

Remote Labs 2.0 to the Rescue

Doing science in a pandemic

Abstract

Lab activities provide an important venue where students learn science and engineering practices and acquire conceptual understanding through inquiry. However, the COVID-19 pandemic has forced labs to cancel or reschedule, leaving teachers with no options except alternatives such as virtual labs. Remote labs, where real experiments are carried out with authentic scientific equipment, provide another compelling option, but they have had little practical impact so far due to their centralized nature, which prevents them from fulfilling experiment requests by large numbers of students simultaneously. Based on a distributed framework dubbed remote labs 2.0, we present an instructional model for teachers to create and run their own remote labs and involve students in remote inquiry. Preliminary results showed that remote labs 2.0 could engage students in science learning and improve their conceptual understanding.

Introduction

Laboratory experiences are a staple of science education (National Research Council 2006): Not only do they provide students with an avenue to acquire authentic skills needed for scientific research, referred to as science and engineering practices by NGSS, but they also allow students to go beyond rote memorization of facts to deepen their understanding of science through inquiry.

Unfortunately, with schools struggling to deal with the COVID-19 crisis, in-person labs are not a priority for many teachers. A popular alternative is virtual labs (e.g., Vasiliadou 2020). But virtual labs cannot provide complete laboratory experiences. A better option is remote labs (e.g., Ma & Nickerson 2006), where real experiments are carried out. Compared with virtual labs, remote labs preserve some key nature of experimental science, such as uncertainty and errors.

However, previous remote labs are based on a somewhat centralized model, where experts design and conduct experiments of a certain type with prescribed user options (e.g., Sauter et al. 2013). Such centralized remote labs didn't achieve widespread application because they offer little room for teachers and students to choose their own topics and subjects for investigation. It is also difficult for students to propose their own hypothesis, design new experiments with their teachers to test their hypotheses, and then analyze the data collected from those experiments.

The status quo calls for a distributed model of remote labs, where students regain their autonomy over inquiry and teachers reclaim their mentorship. We refer to this new model as remote labs 2.0. Similar to the transformation of the Web from 1.0 to 2.0, which democratized content creation, this new technology allows teachers to create their own remote labs and share with their own students (Figure 1). As such, they promise to enrich experimental science on the Internet, providing an important cyberinfrastructure for science education from a distance.

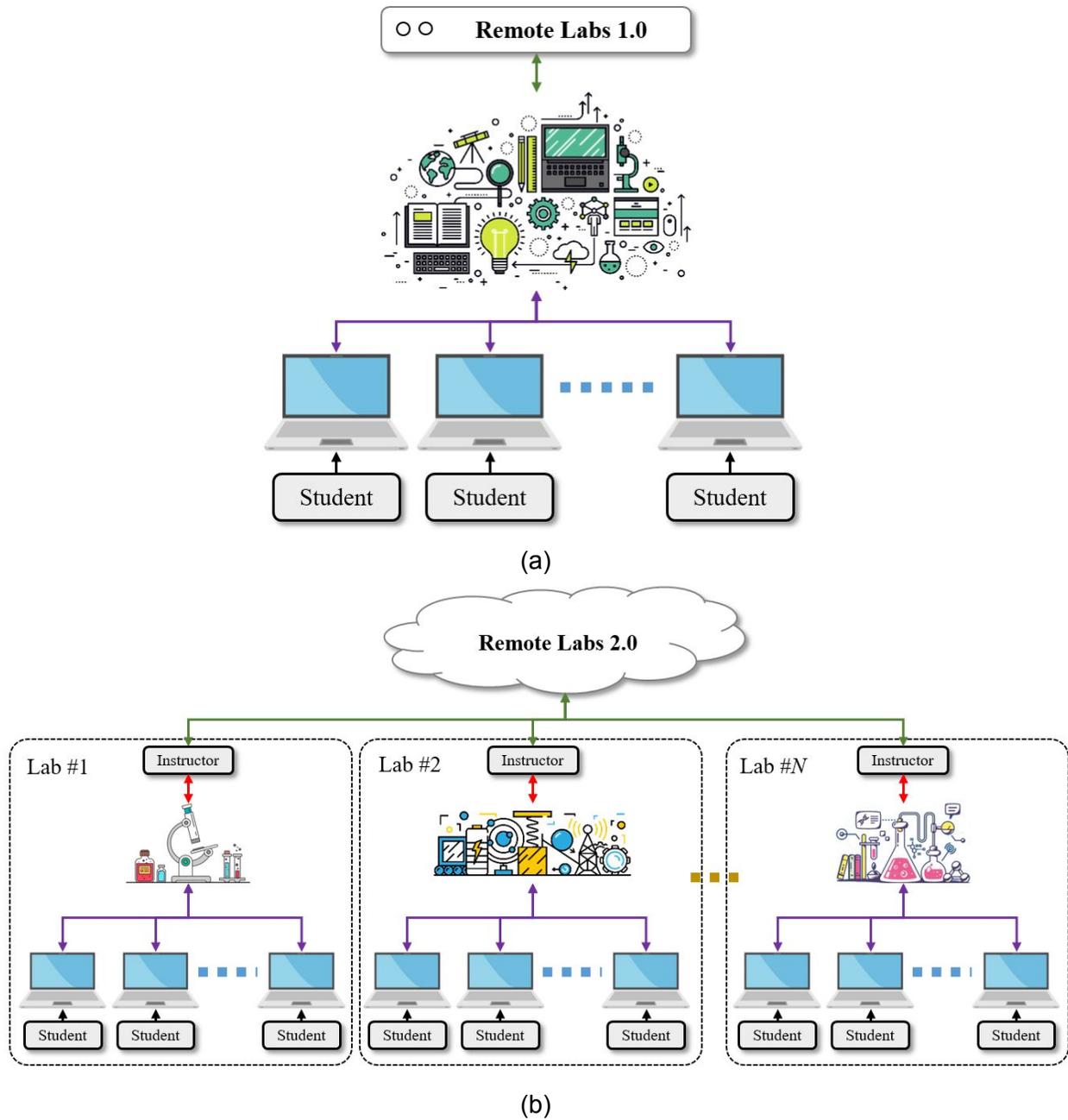


Figure 1. Compared with remote labs 1.0 (a), where a single expert provider serves all students, remote labs 2.0 (b) support science teachers to run their own lab sessions for their students.

An Implementation of Remote Labs 2.0

Telelab is our implementation of remote labs 2.0. The platform consists of sensors that collect data, smartphone apps that transmit data and videos from anywhere, and a Web app that provides a user interface to view, analyze, and control remote experiments. Based on this platform, any science teacher can broadcast their own experiment to any number of students, who will not only observe the experiment unfold over a live stream of images but also receive real-time sensor data for independent analyses. The platform also allows teachers to record experiments along with sensor data and upload them to an online repository, so students who miss the live sessions can also catch up by working with these pre-recorded experiments. As a video- and data-streaming platform, Telelab allows teachers to conduct experiments the same way they would in a physical classroom under normal circumstances, which makes for a comfortable transition to remote labs.



Figure 2. A typical Telelab setup consisting of a smartphone, a sensor module attached to the phone, a phone stand, and the experiment in question. This image shows a demonstration of condensation heating using a piece of paper over a cup of water (Anonymous 2011).

In the following sections, we will demonstrate how Telelab can assist remote teaching with three common examples. For all examples, low-cost infrared (IR) imaging (Figure 2) is used as a high-throughput sensor to collect large quantities of temperature data in real time. Note that Telelab is not limited to only applications of IR imaging.

Basic Live Session: Light Absorption as an Example

Students are familiar with the phenomenon of darker objects often being hotter in the sun. To facilitate a structured inquiry (Martin-Hansen 2002) into this phenomenon, the teacher simply prints out varying shades of gray on a piece of paper, mounts the smartphone above the paper, and connects the IR camera to the phone, such that the paper is at the center of the view window. Using the Infrared Explorer, a supporting app developed by us, the teacher then connects to a Telelab live room, where the thermal image of the paper and the temperature data will be automatically streamed to the live room, and students who connect to the live room using their own devices can both view the thermal image and analyze the temperature data in real time (Figure 3).

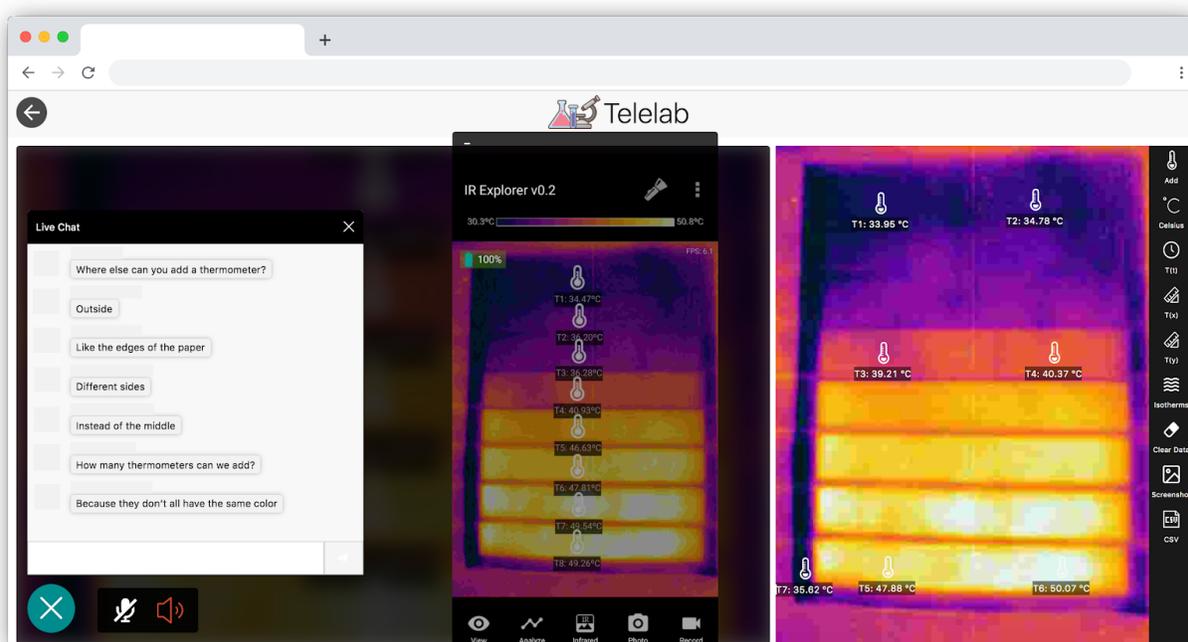


Figure 3. The Telelab live room interface. Students can see a live stream of their teacher's app screen (middle) and analyze data on their own screen (right), while teachers can facilitate discussions using the chat function (left).

Each student can add their own “thermometers,” which will display real-time temperature readings on the thermal image. A live stream of the teacher’s app screen allows the teacher to demonstrate how to use the thermometers and graphs to analyze the ongoing experiment. Using the built-in chat function, the teacher can invite students to explain their thermometer placement or determine whether measuring the ambient temperature is necessary. The teacher can also follow the Predict-Observe-Explain (POE) framework (White and Gunstone 1992) by asking students to predict what they will see when the paper is moved into the sun.

As sunlight shines onto the paper, students will observe a color gradient from blue-purple to yellow-orange in the thermal image, indicating that surfaces with darker shades of gray have higher temperatures. If students place a thermometer on each gray strip and enable the graphing function, they will also see a gradual rise in temperature as time passes (Figure 4). Together with numerical thermometer readings, these different visualizations provide multiple representations of the same data, which helps students learn complex, multifaceted concepts (Ainsworth 2008).

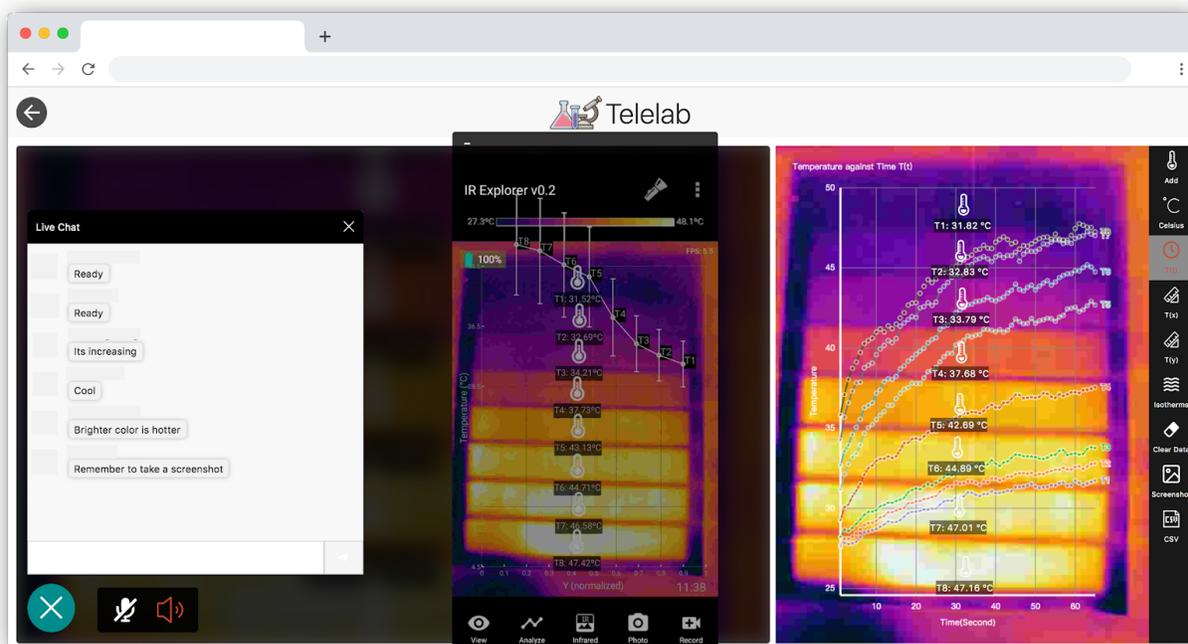


Figure 4. Different representations of the same temperature data from the light absorption experiment: The student screen (right) shows a thermal image overlaid with thermometer readings and a temperature versus time graph, while the teacher screen (middle) shows a temperature versus y-axis graph.

As the last step of the POE framework, students use the screenshot function to collect both qualitative and quantitative evidence for their lab reports and analyze it to determine whether darker colors lead to higher surface temperature in the sun. The teacher then provides a microscopic explanation of how light energy is converted to thermal energy. Finally, students use the Claim-Evidence-Reasoning (CER) framework (McNeill and Krajcik 2011) to synthesize their findings in their lab reports.

Remote Inquiry: An Instructional Model for Science Investigations Online

Take the light absorption experiment above as an example. After the main investigation, one student may be curious how different colors absorb light energy, while another may wonder if different materials of the same color absorb the same amount of light energy, and they may each propose a different hypothesis for their teacher to test. Traditional physical labs afford such helpful classroom interactions that allow students to take ownership of their knowledge building, develop their epistemic agency, and become “doers of science” (Miller et al. 2018). Part of these activities can be facilitated with remote labs 2.0 run by teachers.

Designed to exploit the affordances of Telelab, *remote inquiry* (Figure 5) is an instructional model that reinstates beneficial classroom interactions in a remote setting and supports all levels of inquiry (verification, structured, guided, and open) - especially guided and open inquiries, where students design the experiment procedures to be conducted remotely by a teacher or robot. As the teacher selects student-proposed experiments, performs them, and shares them with the whole class, students have the opportunity to learn from and build on each other’s ideas. This type of *collective inquiry* (Slotta et al. 2018) is a hallmark of laboratory experiences, which can be realized remotely via Telelab.

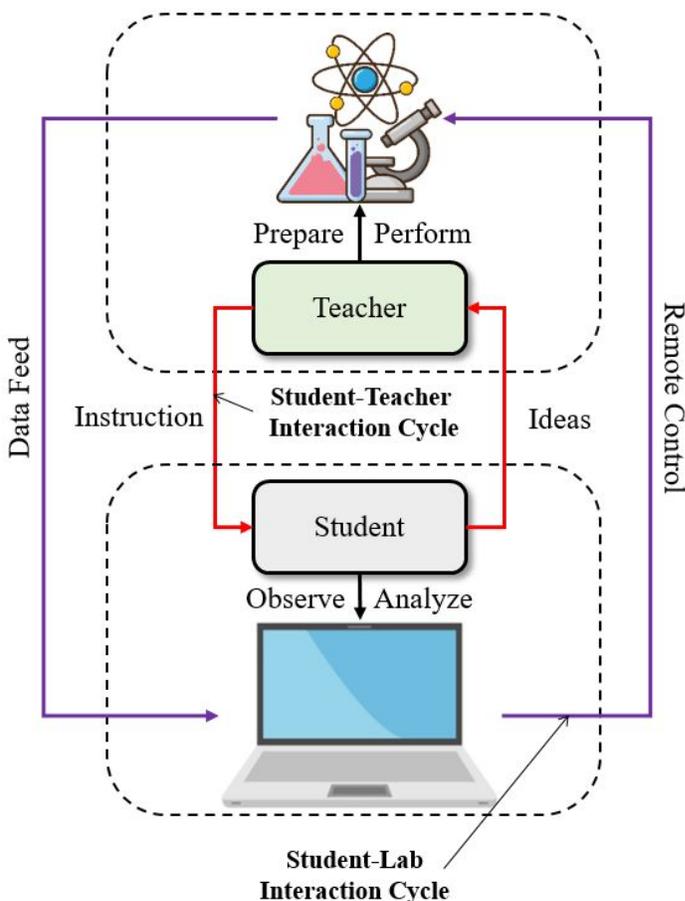


Figure 5. The remote inquiry instructional model comprises a few key elements: 1) The teacher delivers inquiry instructions to the students; 2) the students present experiment ideas and designs to the teacher; 3) the teacher prepares and performs the experiment; 4) the students can also remotely control the lab equipment; 5) the students receive data feed from the remote labs; 6) the students observe and analyze the data feed, after which they re-engage with their teacher to initiate a new inquiry cycle.

Multiple Inquiry Cycles: The Reaction between Baking Soda and Vinegar as an Example

The baking soda and vinegar experiment is a widely-used chemical reaction that feeds into rich discussions about thermodynamics and chemical equilibrium, and it often takes not one, but multiple inquiry cycles with increasing depth and freedom for students to fully explore and explain the phenomena. With Telelab, chemistry teachers can kick off the instructional sequence with a structured inquiry of exothermic versus endothermic reactions and ease into a guided inquiry into key factors that affect reaction rate.

To set up the first inquiry cycle “How do we know if a chemical reaction absorbs or releases energy?”, the teacher fills two petri dishes with vinegar, mounts the smartphone and the IR camera the same way as described in the previous examples, and starts the live stream by asking students to predict how the temperature within the petri dish will change when baking soda is added to vinegar.

When the teacher adds baking soda into one of the dishes, students will observe a drastic color change from yellow-orange to blue-purple on the thermal image, indicating a decrease in temperature (Figure 6). Students then collect and analyze evidence including thermal images, a graph of temperature versus time, and thermometer readings, to determine whether the reaction is exothermic or endothermic. The teacher then provides a microscopic explanation of energy changes during chemical reactions and introduces key concepts such as bond energy, so students can use the CER framework to synthesize their findings from this inquiry cycle.

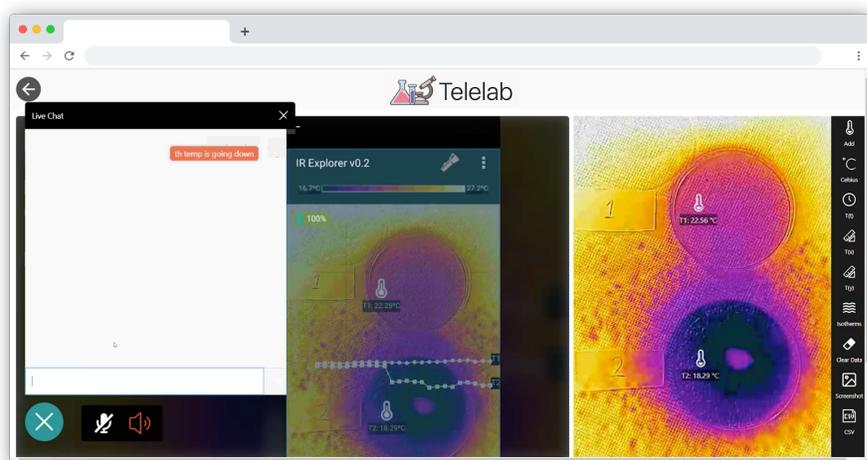


Figure 6. Two petri dishes of vinegar; baking soda is added to the bottom dish. This represents the first inquiry cycle, where students investigate whether adding baking soda into vinegar is exothermic or endothermic.

After observing a temperature change during a chemical reaction in this first experiment, the teacher can direct students to think about the reaction rate, which is represented by how fast the temperature drops, and initiate a new guided inquiry by asking students what factors they think may affect the reaction rate. Students may come up with reasonable guesses such as temperature or concentration, or they may suggest irrelevant factors such as volume. Note that both are worth exploring and enable science learning; the only limitation is the class time available.

The teacher can let students vote on the factor they want to explore the most. Assuming students vote for concentration, they now need to design an experiment that can answer the question “How does concentration affect reaction rate?” The teacher can guide students through the experiment design process with a template provided in the student worksheet (see “On the

Web”) and explain key concepts such as independent variables, dependent variables, and controlled variables.

After students submit their experiment designs, the teacher can either provide feedback on their designs directly or assign peer feedback. Finally, the teacher selects the best experiment design to carry out live for the students, considering criteria such as feasibility, robustness and rationale of data collection. The rest of the inquiry cycle again follows the POE framework, where the teacher asks students to predict how different concentrations of vinegar will affect the degree of temperature drop once baking soda is added, observe the experiment while collecting data using the built-in functions (including thermometers, graphs, and screenshots), and explain the relationship between concentration and reaction rate using the collected data as evidence (Figure 7).

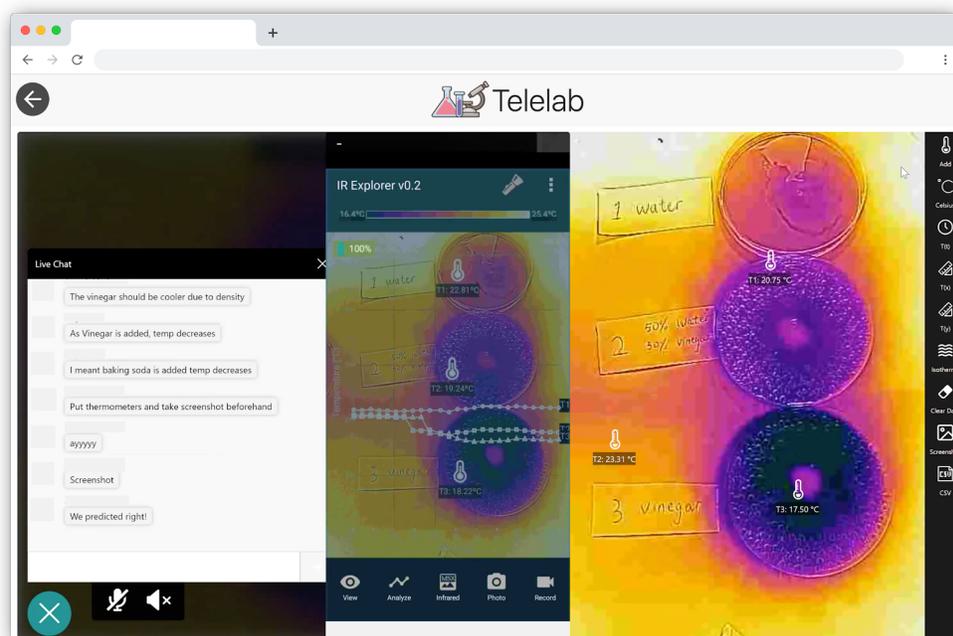


Figure 7. Three petri dishes of vinegar with increasing concentration from top to bottom; baking soda is added to every dish. This represents the second inquiry cycle, where students ask new questions (such as “How does concentration affect reaction rate?”) based on their conclusions from the first inquiry cycle and design new experiments.

Additional advantages of remote inquiry include that teachers can tailor their instruction to the specific needs of their students. If students are unfamiliar with chemical reactions, the teacher can add a structured inquiry at the beginning to investigate the characteristics of a chemical reaction, before shifting the focus to energy change during a reaction. On the other hand, the teacher can also increase the challenge by appending more open-ended inquiries that allow students to explore additional factors that might affect reaction rate. Note that the authenticity of real experiments also adds to the richness of the discussions possible. For example, when setting up the first experiment, the teacher may notice that the two dishes of vinegar have

different initial temperatures, which is a great opportunity to introduce the phenomena of evaporative cooling and vapor pressure lowering to students.

Authentic Scientific Instruments for Deepening Remote Inquiry

Inquiry-based learning works best when the phenomena under investigation are familiar and relevant to the students, but students sometimes lack tools that can probe deeply into those phenomena. One such example is the question “Why does metal feel colder than wood?”, an everyday phenomenon that is deceptively difficult to explicate because it involves the concept of thermal conduction and is further complicated by the mechanism of how the human body perceives temperature.

A lab in a cash-stripped school may not have the proper equipment to measure and collect the data needed for this inquiry, but those underprivileged students can now use Telelab to investigate this question and dispel misconceptions around it.

In-Depth Inquiry: Two Thumbs Up as an Example

This investigation uses a variation of guided inquiry, where the experiment setup remains the same, but students iteratively collect more data. To set up, the teacher places two rulers (one wooden and one metallic) on a flat surface (ideally insulating, to minimize interference from the environment) and mount the smartphone and sensor directly above. The first inquiry cycle begins with the teacher probing the prior knowledge of students with the question: “What do you already know about thermal conduction?” Students predict which material is a better conductor, as well as the temperature along the rulers as the teacher initiates thermal conduction by pressing on the rulers with two thumbs. Thermal imaging will show heat traveling a longer distance through the metallic ruler than the wooden one.

After students conclude that metal is a better conductor, the teacher initiates a second inquiry cycle to connect this new knowledge to the original phenomenon of metal feeling colder by prompting students to collect more temperature data from the same experiment, with options including the thumbnails, the parts of the thumbs touching the rulers, and the parts of the rulers touching the thumbs (Figure 8a). Thermal imaging will show heat dissipating faster along the metallic ruler and localizing at the contact area of the wooden ruler, as well as the thumb having a lower temperature after touching the metallic ruler (Figure 8b). Through Telelab, students are able to capture evidence including instantaneous surface temperature, which would have been nearly impossible to measure without an IR camera, and use them to establish a chain of reasoning that leads them to the conclusion that the metal feels colder because metal absorbs heat from the thumb faster due to its higher conductivity.

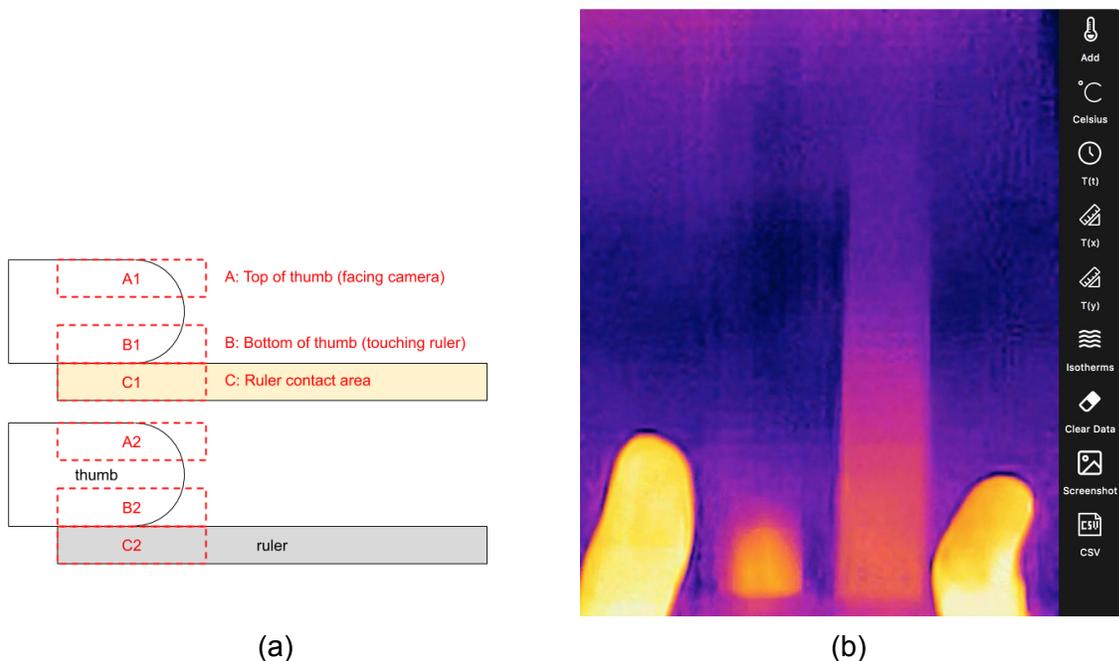


Figure 8. (a) A schematic diagram showing the different areas, the temperature of which students can choose to measure; (b) a thermal image showing the instantaneous temperature along two rulers and the two thumbs that had just been in contact with the rulers (right).

Preliminary Results from Online Classes

Early teacher users of Telelab have confirmed its usefulness. In the own words of one teacher, “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.”

We also conducted a pilot test that involved 44 students in two online high school chemistry classes, using the baking soda and vinegar experiment as a testbed. Pre/post-tests showed an improvement in students’ conceptual understanding of chemical reactions after the Telelab intervention (Anonymous 2020). When asked what they enjoyed the most about remote labs in exit surveys, students identified scientific instruments, social interactions, and live experiments as the three engaging factors. Below are some selected quotes from the exit survey:

- “[The thermal cameras] gave us a nice visual representation of what was happening during the experiments.”
- “[I enjoyed] making observations and reflecting on my thoughts with the evidence gathered from the lab.”

- *“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.”*
- *“[What engaged me the most was] being able to interact and post our things/answers in the chat, as well as interacting with others and hearing what they think.”*
- *“I was engaged by the questions being asked. Especially when it was other students asking questions that I could follow along with as often it was the same questions I was thinking and therefore wanted to pay attention to.”*
- *“The experience of observing all the experiments live was quite fascinating.”*

In addition to researching the effectiveness of remote labs 2.0 in comparison to their local counterparts, we are also expanding the types of sensors supported by Telelab, improving the user experience, and designing more lesson plans to help teachers adopt remote labs. Albeit an emergent response to the pandemic, remote labs are not just a makeshift necessitated by an exigency, but a paradigm shift that unlocks opportunities for science teachers everywhere to deliver authentic lab experiences to their students - even beyond the pandemic.

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