reality (VR), augmented reality (AR), teleconferencing, and social networks, for building the envisaged remote labs 2.0. For example, we can utilize mixed reality technologies to deliver immersive laboratory experiences to remote users based on digital twins augmented with sensor data [38]. As an open cyberinfrastructure powered by the synthesis of such a rich set of technologies—each of which provides a different tool to spark student agency [39], remote labs 2.0 is poised to engender many educational innovations.

C. *Educational Applications of Remote Labs 2.0*

Compared with remote labs 1.0, a major advantage of remote

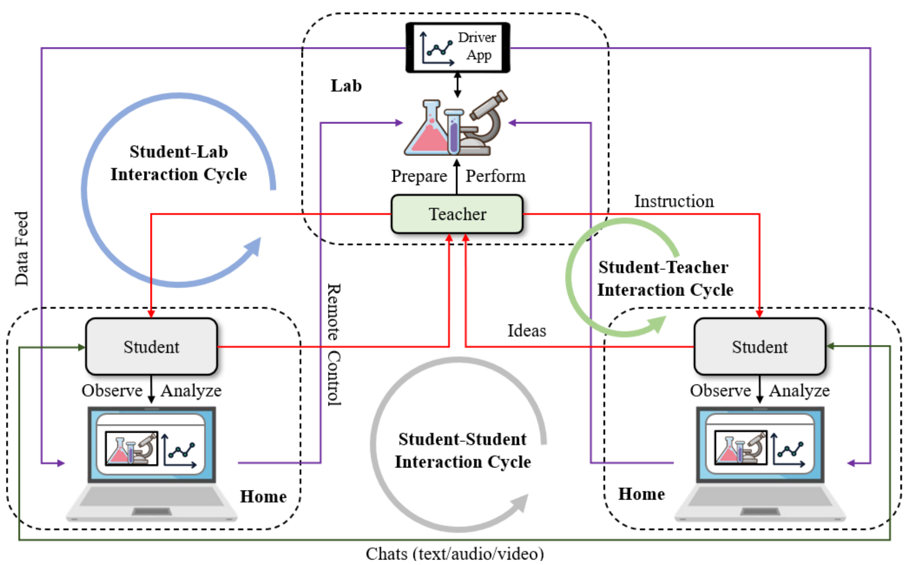


Fig. 2. The learning model of remote inquiry consists of three interlocking cycles of interactions—student–lab, student–teacher, and student–student—that mimic actual experiences in a science lab where students are physically present to participate in hands-on experiments, often in a collaborative fashion. In the student–lab cycle, students observe a remote experiment and analyze raw data on their own computers. If the experiment is being conducted in real time, they can even remotely control it and obtain new data as a result of their own interventions. In the student–teacher cycle, students receive instruction from the teacher about an experiment, but they can also propose their own ideas to be tested in the teacher's next step of experimentation. In the student–student cycle, students can discuss the experimental results through text, audio, or video chat. They can even take turns to remotely tweak an experiment to show their ideas to others. The driver app controls the sensors and actuators in the lab, connects them to students, and manages the life cycle of a lab session.

labs 2.0 is that middle or high school teachers are given full control of labs and autonomy of instruction. For instance, with remote labs 2.0, teachers can 1) design or choose their own experiments, 2) conduct them in places equipped with required supplies and at times permitted by their teaching schedules, 3) stream live data captured by sensors and cameras to students' devices for real-time processing, 4) commentate on interesting phenomena as they emerge, 5) guide students through analyses and interpretation of data, 6) discuss the results with students, and then 7) lead students to iterate through a new cycle of scientific inquiry. Students can also propose new ideas to be incorporated into teachers' next experiments such that they can have their own hypotheses tested with the help of teachers and/or lab assistants. With the support of more advanced hardware, teachers may even be able to permit students to remotely control an ongoing experiment if those actions pose no threat to teachers' safety. As a complete picture, Fig. 2 shows three major interaction cycles of a possible learning model enabled by remote labs 2.0, which we refer to as *remote inquiry*, for approximating the overall student experiences in the local counterparts of remote labs.

As a matter of fact, such an instructional approach may be quite familiar to science teachers who routinely perform demonstration experiments in their classrooms to entice their students, except that it can now be implemented in online settings with remote labs 2.0 and, even better, the experimental data can also be instantaneously shared with students in real time for their own analyses. In this way, analyzing and interpreting data, one of the eight science and engineering practices required by the Next Generation Science Standards (NGSS) adopted by many states in the United States [40], can be supported by remote labs without losing any major fidelity as expected in the local counterparts of remote experiments. Even after schools return to normalcy after the pandemic, remote labs 2.0 may continue to be useful as teachers can still use the technology to stream experimental data to each student's computer for her/his own records while conducting a demonstration experiment in the classroom—as opposed to just showing the live data to all the students on a projector screen. Even though the students are in the same room, it is still advantageous for everyone to receive a copy of the experimental data on the spot to boost a sense of ownership and participation that may make it more likely for her or him to run independent analysis, particularly when the data is perceived to be highly complex and valuable.

With the envisioned technology, students can also start their own remote labs. This capacity can be used to enhance student collaboration in hybrid learning scenarios. Under a hybrid circumstance where there are both in-person and remote students being taught at the same time [41], a student physically in the lab can collaborate with a remote partner to conduct an experiment in tandem. The students in the lab are responsible for gathering data and sending them to their remote partners (e.g., they email a spreadsheet that contains the data). For an experiment that produces a large amount of raw data, manual data collection, sorting, and sharing can become considerably laborious and tedious, chipping away precious lab time from students and reducing their learning experiences to mundane routines. As illustrated in Fig. 3, remote labs 2.0 can provide a tool to streamline hybrid learning in the lab because the data are automatically transmitted behind the scenes to the remote partners and visualized as intuitive images or graphs on their computers. Hence, students in a hybrid group can all concentrate on observing the unfolding of an experiment and making sense of the incoming data. Such a joint investigation may inspire the group to raise even more what-if questions. They can debate about the relevance and testability of these questions and then delegate the student(s) in the lab to conduct further experiments to pursue some of them, thus starting a new iteration of inquiry.

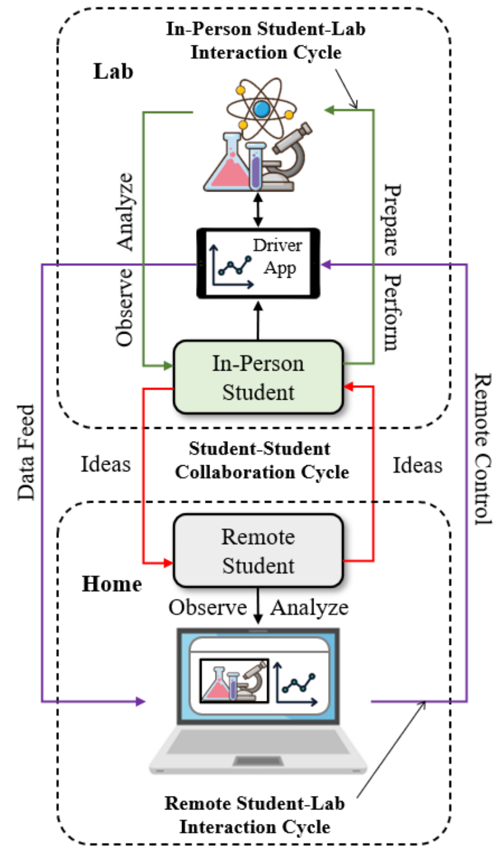


Fig. 3. Remote labs 2.0 can support collaborative hybrid learning in the lab. For example, a student attending lab in-person can pair with a remote partner to conduct an experiment in tandem. The student in the lab can initiate and operate a remote lab so that the data can be livestreamed to the remote partner for co-analysis. They can exchange ideas and discuss results throughout the entire session. Although this illustration shows only one remote partner, the learning model can accommodate more students in the loop.

In addition to the above scenarios of learning and teaching, remote labs 2.0 also opens many other possibilities for formal and informal science education. For example, this technology can be integrated into massive open online courses (MOOCs) to create many types of massive open online laboratories (MOOLs) that bring laboratory experiences across science disciplines to an incredibly large audience [42], [43]. Using mobile sensing and computing, outdoor experiments and observations can expand the scope of remote labs to support remote inquiry in subjects such as environmental science, ecology, and civil engineering. In this way, remote labs may also provide much-needed technology to empower public participation in scientific research, or citizen science [44]–[46], in dire situations such as a pandemic. In terms of logistics, recruitment, and management for these applications, we hope that science educators who have access to scientific instruments supported by remote labs 2.0 will be enthused to sign up, on a voluntary basis or through a reasonable contract with a sponsor, to become remote lab providers. We envision that a growing number of these providers will eventually form a community of practice and a network of service to cover diverse needs for experimental science through the Internet.

III. Architecture

Technically speaking, remote labs 2.0 is a distributed computing system consisting of multiple software and hardware layers, such as physical computing, mobile computing, and cloud computing, interconnected through the Internet (Fig. 4). In the following subsections, we describe the essential elements and functions of these layers, as well as the relationships and interactions among them.

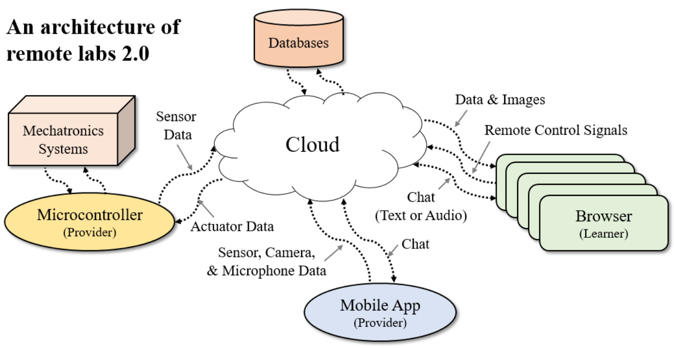


Fig. 4. Remote labs 2.0 is a distributed computing system that can be implemented using a stack of existing technologies. Each remote lab can be driven by one or more supported instruments operated by a provider (e.g., a teacher or a third-party lab assistant). Each can serve an arbitrary number of learners who access it from a Web browser. To prevent intrusion, a remote lab can be password-protected. To further protect privacy, sensitive data generated by providers and learners can be encrypted before transmission.

TABLE I
Some Common Electronic Sensors

Model	Measurement
ACS712	Electric current
BME280	Barometric pressure, relative humidity, and temperature
BMP280	Barometric pressure and temperature
BNO055	Orientation, angular velocity, acceleration, temperature
CAP1188	Capacitive touch sensor (8-channel)
DS18B20 [a]	Temperature
HC-SR04	Ultrasound distance detection
HC-SR501	Passive infrared motion detection
LIS3DH	Three-axis accelerometer
MLX90614	Infrared thermometer
MPU6050	Gyroscope and accelerometer
TSL2561	Visible and infrared light
VCNL4010	Luminance and proximity
VL53L0X	Time-of-flight distance detection

[a] This model uses the 1-wire communication bus system that can support multiple sensors. The rest of the above sensors use the I^2C serial communication bus. Some of these sensors are fused in a single board to allow for measuring multiple properties at the same time.

A. Physical Computing

Physical computing is the foremost layer of remote labs 2.0 that interfaces with the physical objects of an experiment. It enables the system to sense and respond to changes of the physical objects acting in the experiment through sensors and actuators connected to microcontrollers such as Raspberry Pi and Arduino. Electronic sensors that measure physical properties such as temperature, luminance, and acceleration are at the heart of a remote lab. Without sensors to collect experimental data, there would be nothing more than a video to share with students (and developing remote labs would be unnecessary as teachers can just use videoconferencing software to share a real-time video of an unfolding experiment with students). Table I lists some common electronic sensors that are available as breakout boards and/or in hardware attached on top (HAT), which can be purchased online and programmed using Python, C, or Java (most vendors provide free driver code written in one or more of these languages). Through wireless connections, the microcontrollers then transmit the data collected by the sensors used in the experiment to the cloud for storage and aggregation in backend databases and/or stream the data to students' computers for real-time observation and analysis in their Web browsers.

Physical computing also makes it possible for students to remotely control the actuators directly from within their browsers through a full-duplex communication channel such as WebSocket, creating opportunities for them to intervene with an ongoing experiment through the Internet when appropriate. For instance, students can request permission to remotely turn on a Peltier module to heat or cool an object in an experiment designed to study thermal energy transfer. Depending on the actual situation in the experiment, the teacher can grant or deny permission. In more complex scenarios, physical computing with mechatronic systems such as robots can even allow students to remotely program and perform certain laboratory procedures that would otherwise have required their physical presence to take on. For instance, students often move a sensor around in a physical lab to explore interesting phenomena. In an advanced remote lab of thermal physics, for example, students can create a temperature scanner for collecting an array of temperature data over an area by remotely controlling the motion of a pan–tilt module (an actuator) with an infrared thermometer (e.g., MLX90614) mounted on it and configuring the system in such a way that a temperature data point from the sensor is automatically gathered at each panning or tilting move of the actuator.

B. Mobile Computing

Mobile computing, which also occurs at the lab site like physical computing, allows a remote lab provider to videotape an experiment from any fixed or moving vantage points using one or more smartphones and stream the videos to the cloud for storage, processing, and sharing. We use a smartphone to capture the video of an experiment, because it is much more convenient to position and orient its cameras than those of a laptop computer and to program than a standalone wireless camera. This is important to broadcasting an experiment because students should be able to observe what happens from an optimal angle and spot, and the experimenter should be able to adjust the cameras freely during the experiment as necessary. In addition to providing their cameras for videotaping an experiment, smartphones can also use external sensors connected to them through the USB port or Bluetooth to collect data [47], eliminating the need for microcontrollers that may be less robust to use in many mobile computing scenarios. Importantly, this makes it far easier to carry out outdoor activities that extend science exploration beyond school walls.

Another advantage of using smartphones is that it allows remote labs to tap into their considerable computational power for edging computing. In the technical field of IoT, edge computing is a distributed computing paradigm that uses local devices to store and process data to reduce transmission volume and improve system responsiveness. In remote labs specifically, edge devices and apps can play the bridging roles between lab objects and cloud applications. For example, these apps can use computer vision to preprocess the videos recorded by cameras and send the results as modified frames or metadata of the videos so that students receive annotated or synthesized videos that highlight important features or visualize outstanding patterns. Edge computing is usually controlled by lab providers with administrator privileges.

C. Cloud Computing

Remote labs 2.0 relies on cloud computing to ensure its scalability and elasticity needed to handle spikes of usage anticipated in an epidemic or a natural disaster. Common cloud platforms as a service (PaaS), such as the Google App Engine and the Heroku cloud application platform, offer on-demand provisioning of resources that can power any number of active remote labs taking place around the clock.

The delivery of experimental data to students is the core process of a remote lab. As such, the life cycle of a remote lab is typically managed by a driver app running on a device used in an experiment such as a smartphone or a microcontroller that is responsible for collecting, processing, encrypting, and sharing experimental data. A live session starts when such an app begins to stream data to the cloud server of a remote lab and ends when it stops. As soon as the data stream arrives on the cloud, it is immediately distributed to the computers of the students who are currently logged in with the remote lab and also serialized into a database so that the experiment is automatically saved on the cloud for future reference.

Once students receive the data stream, they can examine it immediately using the analysis and graphing tools built in the front end of the remote lab. Or they can record it into sessions on their ends for replaying them later so that they can run any number and type of analyses with the recorded data using the analysis and graphing tools (or exporting the data to external tools for analysis). As all the students of a remote lab share the same data stream stored in a database, their recorded sessions can be simply represented by the starting and ending frames of the shared data stream. When a student plays back a recorded session, the cloud server simply pulls the included frames from the database behind the scenes and presents it as a single episode to the student. The cloud server also provides tools for students to edit their recorded sessions, such as breaking a long session into multiple independent runs, cutting a segment to remove outliers due to experimental errors, or combining segments to reveal trends over a longer period of time. The remote lab keeps students' recorded experiments, analysis results, and lab reports in their accounts so that they can revisit them for reflection or submit them to teachers for grading. Moreover, the same cloud tools can also be used by teachers to record and edit an experiment for students to explore asynchronously if live streaming is not possible.

In addition to supporting students' interactions with remote experiments, remote labs 2.0 also enables social interactions among students, teacher, and a third-party lab assistant (if one is present to help the teacher run experiments from another remote site) in an online class, such as text and audio chat. These social interactions normally occur within a teacher's own remote labs. They are not visible to an outsider because each remote lab is assigned a unique ID and can be protected by a password such that only the students of the owner's classes can access it. If there is a need to share a remote lab with students and teachers from other classes or schools, the owner can simply give them the ID and password. To comply with the Family Educational Rights and Privacy Act (FERPA), sensitive information generated by teachers and students are encrypted before transmission and decrypted only when received by an authenticated participant.

IV. Implementation

We have developed a reference implementation of remote labs 2.0, branded as *Telelab*, as a proof of concept. The goal of the research and development reported in this paper is to demonstrate the feasibility with a few key technologies and focus areas, rather than providing a comprehensive platform that attempts to cover many content areas with all the available technologies (which is the goal of Telelab in the long run). In this section, we describe the implementation details of a prototypical version of the Telelab platform. The latest version of Telelab is available to the general public free of charge at https://intofuture.org/telelab.html.

A. Thermal Imaging as a Versatile Sensing System

One of the sensors that we use in Telelab is the radiometric Lepton module manufactured by FLIR Systems for detecting thermal infrared radiation (8–15 μm wavelength). According to the Stephan–Boltzmann law, the thermal radiant emittance is related to the temperature of the source. Hence, it can be used as a noncontact method to measure temperature. Another reason that we favor this module is because it is in fact an array of thousands of microbolometers integrated in a small optoelectronic chip, which gives rise to its high-throughput sensing power for collecting a lot of radiometric data points at once for thermal imaging and analysis. The module is available in a standalone form that can be used with a Raspberry Pi microcontroller, but FLIR Systems has also built it into their FLIR ONE thermal cameras, which can be attached to a smartphone (Fig. 5). Hence, the Lepton module provides a

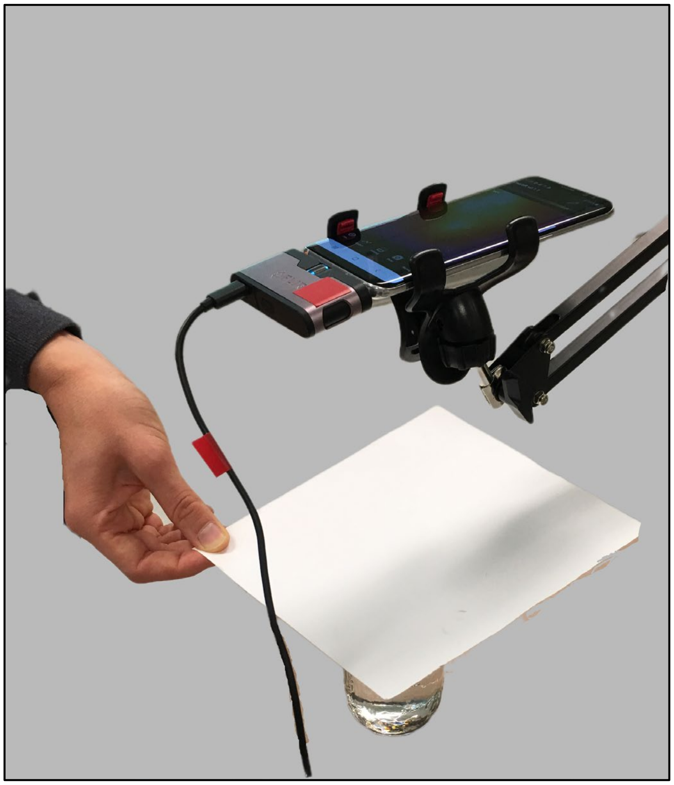


Fig. 5. A FLIR ONE thermal camera attached to a Samsung S9 smartphone mounted on a tabletop smartphone stand was used in an experiment to capture thermal energy transfer (a mix of convection and radiation) from a closed jar of hot water to a piece of paper above it. The thermal camera does not use the battery of the smartphone. Due to the limited capacity of its built-in battery, we recommend keeping the thermal camera charged all the time by connecting it to a power bank. If needed, the charging cable can be temporarily disconnected. The Infrared Explorer, an app running on the smartphone, can stream the thermal images and temperature data to the Telelab server on the cloud.

flexible technology for implementing remote labs 2.0. Note that, when used as a sensor in an IoT network, the FLIR ONE module connected to a smartphone also demonstrates an application of edge computing: It can exploit the processing power of the smartphone to perform some expensive computer vision computation to extract the edge lines from the regular image taken simultaneously by a companion visible light camera and blend them into the thermal image to create a more recognizable view of the phenomenon under observation.

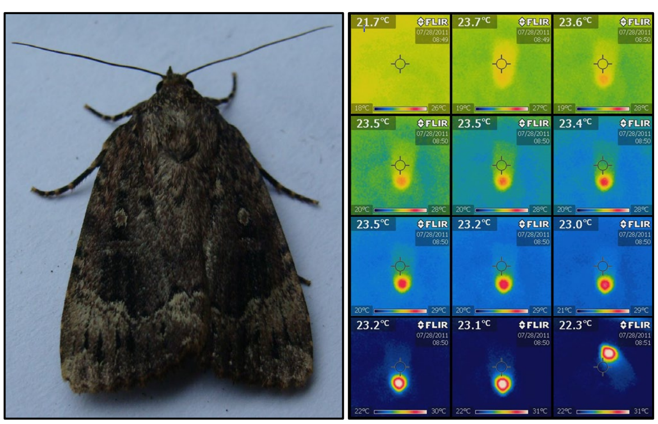


Fig. 6. Thermal imaging reveals that a moth (left) can warm up its thorax by more than 10°C in just two minutes (right). As a result of automatic color remapping (i.e., the heat map was rescaled based on the lowest and highest temperatures detected in the field of view of the camera), the background became more blueish while the moth warmed up and appeared more reddish in the thermal view. The change of the background color does not mean that the environmental temperature had decreased during the observation. An interactive video that shows this process of thermogenesis is available at: https://telelab2.intofuture.org/clip/60bff6ccf20d4ed2d9888b78.

Imaging is an advanced form of sensing that involves many data points sufficient to render a picture for human to recognize complex patterns in it easily and rapidly. Scientists have long relied on powerful imaging techniques to see things invisible to the naked eye and thus advance science [48]. As an example of scientific imaging, a thermal camera renders an intuitive, salient false-color visualization of a phenomenon on the screen and provides an example of how a mobile lab-on-a-chip can support scientific investigations anywhere. Fig. 6 shows an example of visualizing the thermogenesis of a moth with a thermal camera. In general, a thermal camera can reveal any physical, chemical, and biological processes that absorb or release heat (*anything that leaves a trace of heat leaves a trace of itself under a thermal camera*) [49]–[52], making it a versatile instrument for remote labs to deliver a variety of interesting experiments across science disciplines. Similar to using pH, redox, and other indicators to detect or track reactions through visually striking color changes, thermal imaging can be likewise thought of as a universal indicator in science experiments that also visualizes variations and distributions of physical or chemical properties with colorized heat maps. Based on the FLIR ONE thermal camera, we have previously developed an app, the Infrared Explorer (https://intofuture.org/ie.html), to provide basic functionality for thermal imaging and analysis. Adding code to the existing app for users to stream thermal images and temperature data to the Telelab cloud server turned out to be simple and straightforward.

Providing students with access to an advanced laboratory technology is aligned with the original goal of some earlier remote labs [21]–[26]. Although the price for thermal cameras has plummeted from a prohibitively expensive level to a few hundred dollars, it remains unlikely in the foreseeable future that schools would purchase them in large quantities for their students. The realistic chance is that schools may be willing to acquire a few for their labs. Through the Telelab platform, teachers who are equipped with a FLIR ONE thermal camera can share its images and data with any number of students in real time, without having to pass the device to them (thus reducing their risks of contracting the coronavirus). The thermal camera also makes it easy for teachers to convert their existing thermal physics labs into remote labs with upgraded laboratory experiences for their students and without requiring a complete overhaul of existing lab activities, as its noncontact nature allows it to be added to an experiment as an additional or replacement instrument without having to redesign or disrupt the established experimental procedures dramatically. Mounting the camera on a pan–tilt module driven by servomotors controllable through the Internet and exploiting the orientation sensor in a smartphone create an intuitive way for students to remotely manipulate the camera—when a student moves her/his own smartphone, an app running on it can send the data measured by its orientation sensor on the fly to the remote lab for synchronizing the orientation of the pan–tilt module, creating an interactive experience as if the student were directly orienting the remote camera.

B. Web Applications to Deliver Telelab Experiences

Based on Express.js, we developed a server application on the Google Cloud Platform to connect different apps of Telelab as described in the Architecture section. The server also manages the data flow among those apps and the messaging among users. Using React, we developed a client app that has a graphical user interface in the browser for students to observe a remote experiment, analyze the incoming data stream, and discuss the results with others (Fig. 7). As soon as a student logs into Telelab, the client app will be connected to the server. Once a teacher starts to use the Infrared Explorer to feed data to the server, all the connected clients will be timely updated with the incoming data and images to refresh their user interfaces. Students can then place an arbitrary number of virtual thermometers on top of the thermal image displayed in their browsers to collect time series of data for plotting a graph that shows the changes of temperatures at the spots in the view pointed to by those virtual thermometers. Such a feature may be considered as an AR application that elicits multi-presentational thinking [53], as the thermometers are imaginary but the data is real (albeit coming from a remote lab).

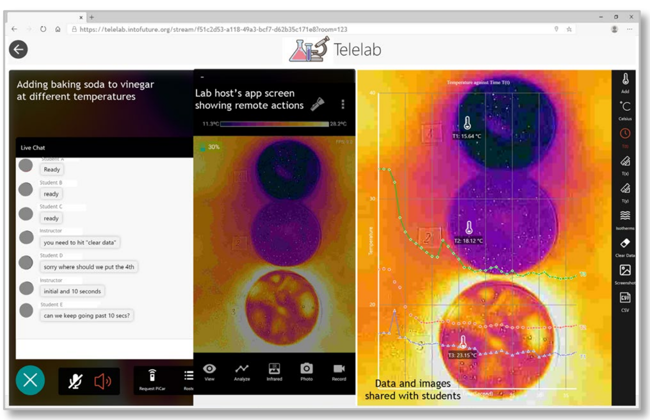


Fig. 7. A graphical user interface of a remote lab for students to observe a live chemical reaction through the lens of a remote thermal camera, analyze the incoming temperature data, and interact with the instructor and other students through online chat. The instructor's Infrared Explorer app screen can also be optionally shown in the middle of the above screenshot to provide a way for the instructor to give a remote demo to students if necessary. Built-in graphing and analysis tools are available in the vertical tool bar on the right for students to use. This screenshot was taken from an actual online class (the names of the students and instructor were redacted in the chat area). In this experiment, the same amount of baking soda was simultaneously added to the same volume of vinegar at different initial temperatures in three petri dishes (60 mm in diameter): The top dish was initially the coolest, the bottom one was initially the warmest, and the middle one was in-between. As the endothermic reactions progressed in the three dishes, the temperature dropped the most in the bottom one and the least in the top one, suggesting that the reaction rate was greater at a higher temperature.

All the client-side data, including 1) the experimental data collected from the remote lab, 2) the log that records student interactions with the user interface, and 3) the communication history among students and teacher, are stored in a cloud database through Mongoose. Containing rich information about student learning, these process data can be mined using multimodal learning analytics [54] to provide insights for design-based research on technology-enhanced learning environments [55], as we show later.

C. Telepresence Through Remote Control

A promising direction of development to improve user experience with remote labs, as suggested in previous studies such as [24], is to give students a sense of being there through telepresence [56]. Besides sending sensor data to students' computers, remote labs often use cameras to stream live views (technically, videos are also sensor data, though they are typically not viewed as such) so that students can observe the experiments closely to get a feeling of participation. An early study suggested that students who watched a live video of the device collecting their data in the remote lab felt most engaged with the task [27]. In many cases, however, the video is shot from a point of view chosen by the remote lab operator. It cannot be altered by students freely. One way to reinforce telepresence is to allow students to remotely control the camera so that they can observe an experiment from different distances and angles just like what they would normally do if they were in the lab. The remote thermography supported by Telelab demonstrates this idea.

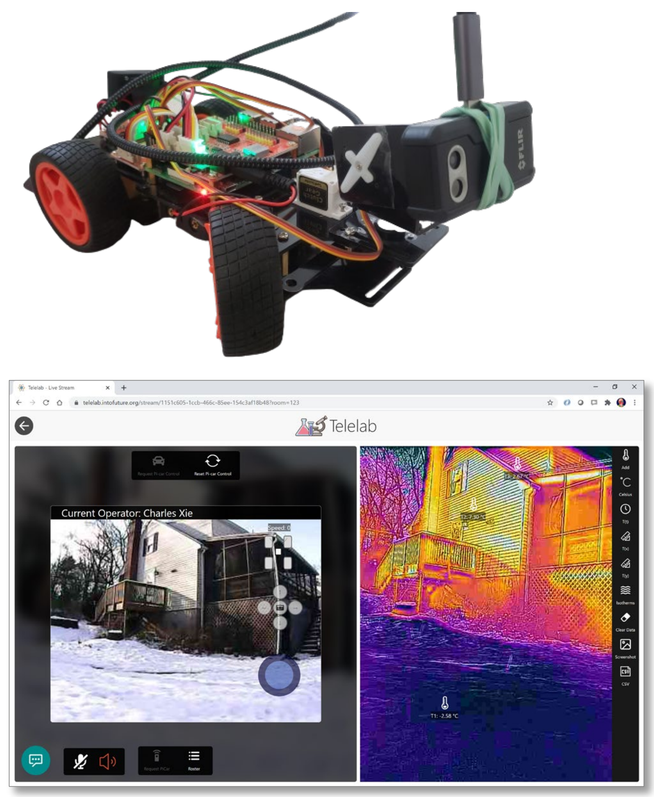


Fig. 8. Telepresence technologies are used to implement remote thermography for inspecting a house. Upper image: A FLIR ONE thermal camera mounted on a motorized pan–tilt device of a commercially available, low-cost video car controlled by a Raspberry Pi microcontroller. Lower image: A Web-based user interface for remotely manipulating the thermal camera to observe a house (or any other object of interest) from different angles and positions. The window on the left shows the visible light image captured by a camera attached to the Raspberry Pi microcontroller and the window on the right the thermal image captured by the FLIR ONE device. The buttons for moving the video car back and forth and rotating the cameras around the pan and tilt axes are shown near the edge on the right in the window for the visible light image. As in Fig. 7, thermal analysis tools are available in the vertical tool bar to the right of the window for the infrared light image.

Using a small video car shown in Fig. 8, the position and angle of the thermal camera (hence the vantage point) can be remotely changed by students using a set of navigation buttons in their browsers, giving them more liberty to explore in a remote lab and boosting their sense of being part of an ongoing experiment or investigation. To avoid conflict, at any time, only one student is allowed to control the video car, but others can request the control and take turns to drive it. As a student moves the video car around, the rest of the class can watch the results of her/his actions on their own screens, creating opportunities of social interactions that may benefit learning of each individual involved. This telepresence experience does not need to be limited to only indoor experiments on a lab bench. Fig. 8 shows that it can also be used in outdoor activities such as visualizing the energy exchange between a house and the environment through its building envelope to detect potential issues that may compromise its energy efficiency (which is a real-world application of heat transfer concepts).

V. Teacher Feedback

Teachers play a crucial role in remote labs 2.0. To evaluate how useful teachers may perceive Telelab to be for enhancing and enriching their online teaching during the COVID-19 pandemic, we provided virtual professional learning workshops about Telelab to dozens of science teachers from three states in the United States. The majority of these participants teach at public secondary schools. Their feedback also helped to improve the design and usability of the technology.

In early summer of 2020, ten workshop participants, including eight in-service and two pre-service teachers, explored several Telelab experiments in a graduate-level Technology for STEM Education course offered online by a major public university in a Southeastern state. The remote experiments covered common topics in physical sciences, such as heat transfer, phase change, and chemical reactions. Overall, the participants viewed Telelab as a valuable tool for science education. Seven of them agreed or strongly agreed that they would use Telelab in their teaching while others were neutral. They liked its ability to provide remote access to thermal imaging, support learning everywhere, record experiments and observations, and share images and data with anyone. When asked about their opinions on the extent to which Telelab could substitute local labs, four participants selected 60%, four selected 70%, and two selected 100%. As for the downsides of the Telelab activities, the participants, not surprisingly, felt that the serendipity of communication and collaboration among students and teachers in local labs was generally difficult to be reproduced in remote labs. Interestingly, the lack of physical interactions with experimental objects did not appear to be a serious issue to this group of teachers, largely because they understood that those interactions were temporarily out of the question in a pandemic and the remote experiments were probably one of the very few options left in such difficult times.

In early fall of 2020, we provided a half-day online workshop to 24 teachers from two other Southeastern states, 22 of which are in-service teachers, on similar topics in physical sciences. Among the participants, 14 have more than a decade of teaching experience. These teachers' reactions were largely positive, to the point that 17 of them signed up for running Telelab in their online courses at the end of the workshop. During the discussion session, there were interesting exchanges about the pros and cons of remote labs. For instance, one teacher pointed out that a "disadvantage with virtual learning is that you cannot see when the kids make mistakes or if they do it at all." Another teacher agreed to that statement but added "I like virtual because students focus more on observing than doing." While we do not take a stance in the argument, the comment of the second teacher does reflect a key feature of remote labs for concentrating students' attentions on the incoming experimental data, potentially giving them more time for conceptual learning through observation and analysis. Hence, this part of Telelab should be reinforced in our next iteration. On the other hand, one way to alleviate the disadvantage raised by the first teacher is to use data logging and mining to collect and analyze students' process data in real time and display the results in a dashboard for teachers to monitor the progress of their students. In a later section, we illustrate this application with some visualizations synthesized from student data we collected from a pilot study. The integration of these infographics into a teacher dashboard has been included as an objective in the next phase of our development.

Finally, we would like to conclude this section by quoting some enthusiastic participants:

- "Students cannot touch the real objects, but they can add thermometers onto the real objects. This is really cool! They can do hands-on investigations even without touching the objects. It would be even better if they can have more interactions with the objects."
- "In real labs, I ask students to do free exploration before giving specific instructions on where to observe and what to analyze. Then we share, as a whole class, what we find. With Telelab, I can do the same thing. They can add thermometers anywhere and share what they find. Some focus on purple colors (cold) and some focus on red colors (hot). From their choices of places, they start to ask questions of why it happens as it shows."
- "With this technology, science learning will involve diverse voices from students, about their houses, gardens, and rivers in their community, to name a few. It's more than extended access through online platforms."
- "I enjoyed that we were able to see the experiments live. I especially enjoyed the water, vinegar, and baking soda lab and the fact that we can use different thermometers [to measure] temperatures!"

VI. Pilot Study

In the summer of 2020, we conducted a pilot study to examine how the Telelab platform might help high school students learn concepts and practices related to chemical reactions in two online chemistry classes with a total of 44 students from different regions of the United States. Among them, 37 consented to be included as subjects in our research (35% of them are ethnic minorities and the gender ratio is close to 1:1). Only their data were included and used in the analyses presented in this paper.

A. Research Hypothesis

Science and engineering practices represent one of the three dimensions of learning mandated by NGSS [40]. Engaging students in science practices is especially challenging in remote learning as science practices often require interactions not easy to realize and orchestrate in online settings. We hypothesize that Telelab can bring to students laboratory experiences that mimic those in the typical physical labs, improving thereby the learning of science practices in distance education.

B. Research Context

Our pilot study was situated in an eight-week online course offered by a reputable online education provider and taught by a high school chemistry teacher, who had six years of in-person teaching experience and two years of online teaching experience at the time of the study, through a combination of synchronous and asynchronous instructions. The teacher did not participate in an earlier workshop described in Section V but received roughly four hours of training on Telelab via teleconferencing prior to the pilot study. The purpose of the online course was to support students to explore the fundamental qualitative and quantitative aspects of chemistry that are typically covered in a high school chemistry course. The exploration included a variety of hands-on experiments in which students were able to share data and ideas with their classmates, with the goal to gain a deeper understanding of chemistry. Students were expected to study for approximately ten hours per week. For the lab part, they were required to use a list of recommended household materials to conduct some simple hands-on experiments. One of the experiments was the chemical reaction between baking soda and vinegar, a safe experiment widely used in chemistry education.

TABLE II
THE DESIGN OF A FOUR-SESSION INTERVENTION BASED ON TELELAB

Session	Mode	Student Activities
Warm-up: Start with a prerecorded experiment	Asynchronous (recorded experiments)	1. Watch a video tutorial about how to use Telelab; 2. Log into Telelab to view and analyze a prerecorded experiment about the reaction between water and washing soda to get familiar with the remote lab environment.
Round-1 Lab: The baking soda and vinegar reaction (energetics)	Synchronous* (live stream)	1. Watch the teacher conducting the experiment in real time; 2. Collect and analyze experimental data through the live stream, paying attention to the energetics of the reaction (i.e., endothermic or exothermic); 3. Ask the teacher questions and discuss the results with classmates through online chat.
Think: Analysis, ideation, and discussion	Asynchronous (recorded experiments)	1. Compile a lab report based on analyzing the collected data; 2. Conceive further experiments to investigate factors that may change the reaction rate (NGSS HS-PS1-5); 3. Post experiment ideas on an internal discussion board and comment on others' proposals.
Round-2 Lab: Factors that affect the reaction rate (kinetics)	Synchronous* (live stream)	1. Watch the teacher conducting the experiment(s) selected from students' proposals in real time; 2. Collect and analyze experimental data from the live stream, paying attention to the kinetics of the reaction (the rate); 3. Ask the teacher questions and discuss the results with classmates through online chat; 4. Complete the final lab report and submit it to the teacher for grading.

* Students who miss a live session can view the recorded experiments and analyze the recorded data to catch up, effectively falling back to the asynchronous mode.

C. Instructional Design

Our intervention was integrated into the online course as four sessions that replaced the baking soda and vinegar experiment originally to be conducted at home. The four sessions, which are described in Table II, varied from four to six hours in total time depending on the commitment of the student. Our treatment specifically targeted student learning outcomes as per HS-PS1-5 of NGSS: "Apply scientific principles and evidence to provide an explanation about the effects of changing the temperature or concentration of the reacting particles on the rate at which a reaction occurs" [40]. Because of its central importance in chemistry, the learning and teaching of chemical reaction kinetics have been extensively studied, with many "alternative conceptions" of students documented in literature [57]. Hypothetically, infrared thermography that visualizes the change of temperature as an indicator of reaction may dispel some of these issues (e.g., misunderstanding of the relationship between energetics and kinetics that drives students to think exothermic reactions occur faster than endothermic ones), but the effect may depend on individual students' understanding about the instructional scaffolding designed to help them connect experimental results with chemistry concepts. Although a macroscopic experiment cannot reveal the particulate picture of the reaction, it can provide indirect evidence to support and guide scientific reasoning with a molecular theory (which is exactly the way chemists think).

D. Experiment Design

Without the thermal camera provided through Telelab, it would have been cumbersome, if not impossible, for students to experimentally explore the concepts related to the NGSS HS-PS1-5 standard at home. Experiments that probe into higher order problems such as reaction rates require much more efforts than just adding baking soda to vinegar and observing the gaseous CO_2 bubbles venting out of the mix, as students must think about how to set up a comparison study to focus on altering one or more variables (e.g., temperature and/or concentration) that may influence how fast the reaction proceeds. In terms of the experiment design, the challenging part is to find a method to measure the rate of reaction with a sufficient accuracy. Counting the bubbles may not be a reliable approach as they form and burst in a fleeting way. True to form, thermal imaging provides a viable indicator for differentiating the subtle changes under different conditions, as the temperature drop caused by the endothermic reaction is a cumulative effect. In other words, a higher reaction rate lowers the temperature even further as more heat is absorbed.

Fig. 7 shows an experiment design enabled by thermal imaging that compares three petri dishes containing the same volume of vinegar heated or cooled to different initial temperatures. The same amount of baking soda is then added to the three dishes at the same time. If the initial temperature had no effect on the reaction rate, the three dishes would exhibit the same degree of cooling as baking soda reacts with vinegar. The fact that the dish filled with vinegar at the highest initial temperature undergoes the largest drop of temperature can only suggest that the reaction occurs at the fastest speed under that condition. Students can also use a similar experiment design to investigate the relationship between the reaction rate and the concentration of vinegar.

VII. Learning Outcomes

In this section, we reported the results about student learning of science practices through Telelab from our pilot study described above. Our assessment focused primarily on student outcomes using three types of data sources: Pre/posttests, lab reports, and data logs.

A. Student Learning of Science Practices

Scientific reasoning is one of the fundamental abilities that students are expected to acquire through science practices. To measure student learning of scientific reasoning, we used the Evidence-Based Reasoning Framework [58] to design pre/posttest items that asked students to predict the effects of increasing the concentration of a reactant (e.g., baking soda) in a chemical reaction (claim) and then propose a hypothetical

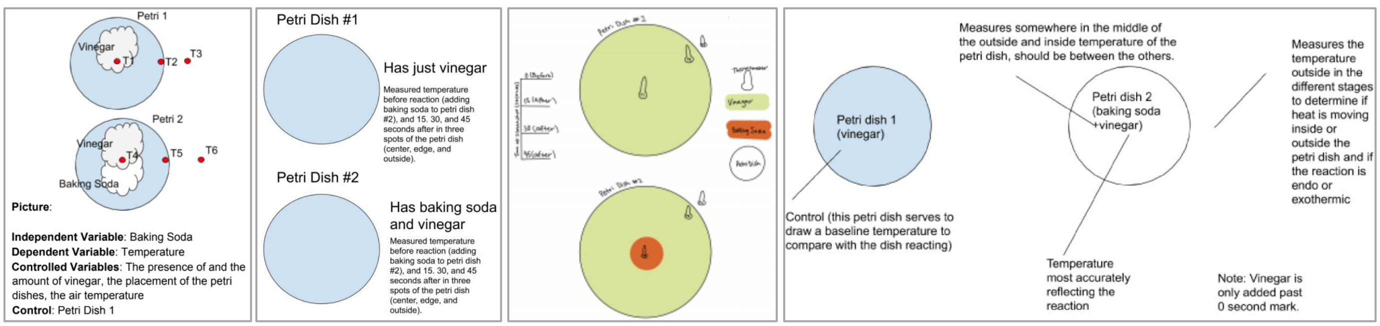


Fig. 9. Four designs of experiments proposed by students to investigate the energetics and kinetics of the chemical reaction between baking soda and vinegar.

TABLE III
Types and Samples of Student Claim–Evidence–Reasoning Performance Revealed in Lab Reports

Type	Claim	Evidence	Reasoning
Observational and contemplative (valid claim and evidence, sophisticated reasoning involving concepts of molecular motions [a])	The reaction that showed the greatest change in temperature was the reaction that contained the heated vinegar.	The temperatures measured and recorded during the experiment show that the dish with the refrigerated vinegar started at 13.00°C and dropped to 12.46°C. Also recorded was that the dish containing room temperature vinegar started at 25.08°C and dropped to 20.36°C. Lastly, the recorded temperature of the dish containing heated vinegar started at 46.72°C.	The record temperatures show that petri dish 3 had the largest change in temperature. Petri dish 3 dropped 11.35°C, while petri dish 2 dropped 4.72°C and petri dish 1 dropped 0.54°C. One possible reason for these findings is that the molecules in the hot vinegar are moving faster than the molecules in the cold or room temperature vinegar. If the molecules are moving faster, then the rate of reaction increases because the molecules of baking soda and vinegar are bumping into each other sooner and at a more frequent rate. When the rate of reaction increases, that means that the rate of heat and energy absorption also increases causing a more drastic decrease in temperature.
Observational (valid claim and evidence, poor, wrong, or no reasoning [b])	Dish 3 had the greatest temperature change.	T1 had a difference of 1.27, T2 had a difference of 4.25, and T3 had a difference of 14.7.	I believe that the reason the cold and room temp vinegar did not decrease by 5 or more was because the temperature of the reaction stops after a certain temperature and before it stops it slowed down which caused it to not have a large change in temperature like the hot temp vinegar.
Problematic (wrong claim, valid evidence, erroneous reasoning — indicating misconception)	The chemical reaction released energy, therefore making it an exothermic reaction.	During the experiment the core temperatures of each petri dish dropped considerably. In petri dish #1, the temperature started at 13.09°C and ended at 12.61°C (ended meaning 10 seconds after the reaction began). Petri dish #2 started at 25.32°C and ended at 21.26°C. Petri dish #3 started at 46.85°C and ended at 35.19°C. Even the room temperature, measured by the 4th thermometer, dropped a bit in temperature even though it was a bit away from the occurring reactions in the petri dishes. It started at 27.44°C and ended at 26.98°C. The drop in temperature proves that the energy in this chemical reaction was released and not absorbed, making this an exothermic reaction.	The temperature drop in the petri dishes shows that the energy was released. The experimental question was “Does the chemical reaction absorb or release energy?” This question was answered by the data that came as a result of the chemical reaction between the three different temperature vinegars mixing with the baking soda in the petri dishes. The exothermic reaction that occurred is the release of energy. The internal temperatures of the petri dishes dropped meaning that the heat energy had to have been released. This experiment had a chemical reaction that released energy, therefore making it an exothermic reaction.

[a] Scored 4–6 on the Conceptual Sophistication Scale according to the Evidence-Based Reasoning Framework [58].
[b] Scored 0–3 on the Conceptual Sophistication Scale.

experiment to collect evidence and use reasoning to back their predictions or claims. Using a coding rubric, multiple researchers in our team scored the results to ensure the interrater reliability. A two-tailed paired samples t-test analysis (α=.05) shows improved scientific reasoning ability of the participants, indicated by the difference between the posttest results (M = 3.593, SD = 1.056) and pretest results (M = 2.370, SD = .905). The difference was significant $t(26) = 8.7597$, $p < .00001$, with a large effect size (d = 1.35).

To promote epistemic agency [59], students were also challenged to propose their own experiment designs that were reviewed by their peers and the teacher during their reflection about the previous experiments and their joint planning for the next ones. In their designs, they described how they would set up a comparison experiment, what the dependent/independent /controlled variables would be, and where they would place thermometers to capture the expected results as they emerge. Fig. 9 shows some sample designs from the students. These artifacts clearly indicate a high degree of understanding about the essence of experimental design of their creators (e.g., using the terms "independent," "dependent," and "control variables" to correctly describe the concepts related to the chemical reaction under investigation).

Like in any lab, students were required to compile a lab report to address a series of driving questions. In our pilot study, these questions were scaffolded using the claim–evidence–reasoning (CER) framework [58] to also provide embedded assessment of students' scientific reasoning abilities. The lab reports can be used to verify students' observations of remote experiments and gauge their abilities to explain the experimental results based on the evidence collected through Telelab. As expected, *all* students described the phenomena they observed in the remote experiments to a satisfactory degree. Their thermometers were placed in the right places and recorded correct temperature data. Hence, the live Telelab session succeeded in ensuring 100% student compliance with lab procedures. While this was an impressive accomplishment, not all students made the right claims or reasoned correctly. We identified three different types of CER performance, shown in Table III with samples from the pilot study. Importantly, students' CER pieces show how their performance might meet the requirements of NGSS HS-PS1-5, which requires using evidence and principles to explain how the rates of chemical reactions can be changed by factors such as temperature and concentration. Among 34 submitted lab reports, there were 13 that can be categorized as observational and contemplative, 15 as observational only, and 6 as problematic. Contemplative students inclined to invoke abstract concepts of molecular motions (such as the collision theory for chemical reactions) in their reasoning, while others tended to use only phenomenological knowledge. As shown in Table III, problematic reasoning of some students might have arisen from misconceptions about energy absorption vs. release, or endothermic vs. exothermic processes, that are commonly encountered in chemistry education [60].

TABLE IV
ENGAGEMENT AFFORDANCES MENTIONED BY STUDENTS

Affordance	Description	Students (out of 31)
Live experiments	Observe reactions occurring in real time while listening to the teacher's instruction what to pay attention to and how to analyze the data.	26
Scientific instruments	Visualize the invisible thermal energy changes in reactions with remote thermography and use the graphing tools to analyze the data.	22
Social interactions	Communicate with the teacher and other students through online chat.	17

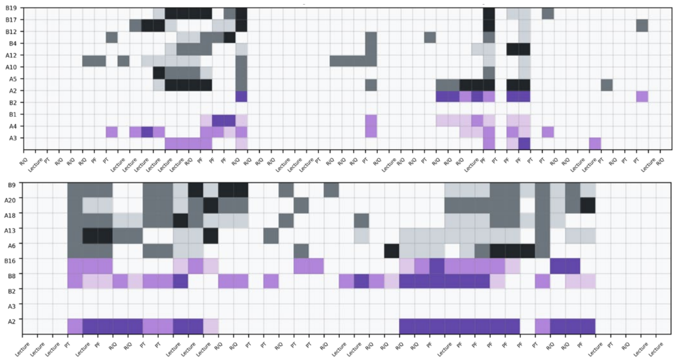
B. *Student Engagement Measured by Exit Survey*

We administered an exit survey to get a sense about students' experiences with and opinions about Telelab. The results revealed three key affordances of Telelab that students found engaging: live experiments, scientific instruments, and social interactions. All 31 respondents were engaged by one or more of these affordances. Table IV shows the number of students who mentioned each affordance when answering questions about what features of Telelab they found enjoyable. The following are some excerpts from their specific responses:

- "I thought it was really cool that although we are all so far apart in distance, we were all able to participate in the live experiment together in real time. I liked the thermal cameras since we were not able to be there in person it gave us a nice visual representation of what was happening during the experiments."
- "[I like] being able to do the whole lab, instead of sharing steps with partner, [and] seeing how reactions works."
- "I liked being able to discuss the reaction live and comparing data [and] the live temperature reading and screenshot feature."
- "[I like] seeing the temperature change with the IR camera and seeing the reaction happen live."
- "I enjoyed seeing the video of what was happening in the reaction and being able to see the graphs of the reaction at the same time."
- "[I like] being able to participate in a lab as a class [and] listen to commentary and additional information from my teacher."
- "[I like] being able to watch in real time as a reaction is taking place [and] getting to chat and talk with the teacher and discuss real-time results like you would in an actual classroom."
- "I learn best from person to person communication and example, so I enjoyed the discussion and the fact that I was able to ask questions in real time. I also enjoyed that Telelab had so many options and resources for how I was collecting my data."
- "[I like] the opportunity being able to work as a class despite the lab being a virtual experience [and] my ability to control things such as live graphs of the data I was collecting."

C. *Behavior Analysis Using Interaction Data*

We added a data logger in Telelab to capture student actions in the background while they were interacting with the software and communicating with other participants. These digital



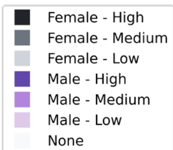


Fig. 10. Heat maps that represent student–lab and student–teacher interactions in two live sessions from two online classes. A darker color indicates a higher frequency of interactions (the white color stands for no recorded action during that time interval). The instruction stamps include lecture, prompt to type (PT), prompt to interact with a feature (PF), and response to a question (RQ).

footprints of students in Telelab were transmitted to the cloud server and stored in a database, providing "stealth assessment" for tracking the progress of each student or a group of students without disrupting their learning [61]. As an extension of our earlier work in this direction [62]–[65], we are particularly interested in examining how students respond to instruction, practice science investigations, and self-regulate their learning in Telelab through analyzing and visualizing these rich data.

Fig. 10 uses heat maps to represent the frequencies of students' multimodal interactions with main features of Telelab as a result of teacher instruction in live experiments conducted in two online classes. Each row indicates one student's interactions against the teacher's instruction stamps marked on the horizontal axis. The darkness of color in each grid cell represents the total number of interactions recorded within 60 seconds after each instruction stamp. On both the interaction heat maps, there are approximately two clusters. In the upper one of Fig. 10, the first cluster appeared right after the sixth instruction stamp of lecturing. This is expected as the online class started in a Zoom room and the students were redirected to Telelab at the end of the Zoom meeting. The second cluster emerged in the second half of the session after the teacher prompted students to use Telelab for the second experiment. Similar patterns can also be observed in the lower image of Fig. 10. Interestingly, the results of these two classes revealed that the female students were generally more active in responding to instructions than the male students. But the responsiveness of the male students appeared to increase when prompted to use the tools in Telelab.

Heat maps like Fig. 10 show the time evolution of the overall activeness of individual students. But they disclose nothing about exactly what students did in an experiment. To extract those details, we needed to track down their actions in the experimental space on concrete, meaningful objects. In the pilot study about chemical reactions, the thermometers that students added to their own thermal images to collect temperature data are such objects. The positions of the thermometers and their

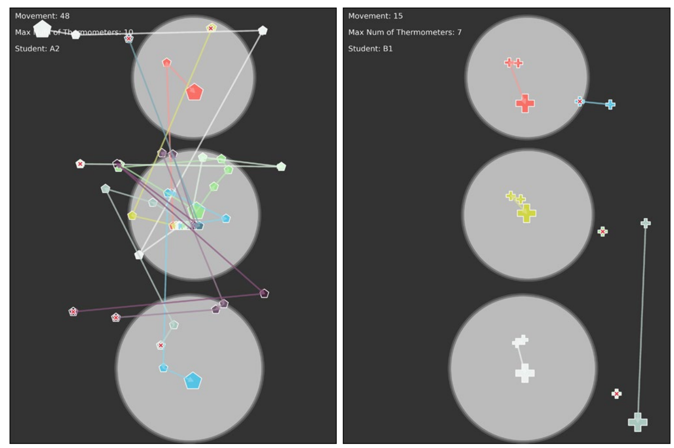


Fig. 11. Different behaviors of using thermometers observed in the logged data: inquisitive (left) vs. determined (right). The large gray circles represent the three petri dishes shown in the thermal image (the dishes have the same size in reality but are somehow distorted in the image because of their differences in the relative distance to the lens of the thermal camera). The large symbols represent the final positions of the thermometers that still remained towards the end of the live experiment. The lines of the same color represent the trajectory of a thermometer movement during the experiment. The small cross signs represent the last seen positions of the thermometers that were deleted (students tended to add more thermometers than they needed and had to remove the extra ones when they plotted the data in a graph for clarity).

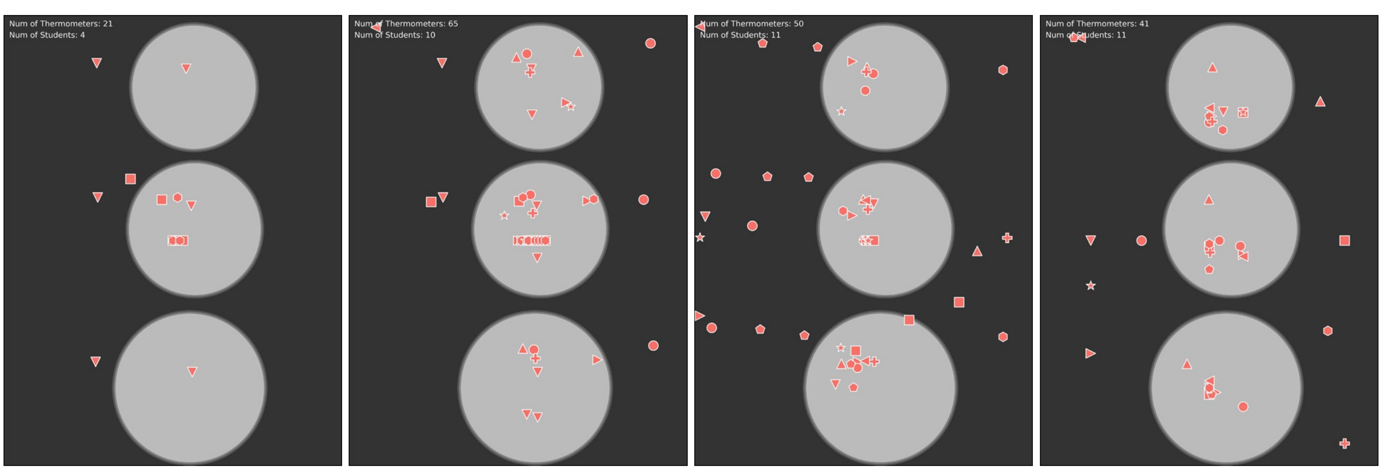


Fig. 12. Four herd diagrams show how an online class of students used the thermometer tool in Telelab over time. The behavior of the "herd" eventually converged to an expected pattern, which shows three clusters of thermometers on top of the petri dishes and a random distribution of the fourth thermometer used to monitor the ambient temperature (it doesn't really matter where the fourth thermometer is as long as it is outside the dishes). In each diagram, the thermometers of each student are represented by a type of symbol.

changes over time implicate students' understanding of the experiment and their strategies to explore the underlying science such as the examples shown in Fig. 11. The two images of Fig. 11 portray two different behaviors of using thermometers during a remote experiment. The number of thermometer moves may be used to characterize a student's behavior. Students who logged more moves may be considered more inquisitive as they explored the problem space more thoroughly. Irrespective of the numbers of thermometers the students added and the times they moved the thermometers, all students eventually placed one and only one thermometer anywhere above each petri dish and used the fourth to monitor the ambient temperature, as guided by the teacher. These process data can also be aggregated to generate a *herd diagram* for visualizing the behavior of the whole class during a remote experiment (Fig. 12). We refer to this kind of point cloud visualization as the herd diagram as it shows the dynamic behavior of a group of students in a given problem space where they explore with or without the guidance of an instructor. Herd diagrams allow researchers to use clustering to identify subgroups of students or actions that may need to be targeted with instructions specific to those subgroups. If used in a dashboard, a herd diagram can provide an intuitive representation to help the teacher spot students who may have gone astray and respond accordingly.

VIII. Discussion and Conclusion

This paper presents a vision of remote labs 2.0, proposes a technical framework for implementing it, and describes preliminary results from pilot testing a prototype with teachers and students in online classes. This foundational work paves the road to the ultimate goal of building a cyberinfrastructure for next generation remote labs that supports teachers to deliver authentic laboratory experiences to students through the Internet and, in so doing, strive to help them achieve the objectives of science learning through inquiry in online settings. Although the technology was conceived as a timely response to the COVID-19 crisis, it has the potential to grow into a valuable addition to distance education in the long run.

A significant advantage of remote labs 2.0 is that teachers do not need to rely on a particular lab provider to run a remote experiment for their students. All they need to do is to purchase the necessary sensor and actuator hardware from a third party (e.g., the FLIR ONE thermal camera featured in this paper), download the driver apps (e.g., the Infrared Explorer used in our pilot study), and learn how to use the apps to stream sensor data to the cloud and, as an option, allow remote controls by students through the Internet. Once the initial steps are completed, they can create their own remote labs and operate them on their own schedules freely. In the case of infrared thermography, using the technology is as simple as using a digital camera to take pictures or record videos—no complicated setup is required to collect temperature data with this noncontact sensing technology. In applicable content areas, such as heat transfer (conduction, convection, and radiation) widely taught in schools, teachers can apply this technology to transform an existing lab into a remote one by simply adding a thermal camera as an additional tool for data collection.

Our implementation of remote labs 2.0, Telelab, were well received by teachers and students. Students' exit surveys indicated that they were engaged by one or more of its three affordances: live experiments, scientific instruments, and social interactions. Pre/posttests results show that students significantly improved their evidence-based reasoning skills—an important outcome expected in learning through laboratory experiments. Students' lab reports shed light on how they used evidence collected from Telelab to reason and explain the results of the remote experiments about chemical reactions. The logged process data about students' interactions with the software and with others in the Telelab environment confirmed their active engagement throughout the live experiments. It is remarkable that all of the students collected the correct data for investigating the temperature dependence of reaction rate, possibly through the real-time social interactions facilitated by Telelab in sync with the ongoing experiment. In a sense, Telelab provides a platform for teachers to create an atmosphere of participation to concentrate students on science experiments for fostering online inquiry-based learning.

In terms of conceptual learning through inquiry with remote labs, it is noteworthy that the Telelab experiences spurred some students to apply sophisticated molecular reasoning to connect the dots observed in the remote experiments that are related to complicated concepts in chemical energetics and kinetics, thus attaining the pertinent performance expectation set forth in NGSS. The experimental and analytical performance of these students were likely original as virtually none of them had any prior knowledge and experience in infrared thermography and its applications in chemistry.

A major drawback of the pilot study reported in this paper that may weaken our conclusion is the lack of a comparison with a traditional hands-on lab on the same topic of chemical reactions using a local version of thermal imaging. Because of the COVID-19 restrictions, it was not feasible for us to administer quasi-experimental studies that involve implementations of local labs in schools to establish a baseline for comparison. We plan to follow up with such studies in the future when the situation improves.

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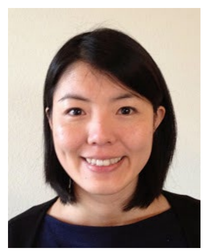

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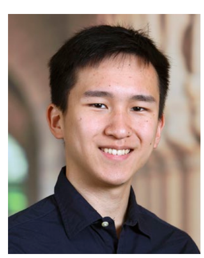

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