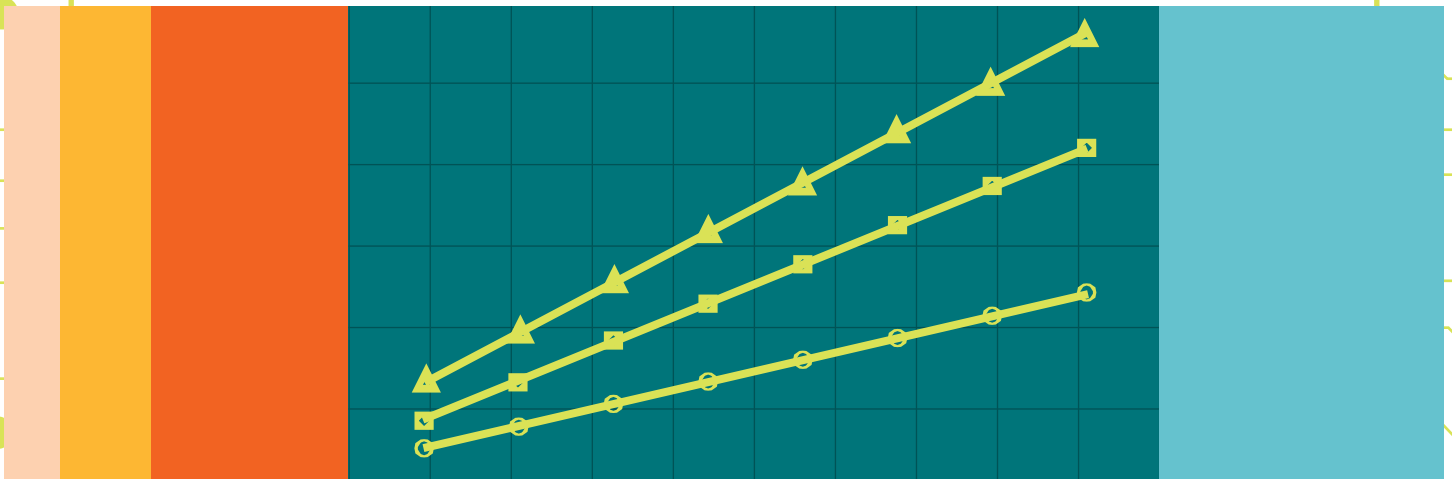


# Exploring the Data:

A Comprehensive Review of Research  
on Probeware and Three-Dimensional Teaching



Prepared for Vernier Science Education by Theresa Deussen, PhD,  
Velma Itamura, and Christopher Lazzaro, PhD



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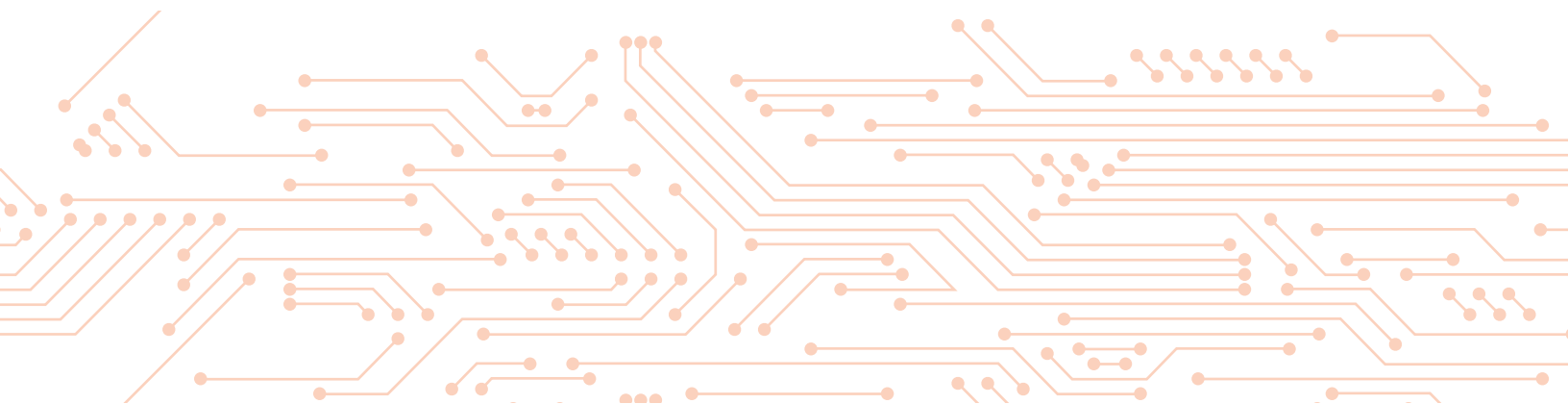
## Introduction

Over the past decade, national and state science standards have dramatically shifted the way that educators think about teaching science. Building off *A Framework for K–12 Science Education* released by the National Research Council (NRC) in 2012, the new standards aim to integrate scientific concepts with real-world applications. What this means is that in science classrooms, students are no longer asked to memorize terminology or formulas or to replicate previously designed experiments. Instead, students engage in dynamic, hands-on learning to answer scientific questions in much the same way that professional scientists do.

The significance of this shift can hardly be overstated. It affects the curriculum, materials, and activities in the classroom. It alters the role of the teacher, who far from being the “sage on the stage” must instead serve as a facilitator while students play the role of scientists, collecting and evaluating data to make sense of the world. In terms of curriculum, this translates into an immersive and interdisciplinary approach, where scientific principles are no longer taught in isolation, but instead are connected to broader concepts and real-world phenomena.

Sense-making is central to the purpose of the new standards. A curriculum that supports sense-making places a strong emphasis on student engagement in natural phenomena that supports learning and exploration. In this approach, students are actively engaged in understanding and explaining phenomena, using scientific and engineering practices to apply their science content knowledge to new situations or challenges. Students collect data by planning and carrying out investigations. Then, they analyze and interpret data and use computation and reasoning to construct an explanation. When they learn science this way, students develop a deeper understanding of scientific concepts and principles, because they have connected them to tangible, observable events. This approach not only enhances engagement and curiosity but also fosters critical thinking and problem-solving skills as students learn to investigate, model, and explain complex systems and processes they encounter in their daily lives.

The *Framework* (NRC, 2012) identified three dimensions that convey the core ideas and practices that underlie K–12 science and engineering education: Scientific and Engineering Practices (SEPs), Disciplinary Core Ideas (DCIs), and Crosscutting Concepts (CCCs). New curriculum and instruction need to be designed to provide students with opportunities to develop the knowledge and skills encompassed in this approach. One way of doing this is to provide students with access to tools that can build their practical competence while providing them with meaningful data, so they can develop the scientific literacy to make sense of the world in which they live. Probeware is just such a tool.





## Probeware as a Tool for 3-Dimensional Learning

Probeware is technology that allows probes or sensors (measurement devices) to collect data and link them to computers or mobile devices for analysis. This allows students to collect, analyze, and interpret data in real time.

A wide variety of probeware can be used in STEM classrooms to support curriculum. Most commonly, students use probeware to measure light, distance, or temperature, especially at the elementary level, where students typically collect data on only one variable at a time. In middle and high school, students increasingly work with multiple probes to collect and interpret data on pressure, color, pH, light, magnetic fields, relative humidity, salinity, oxygenation, force, and velocity, among many other variables.

The use of probeware in science classrooms is not new; on the contrary, it dates back to the 1970s, when sensors were wired directly to the first computers that students started to have access to in schools, using analog-to-digital converters (Tinker, 2002; Metcalf & Tinker, 2004; Park & Slykhuis, 2008). Over time, a new generation of wireless probeware has expanded the ways that students can collaborate and conduct scientific investigations, including investigations of phenomena occurring far away from the classroom or on spatial or temporal scales that are not measurable by other means (Bondaryk, Hsi & Van Doren, 2021). For example, students can place probes around their school to measure temperature or wear sensors to track heart rate or distance walked. They can also access and analyze data collected by remote probes that they or others have set up in their community or even across the country.

Vernier's dedication to the use of probeware to facilitate authentic science investigations also has a substantial history that predates the *Framework* (NRC, 2012); it has been a focus of the company for over 40 years. It has been part of the company's dedication to supporting phenomena-based teaching and learning in STEM classrooms.

However, some educators and STEM curricula have been slow to adopt scientific tools and probes, since for decades, the pedagogical norm was to deliver STEM education as a collection of knowledge of facts that students must learn. With the publication of the *Framework* (NRC, 2012) and the adoption of three-dimensional standards, this pedagogical norm is now being challenged. Consequently, the recognition of wireless technology and probeware as an increasingly valuable classroom tool has grown more widespread. Probeware plays a pivotal role in creating opportunities for students to make sense of phenomena in the ways envisioned by newer standards.

## Probeware and the supporting software enhances the learning experience in several ways:

- **Learning through investigations.** Probeware provides a tangible, interactive way for students to engage with scientific concepts. By using these tools, students can actively conduct investigations, gather data, and observe results, making abstract concepts more concrete and understandable.
- **Real-time data collection.** Probeware enables the collection of real-time data and the immediacy helps students make direct connections between the phenomena they are observing and the data they are collecting.
- **Enhanced understanding through visualization.** Supporting software such as that which Vernier provides often includes visualization tools that help students analyze and interpret data. Graphs, charts, and other visual representations of data can make complex concepts more accessible and easier to understand.
- **Encouraging exploration.** With the ability to make accurate and precise measurements, students can explore phenomena that are otherwise not easily observable in a classroom setting. These precise measurements allow students to experience phenomena from an experimental perspective that would otherwise be constrained to only theoretical observations. This fosters a sense of curiosity and encourages a deeper exploration of scientific phenomena.
- **Developing scientific skills.** Using probeware helps students develop important scientific skills, such as hypothesis testing, data analysis, and critical thinking. It aligns well with the Framework's emphasis on process skills and understanding the nature of scientific inquiry. Students use scientific skills as tools to know the world around them. Probeware supports these skills by furthering students' investigations of natural phenomena with added precision.

Educational researchers have identified a wide range of benefits from the use of probeware, ranging from opportunities for authentic learning and higher student engagement to affordability for schools and districts.

**Authentic learning.** Probes that measure air temperature, water acidity, and the volume of gases, or probes that detect motion and acceleration (among many other types of data) all provide opportunities for students to grapple with information about the real world they inhabit. Probes can be very useful in the learning of algebra (Lyublinskaya & Zhou, 2008) for example, where concepts such as slope can be explored and connected to real-world phenomena. Similarly, the concepts of derivatives and differential equations can be illustrated through measures of the variation in the rate of temperature change over time, for example. Connecting these sometimes abstract mathematical or scientific formulas to measurable events heightens the relevance of what students are learning and addresses the perennial question: “why do we need to know this?”

Probeware also allows students to study phenomena they might otherwise not easily be able to examine, such as processes that occur too quickly to be observed with the naked eye, too slowly to be observed during a single class period, or in remote geographic areas (Zacharia, Lazaridou & Avraamidou, 2016). Furthermore, particularly at the secondary level, networked probes allow students to engage in increasingly sophisticated analyses of environmental investigations influenced by multiple variables (Lee & Wilkerson, 2018).

Authentic learning inevitably means that students are confronted with the challenge of reconciling theory and the actual data collected. Sometimes results are different than anticipated; other times data are subject to human or environmental factors that may distort findings. This means that students must learn to reconcile and explain differences between theory and the unexpected results that may come up when conducting experiments—just as professional scientists do. Sometimes this creates experiences of cognitive dissonance, where students’ preconceived notions are challenged, prompting them to critically evaluate and rethink their understanding and expectations. It is precisely such experiences that can not only deepen their knowledge of science but also enhance critical thinking skills that are crucial for evaluating the claims of others.

**Enhanced practical skills.** Because probeware requires students to set up the technology, as well as monitor its functioning and troubleshoot issues, students develop practical skills and enhanced confidence with handling machinery (de Jong, Linn & Zacharia, 2013).

**Computational benefits.** The use of probeware also provides students with rich opportunities for computational thinking (Sneider et al., 2014). This includes the gathering and use of automated data collection and programming, as well as the analysis and interpretation of the data, and obtaining and evaluating evidence, all with the purpose of constructing an explanation for the phenomenon they observe (Van Doren et al., 2022; Metcalf & Tinker, 2004).

**Instructional shifts.** The flexibility of probeware systems means that teachers can allow students to expand the classroom investigation to develop a deeper understanding of phenomena, rather than follow textbook “recipes” for particular experiments. Furthermore, that same flexibility facilitates the exploration of questions at various levels of complexity, so there can be more differentiation within a single classroom—including differentiation across student interests and diverse backgrounds (Van Doren et al., 2022). Also, the use of probeware can facilitate the shift from teacher- to student-centered classrooms, where the teacher plays the role of supporter and facilitator (Kamarainen et al., 2013).

In a different investigation, Marcum-Dietrich et al. (2021) conducted a large study looking at middle and high school students in eight states using a curriculum that used probeware, national data sets, and a modeling application to investigate local watersheds. They found that the curriculum significantly improved students’ content knowledge as well as their knowledge of actions that could be taken to protect watersheds.

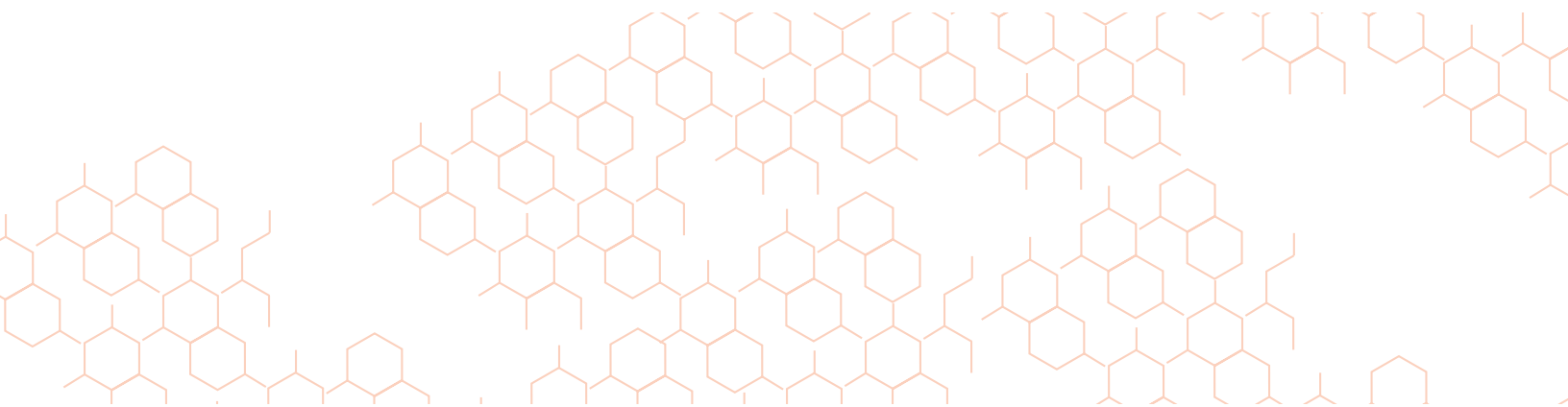
**Affective benefits.** Researchers have long argued that probeware increases students’ interest, curiosity, motivation, and engagement in science and engineering classes (Kapila & Iskander, 2014; Metcalf & Tinker, 2004; Van Doren et al., 2022). For example, Playton, Hite, and Leach (2021) conducted a case study of three teachers who developed lessons using probeware to measure friction while pushing or pulling an object; this task required students to program a small robot. They found that the new lessons significantly increased students’ interest in and attitudes toward science, particularly for girls.

Furthermore, a number of studies support the idea that using probeware can boost students' content knowledge and achievement. For example, Yerrick and Johnson (2009) conducted a study in a high-achieving middle school. Two teachers reworked their curriculum and lessons to incorporate probeware and laptops in their earth science and physics classes. The researchers compared student achievement on classroom assignments and on the New York State assessment scores to those of students over the previous five years. Even though prerequisites for the earth science course were eliminated that year, enabling less highly prepared students to enroll in the class, substantially more students achieved the highest level of success in this rigorous course than in previous years. Furthermore, no students dropped the class during the school year. For the physics class, the percentage of students scoring a 3 or 4 on the New York State eighth-grade science assessment increased from 96 percent the previous year to 99 percent (excluding mainstream special education students—including the special education students, those figures were 91 and 94 percent of all students).

**Access for students with disabilities.** Students with disabilities have sometimes reported insufficient opportunities to participate in science investigations, but the use of digital devices has the potential to significantly increase participation. If probes can be controlled and data collected via computer or handheld devices, students who are limited by physical disabilities have many more options for fully engaging with experiments (Cooper, 2005). Also, Madden and Madden (2005) argue that probeware grabs and holds the attention of students who have challenges with focusing on academic tasks. They found that the instantaneous reporting that comes with the use of a probe helps engage at-risk learners by providing an immediate context for understanding concepts such as temperatures or gases.

**Logistical and cost benefits.** Many educators report a preference for labs that use probeware, noting that these require less setup time and generally yield faster results, leaving time to highlight the most important information, dive deeper into analyses, or repeat experiments in order to investigate new hypotheses (Tinker, 2002; Madden & Madden, 2005; Trundle & Bell, 2010; Zacharia, Olympiou & Avraamidou, 2008).

Some types of probes, such as Vernier Science Education probeware, yield data that are stored in the cloud. This means that data can be accessed anywhere by relatively inexpensive devices, including when students are off-site, if desired (Van Doren et al., 2022). This also means that students have more opportunities and more time to complete and revisit investigations, as well as the chance to repeat and modify the labs to foster deeper learning (Lang, 2012). Educators and administrators alike appreciate that handheld devices and probeware are comparatively low-cost strategies to raise the rigor of science classes, particularly for elementary and middle schools (Metcalf & Tinker, 2004).





# Effective Implementation of Probeware in the Classroom

Whenever schools adopt new technologies, implementation matters. This is particularly true when the adoption of a technology such as probeware is part of an effort to support or expand teaching practices aligned to newer state or national standards. The research literature provides useful guidance about planning effective implementation.

**Shifts in classroom culture.** If used as intended to foster standards-based science skills, probeware sets teachers up to become facilitators of student-driven experiments rather than experts who show students how to follow traditional “recipe-style” experiments with expected outcomes. If this is a new way of doing science in a classroom, it can feel awkward to teachers and students alike.

Also, when outcomes of experiments are not necessarily known ahead of time, teachers need to be comfortable assisting students with emergent findings, and students need to learn to have productive conversations about results. This requires teachers to build a culture of small-group conversation about the meaning of findings (Van Doren et al., 2022).

These are all feasible shifts, and they are easier to make when teachers have professional development that allows them to practice the new skills they need.

**Teacher-provided tech support.** After initial installation, teachers often must take on the role of tech support for students and build students' capacity to use a new system effectively. This is sometimes anxiety-provoking for an already-busy teacher. For example, in the sixth-grade field trip study (Kamarainen et al., 2013), teachers expressed concern about their ability to manage the technology and devices when orchestrating the field trip on their own, without assistance from the research team. Van Doren et al. (2022) also mentioned the new role of tech support as a challenge for many teachers. However, this challenge can be mitigated substantially by working with reputable educational technology companies that provide ongoing support to teachers.

**Ongoing software updates.** Even after becoming comfortable with new educational technologies, teachers will need to continue their learning about the software to analyze and graph data. Data from probeware offer rich opportunities for sophisticated computational thinking, but this means teachers must use and teach about various data-analysis platforms, such as spreadsheets, data visualization tools, and statistical computing languages (Lee & Wilkerson, 2018). This demands ongoing professional development, even beyond initial implementation, as software evolves, platforms change, and new tools become more widely used.

**Contextualization of data.** One thing that teachers have reported is that students sometimes struggle to understand what data collected from remote probes mean. Therefore, teachers have to find a way to contextualize the data so they connect to real phenomena for students (Lee & Wilkerson, 2018). Some projects involve students in setting up probes in outdoor locations, which can help connect data to the setting, but others use data from already-placed probes, and this is where field trips, videos, and other approaches may be needed to help students make connections.

Another common student misconception is that data from probeware are always accurate representations of the world. Teachers need strategies to build students' critical awareness of data quality issues and their ability to understand that data they collect may be fallible. (Lee & Wilkerson, 2018; Hardy, Dixon, Van Doren & Hsi, 2022). For example, research suggests that actively involving students in collecting measurements and collaboratively negotiating methods for taking measurements is one effective way to help students to recognize measurement as a source of error that can produce variability (Lehrer, Kim & Schauble, 2007). These and other approaches are strategies that teachers can develop during collaborative planning or professional development.

**School or district infrastructure.** Finally, effective use of probeware makes some demands on schools and districts. They need an appropriate infrastructure of digital devices—which means a sufficient number of appropriately powerful computers, adequate software, and a sufficiently fast Internet connection; indeed, these school-level factors are associated with higher test scores (Bozkus, 2021). Schools must also have the capacity to manage the collection and secure storage of large data sets (Lee & Wilkerson, 2018). Again, these are issues that a trusted educational technology company should be able to help schools plan for.

**High-quality teacher professional development.** Teachers use technology that they have been taught to use in the classroom, and they do not use what they have not been taught. In a study of which technology tools secondary science teachers in New York state used on a regular basis (Waight, Chiu & Whitford, 2014), the authors found that teachers who had received more professional development on the use of a tool used that tool more. Unfortunately, however, few teachers received this needed support, and many expensive tools were underutilized. In short, professional development is essential.

In a review of the literature, Gerard et al. (2011) noted that professional development efforts of less than a full school year saw little success because teachers needed that long to overcome technical challenges and to transition their instruction to incorporate the new tools. Longer periods of professional development were associated with increased change in teachers' pedagogy as well as with student learning gains. Finally, Lee and Wilkerson (2018) recommended that both teacher preparation programs and professional development experiences involve teachers in using probeware for full cycles of inquiry rather than as brief, single-visit inservice demonstrations.



## Empirical Evidence for Impact of Probeware

How can we know whether incorporating probeware into the science classroom will enhance outcomes for students? Fortunately, there is some research that demonstrates the positive impacts in science content knowledge and achievement, social and scientific communication skills, and student engagement in science.

Science content knowledge and achievement. As described earlier in this white paper, the use of probeware has already been linked to authentic learning (Lee & Wilkerson, 2018; Lyublinskaya & Zhou, 2008; Zacharia, Lazaridou & Avraamidou, 2016). In addition, other studies have investigated whether students acquire the same amount of science content knowledge and perform as well on exams using probeware, compared to using other technologies that might be used in teaching and learning science.

Purba, Hwang, Pao and Ma (2019), for example, compared two ways of teaching about planes and acceleration in a physics class. One method had students using probes and an app that had students interpreting graphs, applying formulas, and cooperatively sharing their conclusions. The comparison group used more traditional tools, such as a stopwatch. The group using probes and the app significantly outperformed the comparison group.

In another example, Struck and Yerrick (2010) conducted a study with high school physics students who were learning to graph kinetics using distance, velocity, and acceleration. Some students were taught by digital video analysis, while others were taught using data-acquisition probeware. The authors found that both approaches were effective for improving students' capacity to create and understand graphs, although digital video analysis was more time-consuming.

Achievement gains have also been noted among younger students. In a study of probeware used in science classes with students in grades 3 through 8, Zucker et al. (2008) compared the performance of students from the previous year, with no probeware, to those of the year afterwards, in which teachers included the use of probeware in multiple lessons. There were significant improvements in the learning of science for units on sound, electricity, temperature, and motion, though not for some other units.

Other, less rigorously designed studies provide suggestive evidence that probeware is associated with increases in test scores as well as better student-developed questions and higher student interest and engagement. For example, one study found a significant gain in science knowledge and understanding after students had used probes on a sixth-grade ecology-focused field trip (Kamarainen et al., 2013). Another study found statistically significant gains after a unit on climate change that utilized data from sensors on kites (Xie, Henry & Bydlowski, 2014). Still another preliminary study found that simple handheld data-collection probes incorporated into two middle school science units (forces and motion, and transfer of energy) allowed students to experience the alignment between models and the actual phenomenon they were studying, deepening their understanding and correcting misperceptions (Metcalf & Tinker, 2004). These studies all lacked comparison groups, however. But what these studies do suggest is that the use of probeware can be helpful across a wide range of topic areas within science.

Student interest and engagement. Adnan et al. (2017) showed, using student surveys, that students' interest and motivation in physics increased with the introduction of probeware technology into physics classes. This is a particularly important finding since students often report that they see physics in particular as difficult, abstract, or uninteresting (Williams et al., 2003). Also, in the study of planes and acceleration mentioned above (Purba, Hwang, Pao & Ma, 2019), most students who had used the probeware and the app reported that they were highly motivated to use it again in the future. In a separate study, Drake, Cain, and Lee (2017) reported that, given the chance to work with activity trackers (a form of probeware) to collect data for their science experiments, fifth- and sixth-grade students raised important substantive questions and became interested in further exploring phenomena.



# Conclusions

Probeware can be a powerful tool in the implementation of an engaging, high-quality, hands-on science curriculum aligned to the *Framework* (NRC, 2012). Students develop real-world scientific skills while engaged in interactive investigations, real-time data collection, and data visualization.

Research has demonstrated the benefits of probeware for authentic learning, improvements in science content learning, and enhanced computational and practical skills. It has also shown that probeware can boost student interest and engagement in STEM.

Integrating probeware into classroom teaching effectively requires that the curriculum is aligned with the *Framework*. Applications such as Vernier Connections™ that make use of the data collected by probeware significantly aids teachers as they navigate the adoption of new technologies and shift from traditional teaching methods to roles that emphasize facilitating student learning. Focusing on investigations, lab work, and projects that use real measurement tools, like the Connections platform, enables students to engage more deeply with their environment, aligning with the objectives of the new three-dimensional standards. This approach, as demonstrated in this paper, leads to improved student outcomes.

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