A New Type of Interactive Video for Physics Education

Rundong Jiang, Xiaotong Ding, Shannon H. Sung, Dylan Bulseco, and Charles Xie, Institute for Future Intelligence, Natick, MA
Chenglu Li, University of Florida, College of Education, Gainesville, FL

Video analysis tools such as Tracker[1] are used to study *mechanical motion* captured by photography. One can also imagine a similar tool for tracking *thermal motion* captured by thermography. Since its introduction to physics education,[2] thermal imaging has been used to visualize phenomena that are invisible to the naked eye and teach a variety of physics concepts across different educational settings.[3–11] But thermal cameras are still scarce in schools. Hence, videos recorded using thermal cameras such as those featured in "YouTube Physics"[12] are suggested as alternatives. The downside is that students do not have interaction opportunities beyond playing those videos.

A simple experiment[13] may illustrate our point: Fig. 1(a) shows a small dish filled with hot water placed in a large dish filled with cold water. A thermogram video only shows that the color contrast between the two dishes diminishes over time due to thermal equilibration [Fig. 1(b)], but what if students can also measure the temperatures of objects in the video [Fig. 1(c)] and plot a graph to visualize their changes [Fig. 1(d)]? In this way, students have more to explore. For example, it may be easier for them to notice that, while the rate of temperature change measured by T1 (the hot water) decreased over time, the temperature measured by T2 (the cold water) increased initially but then decreased, suggesting the existence of heat exchange with the environment (i.e., a third party) in both dishes. This is easily overlooked by students in an idealized textbook model that includes only two objects in contact.

The student experiences described above are possible because they can observe not only the video (pixels) but also the graph (data). In the case of thermography, the pixels come from both visible and infrared light cameras, and the data come from tens of thousands of microbolometers built in a thermal camera.[14] When the data are used to augment the pixels, a new type of video that is unprecedentedly interactive is created.

In this paper, we present Telelab as a free and open-source reference implementation of this new type of interactive video. Telelab is a cloud platform that we have developed to allow anyone to host, stream, analyze, and share such interactive videos in ways similar to YouTube. With Telelab, students and teachers can explore hundreds of interactive videos about physics phenomena related to energy, heat, light, phases, etc.; observe the phenomena through both a regular camera and a thermal camera; analyze temperature data across time and space; and connect physics concepts to real life through inquiry. We present three experiments related to light–matter interactions to demonstrate how this new medium may be used in the classroom, and how it can support citizen science by extending scientific inquiry from the classroom to everyday life.

There is invisible light on the other side

In 1800, William Herschel accidentally discovered infrared radiation when he let a sunbeam shine through a prism onto a table and noticed that the temperature increased beyond the red end of the rainbow spectrum produced by the prism. Physics teachers have since improved Herschel's original experiment and devised more ways to detect infrared radiation,[15,16] but the variations either require elaborate setup or lack visual impact. A YouTube video used to be the only alternative, but students can now analyze Herschel's experiment on their own with an interactive video.[17]

To produce this interactive video, we put a prism under the sun to project a rainbow pattern on two sheets of dark paper separated by a small gap [Fig. 2(a)] that marks the boundary between the visible and infrared zones and minimizes thermal

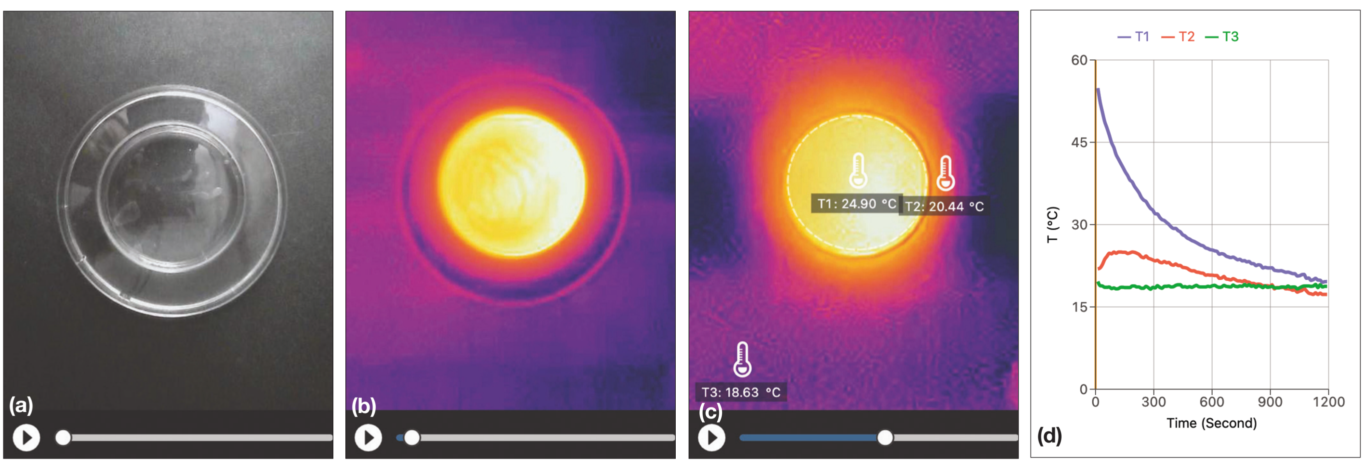

Fig. 1. (a) A small dish filled with hot water is placed in a large dish filled with cold water. (b) A thermal image shows the color contrast between the two dishes. (c) An interactive video allows students to use three virtual thermometers to measure the temperature of the two dishes and the ambient temperature. (d) A graph visualizes the temperature changes measured by the virtual thermometers. Reproduced from Ref. 13.

 DOI: 10.1119/5.0059350

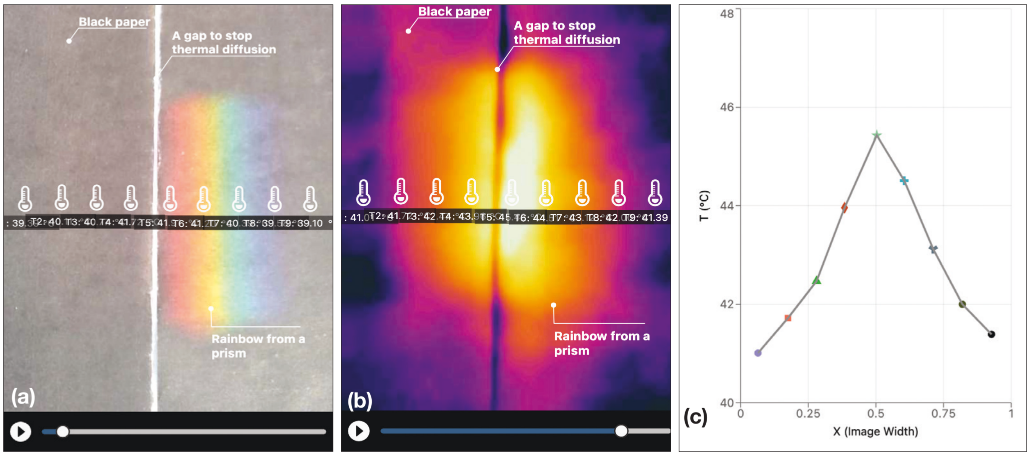

Fig. 2. (a) A rainbow spectrum is projected by a prism onto two sheets of dark paper, separated by a gap at the red end of the visible spectrum to prevent thermal conduction. (b) A thermal image of the experiment shows warming on both sides of the gap. (c) Temperatures from the virtual thermometers are plotted against their relative positions along the horizontal direction. Reproduced from Ref. 17.

conduction between them. We then streamed the experiment to Telelab to show how the sheets warmed up as a result of light absorption. Unlike Herschel's original experiment, our experiment was conducted under the sunlight without using a slit to shine a beam of sunlight into a shaded space. While the entire sheets of paper received direct sunlight, additional sunlight was refracted by the prism and absorbed by the rainbow area, which can easily be picked up by a thermal camera as additional warming.

With this interactive video, students can add virtual thermometers anywhere in the video's view window to measure temperatures, as shown in Fig. 2(a). While Herschel could only afford three thermometers at his time, students can add as many virtual thermometers as they want to explore the data freely and thoroughly.

To observe temperature changes and differences across and outside the rainbow, students can play the interactive video [Fig. 2(b)], which shows the change of thermal images. They see that not only did the rainbow zone warm up the paper, but temperature also increased on the other side of the gap (outside the rainbow). To visualize this pattern with clarity, students can use the built-in graphing tool to plot the temperature distribution over a distance [Fig. 2(c)]. Because we set up a gap using two sheets in the experiment, students can rule out the effect of thermal diffusion from the heated rainbow zone to the infrared zone, leaving only one sensible explanation: there is invisible light energy beyond the red limit. We know this today as near-infrared light.

Compared with a YouTube video, such an interactive video gives students much more scientific data and provides ample room for scientific exploration. It gives students experience with observation and analysis, both of which are central to science. For teachers who have limited time to repeat Herschel's experiment, the interactive video profvides an alternative.

Light incident on various shades of gray

While our first experiment (Herschel's experiment) explores how *different colors of light* are absorbed by the same surface, the second experiment we present[18] investigates how *different colors of surfaces* absorb the same light. This experiment can be linked to everyday experiences such as why people wear light-colored clothes in the summer.

To produce this interactive video, we printed different shades of gray stripes on a piece of paper [Fig. 3(a)], moved the paper from the shadow into the sun, and streamed the data and images to Telelab. To monitor the temperature changes of the different shades of gray over time, students can add a virtual thermometer on top of each gray stripe and use the built-in tools to analyze the data. For example, if students plot the temperatures over time [Fig. 3(b)], they see that they all increase, indicating that sunlight is constantly being absorbed and converted into thermal energy

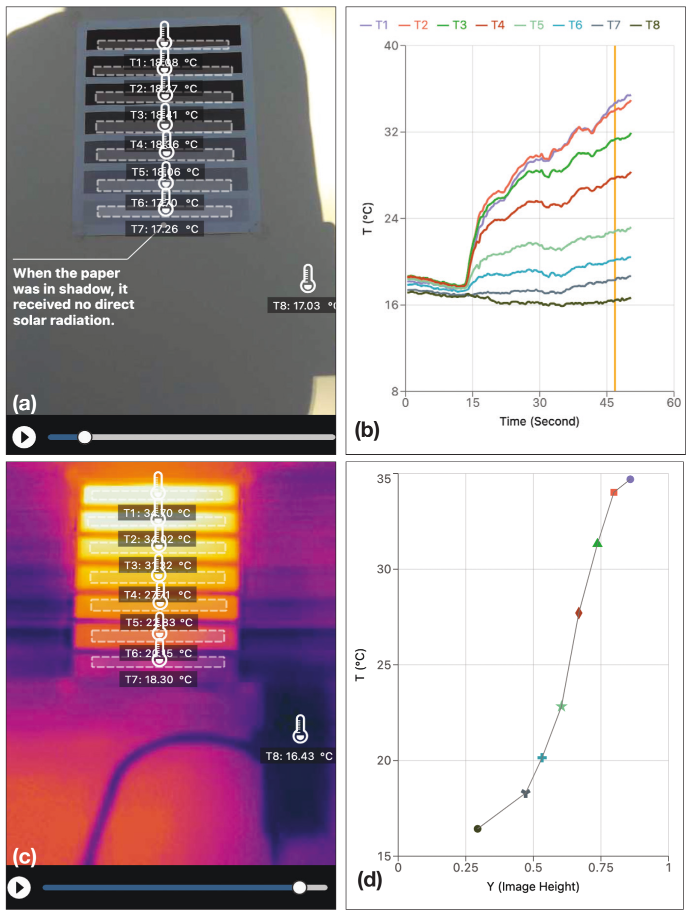

Fig. 3. (a) The setup of the solar radiation heating experiment: a piece of paper with varying shades of gray strips is initially in the shadow and then put in the sun for 30 s. (b) A time graph of temperature shows that all gray stripes warmed up. (c) A thermal image shows that the gray stripes warmed up at different rates. (d) A space graph of temperature shows that darker stripes warmed up more than lighter ones. Reproduced from Ref. 18.

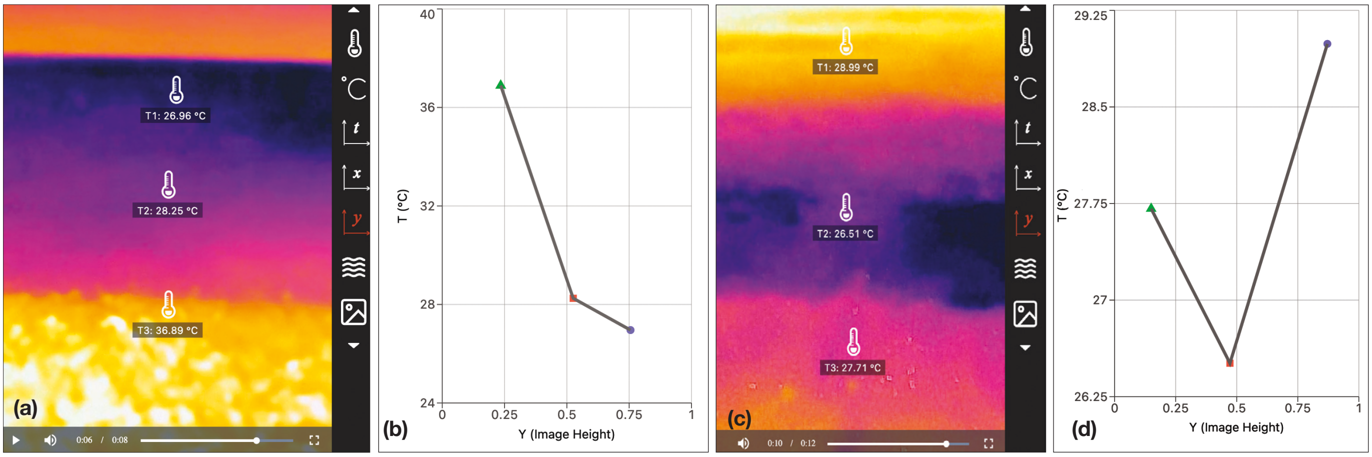

Fig. 4. (a) A thermal image of a beach at noon shows temperature differences between the water and land. (b) A temperature graph of the beach at noon shows that the beach is warmer than the shallow water, which is warmer than the deep water. Reproduced from Ref. 20. (c) A thermal image of the same beach at night shows a different pattern than at noon. (d) A temperature graph of the beach at night shows that the shallow water is cooler than both the beach and the deep water. Reproduced from Ref. 21.

regardless of the shade of gray.

Students can compare the relative temperatures of the gray stripes using different visualization options available in the interactive video. In addition to comparing the exact temperature readings from the virtual thermometers, students can observe the thermal image for a qualitative comparison, where darker stripes look much brighter than lighter ones [Fig. 3(c)].

When students observe the graph of temperature vs. time, or the $T(t)$ graph, they see that the temperature curves for darker stripes are almost always above those for lighter ones [Fig. 3(b)]. This can also be seen using a graph of temperature vs. position, or a $T(y)$ graph, which shows the distribution of temperature [Fig. 3(d)].

In this way, the interactive video allows students to collect multiple types of evidence to conclude that the darker stripes absorb more light energy and therefore generate more heat than the lighter ones. Students can make the connection between this experimental result and the fact that people tend not to wear dark-colored clothing in the summer.

Interactive videos like this also support various pedagogies. For instance, teachers can use the Predict-Observe-Explain (POE) framework.[19] They can first ask students to predict the relative temperatures of the gray stripes over time, then let students analyze the interactive video on their own to verify their predictions, and finally lead students to discuss light–matter interaction and energy conversion.

The physics of the beach

Physics evokes images of blackboards and problem sets. Beaches evoke images of warm sand and cool water. Nothing seems further apart than the two. For our third experiment, we created a pair of interactive videos to show how physics may be relevant even when you are on the beach.

The first interactive video[20] shows thermal images of a beach at noon and draws attention to the contrast between the water and land [Fig. 4(a)]. Students can observe that the ocean is cooler than the land during the day and connect this observation to physics concepts they learned in class: the high heat capacity of the ocean and the convective water flow make it a giant thermal reservoir that gains and loses heat more slowly than the land mass. Students can also discover an interesting pattern: the shallow water appears to be warmer than the deeper water at noon.

An interactive video from everyday life like this may intrigue students to ask deeper questions: How great is the temperature difference? Why do these patterns form? Students can add thermometers to different regions of the water and the landmass directly on the video, and they can generate temperature graphs for a visual comparison [Fig. 4(b)]. The teacher can then help students brainstorm plausible explanations, such as

1) the warmer beach might conduct heat to the shallow water, or
2) given the same solar irradiance, deeper water gets less energy per volume and therefore has a lower temperature.

The second interactive video[21] shows a surprising thermal image of the same beach at night. While we may expect the land to also cool down more quickly than the water after sunset, the thermal image [Fig. 4(c)] and the temperature graph [Fig. 4(d)] both indicate that the shallow water is in fact cooler than both the beach and the deep water at night. A plausible explanation is that the perpetually crashing waves cool down the shallow water via forced convection. This is the same mechanism that causes a hot drink to cool more quickly when it is stirred.

Teachers can again use the POE framework to guide student inquiry. First, teachers show two images of the beach at noon and at night, ask students to predict the relative temperatures of different regions, and encourage them to explain their predictions based on their prior knowledge. Then, students analyze the two interactive videos, observe temperature patterns, and compare their conclusions with their predictions. Finally, teachers can springboard discussions about concepts such as heat capacity and different mechanisms of heat transfer and how they can be applied to explain the thermal physics on the beach.

Conclusion

Videos are useful for getting science ideas across, but they typically lack support for student interactions to deepen inquiry. Interactive videos offer an active learning solution by integrating videos as contexts and sensor data as content. Such a new type of medium provides powerful analysis tools for students to sift through the raw data, visualize them in a way that makes sense to them, observe patterns of scientific significance, and explain these patterns using the physics concepts they learned at school. To extend the analytical ability, we can also add modeling capabilities to reinforce the conceptual links, similar to Tracker, which uses Newtonian simulations to fit motion trajectories constructed from videos. In the case of Telelab videos, computational fluid dynamics simulations[22] can be added to support modeling of many thermal phenomena.

The educational potential of interactive videos goes even further. What if teachers and students can become creators of such interactive videos? If thermal cameras become more commonplace in schools, teachers can livestream experiments to students. Students with thermal cameras can also film their own observations, attach their analyses, and share them with others as interactive videos or even live vlogs. Similar to how streaming services such as YouTube and TikTok have allowed everyone to create and share entertaining experiences, interactive video platforms as demonstrated by Telelab have the potential to allow everyone to broadcast their own scientific discoveries.

Web link

Telelab and additional curriculum materials (including student worksheets and teacher guides) are freely available at http://intofuture.org/telelab.html.

Acknowledgments

This work was supported by the National Science Foundation (NSF) under Grants 2054079 and 2131097. Any opinions, findings, and conclusions or recommendations expressed in this paper, however, are those of the authors and do not necessarily reflect the views of the NSF.

References

1. D. Brown and A. J. Cox, "Innovative uses of video analysis," *Phys. Teach.* **47**, 145–150 (2009).
2. M. Vollmer, K.-P. Möllmann, F. Pinno, and D. Karstädt, "There is more to see than eyes can detect," *Phys. Teach.* **39**, 371–376 (2001).
3. K.-P. Möllmann and M. Vollmer, "Infrared thermal imaging as a tool in university physics education," *Eur. J. Phys*. **28**, S37–S50 (2007).
4. C. Xie and E. Hazzard, "Infrared imaging for inquiry-based learning," *Phys. Teach*. **49**, 368–372 (2011).
5. E. Melander, J. Haglund, M. Weiszflog, and S. Andersson, "More than meets the eye – Infrared cameras in open-ended university thermodynamics labs," *Phys. Teach.* **54**, 528–531 (2016).
6. J. Haglund et al., "Infrared cameras in science education," *Infrared Phys. Technol.* **75**, 150–152 (2016).
7. J. Haglund, F. Jeppsson, and K. J. Schönborn, "Taking on the heat—a narrative account of how infrared cameras invite instant inquiry," *Res. Sci. Educ*. **46**, 685–713 (2016).
8. M. Vollmer and K. P. Möllmann, "Teaching physics and understanding infrared thermal imaging," in *ETOP 2017 Proceedings*, edited by X. Liu and X. Zhang (Optica Publishing Group, 2017), paper 104522C.
9. F. Jeppsson, J. Frejd, and F. Lundmark, "'Wow, it turned out red! First, a little yellow, and then red!' 1st-Graders' work with an infrared camera," *J. Res. Childhood Educ*. **31**, 581–596 (2017).
10. M. Vollmer and K. P. Möllmann, "Infrared cameras as accessories to smartphones: facts you need to know," *Phys. Educ*. **53**, 065019 (2018).
11. C. P. Wong and R. Subramaniam, "Seeing in a different light—using an infrared camera to teach heat transfer and optical phenomena," *Phys. Educ.* **53**, 035007 (2018).
12. D. Riendeau, Column Editor, "Youtube Physics," *Phys Teach*. **50**, 312–312 (May 2012).
13. Telelab, "Newton's law of cooling," https://telelab2.intofuture.org/clip/608620fad530c10022650bac.
14. C. Xie, "From sensing to imaging: The power of many" (2021), http://intofuture.org/ie-from-sensing-to-imaging.html.
15. E. E. Pursell and R. Kozlowski, "Infrared radiation: Herschel revisited," *Phys. Teach.* **38**, 559–560 (2000).
16. J. Lincoln, "Infrared light revisited," *Phys. Teach.* **56**, 570–571 (2018).
17. Telelab, "Herschel's experiment," https://telelab2.intofuture.org/clip/60aef80ba4b680002210b017.
18. Telelab, "Effect of grayness on sunlight absorption," https://telelab2.intofuture.org/clip/6076050578844f002359baf4.
19. R. White and R. Gunstone, *Probing Understanding* (Falmer Press, London, 1992).
20. Telelab, "Beach at noon," https://telelab2.intofuture.org/experiment/0c966234adf64894033285da7ed5a5cd.
21. Telelab, "Beach at night," https://telelab2.intofuture.org/experiment/5ff9302a6f2bf318901cc394c02a223a.
22. C. Xie, "Interactive heat transfer simulations for everyone," *Phys. Teach*. **50**, 237–240 (2012).

Institute for Future Intelligence, Natick, MA 01760; rundong@intofuture.org