Physics Education Research: a replicable model for Discipline-Based Educational Research at European universities?

Gerd Kortemeyer[1]

Educational Development and Technology, ETH Zurich
8092 Zurich, Switzerland

Abstract

How can a practicing teacher focus on student learning in a scholarly fashion? Over the last three decades, in several physics departments at American universities, Physics Education Research (PER) established itself alongside traditional fields such as Solid State or High Energy Physics. Promoted and advanced by discipline-scientists, PER critically evaluates the effectiveness of approaches to higher-education teaching and learning. What brought about this cultural change? The paper chronicles the slow but steady rise of a new field of inquiry and discusses opportunities and challenges for replicating the establishment of Discipline-Based Educational Research (DBER) at European universities.

1 Introduction

In higher education, scholarship and teaching are traditionally joined through the discipline: you are supposed to be a better teacher of physics because you are a practicing physicist. When I started out teaching in the United States, I felt rather unprepared for the task — my scholarship was in theoretical nuclear physics, not in teaching. Essentially all I could do was try to mimic the teachers that I had appreciated as a student. All along, I had the feeling that this was the wrong approach: while these teachers served as role models, resources for my questions, and enforcers of standards, most of my *learning* happened while doing homework or studying for exams.

To become a better teacher and facilitator of *learning*, much of what was out there in literature seemed meaningless to me: strange vocabulary, unrealistic expectations, and recipes that seemed far away from the reality of my classroom — both because it was too general, i.e., not focusing on physics, and because it neglected the constraints I was under to get through the material. The literature on teaching and learning was simply too far away from my discipline.

Discipline-Based Educational Research (DBER) is closely related to the Scholarship of Teaching and Learning (SoTL) (Shipley et al. (2017)), however, there are important distinctions. SoTL is not necessarily driven by subject-area specialists, but focusses on generally applicable principles of evidence-based teaching methods (Boyer (1990); Huber and Morreale (2002)). DBER on the other hand is most frequently driven by faculty within science disciplines, for example physicists, who aim to advance the theoretical and empirical knowledge base of teaching and learning within those disciplines (Singer et al. (2012)). Methods and vocabulary are frequently borrowed from the disciplines, so for example, physics education research (PER) papers frequently read and feel like other physics research papers.

Researchers in DBER are oftentimes housed within their respective subject-area departments, and several of them are pursuing both traditional and educational research. As such, these researchers frequently connect more effectively with their colleagues on topics of teaching and

---

[1] gerd.kortemeyer@let.ethz.ch

learning, and they have become agents of change and the driving forces behind reformed curricula not only in their own classrooms, but in their departments and wider professional communities.

Historically, DBER developed in the United States, and an important question is whether or not a similar infiltration of science departments is possible within the very different European higher education landscape.

2 History

PER can serve as an example for the development of a branch of DBER. Its history stretches back several decades, and only a short and incomplete overview can be given. While literature references are given, they are meant to be illustrative; they are neither exhaustive nor necessarily the earliest, most authoritative, or most influential publications on the subject. Much more exhaustive historical reviews of DBER in general and PER in particular can for example be found in Singer et al. (2012); Handelsman et al. (2004); Cummings (2011), and Meltzer and Otero (2015) (the latter also reaching back far deeper into history).

2.1 Sputnik and Career Switchers

Science education reform arguably started in 1957 when a little radio transmitter was launched into an elliptical low-Earth orbit. With the beginning of the space race, the United States also launched STEM-education initiatives in an effort to ensure future competitiveness (Wissehr et al. (2011)).

Robert Karplus might have been the first career-switching physicist, switching from theoretical physics to what would become PER (Karplus (1964)). In the late 1960s, more physics faculty switched (at least partially) to PER, and they started having graduate students. An additional boost was given by workshops in the late 1970s, organized by Karplus, Arnold Arons, and Lillian McDermott from the University of Washington, in which several future career-switchers participated (Cummings (2011)). Eventually, many of those faculty members got started in their new field through sabbaticals at the University of Washington (Cummings (2011)).

These career-switching physicists now include leaders in professional societies and at least two Nobel laureates (Wilson (1993); Bardeen and Lederman (1998); Burnstein and Lederman (2001); Wieman and Perkins (2005); Adams et al. (2006); Deslauriers et al. (2011); Wieman et al. (2013)). Having physicists who are already respected in the field switching their focus certainly helped to more quickly establish PER.

2.2 Dedicated PER Hires

In 1970, Dean Zollman was hired at Kansas State University as the first dedicated PER faculty, i.e., right from the start outside of the previously established research fields. In 1999, the American Physical Society issued an explicit statement encouraging the incorporation of PER into departments (American Physical Society (1999)). Today, there are over 60 physics education research groups within the United States, even though some of them only have one faculty member.

These faculty are now slowly moving through the tenure process, with a sizable number having reached full professor status (where many of the career-switching physicists started out). Naturally, they in turn have graduate students and postdocs (Barthelemy et al. (2013); Knaub et al. (2018)).

2.3 Funding

An important element in developing a research field is the availability of funding; departments are interested in faculty who bring in external funds, and external funding validates research in the eyes of peers. Starting in the 1980s, these were oftentimes US Department of Education Fund for the Improvement of Postsecondary Education (FIPSE) grants, and since the late 1990s, grants by the US National Science Foundation (NSF) undergraduate education grants (Henderson et al. (2012a)). Mostly missing, though, were grant opportunities out of NSF's Division of Physics. Also, there exists a hard boundary to grants in the elementary and secondary realm ("K-12"), which are largely closed to PER.

2.4 Force Concept Inventory

The Force Concept Inventory (FCI) (Hestenes et al. (1992)), which assesses the understanding of the basic Newtonian concept of force, has arguably been one of the most influential milestones in mainstreaming PER.

Most physics faculty would agree that learners cannot and thus should not proceed to more advanced topics without mastering the concept of force. Most uninitiated physics faculty would likely also argue that the associated FCI is straightforward to a fault, if not trivial. However, almost invariably, administering the FCI to a class leads to disappointing revelations, which opens minds to a re-evaluation of teaching practices (particularly in light of a 6000-student study showing that activating teaching techniques could lead to significant improvements in pre-/post-test gains (Hake (1998)).

The genius of the FCI is that it limits itself to a single concept, the importance of which virtually all physicists agree on. It does not attempt to be smart or tricky, so the frequently devastating results come as a surprise with no excuses (some test-theoretical properties are questionable, though (Yasuda et al. (2018); Stewart et al. (2018); Traxler et al. (2018)). Through this simple inventory test, both the need for and the potential of PER affirmed themselves among teaching faculty.

In the meantime, many more concept inventories developed with varying degrees of sophistication (Lindell et al. (2007)) (also across disciplines (e.g., Libarkin (2008)), including the now widely used Force and Motion Conceptual Evaluation (FMCE) (Thornton and Sokoloff (1998)).

2.5 Research Frameworks

PER started out as a mostly empirical science, but has since developed strong research frameworks (Docktor and Mestre (2014)). Early on, intuitive, straightforward models for student learning such as the concept of fixed learning styles (Kolb (1984)) and binary expert-novice distinctions (Chi et al. (1981)) were "imported" to PER, but eventually PER started to develop its own, more differentiated theoretical frameworks with multiple representations (Meltzer (2005); Kohl and Finkelstein (2005)) and the influence of expectations, attitudes, and epistemology on learning physics (Redish et al. (1998); Lising and Elby (2005); Adams et al. (2006)). Also, the concept of misconceptions was slowly replaced by the toned-down concept of difficulties (Heron (2018)) and the more differentiated concept of p-prims (Hammer (1996)) and resources (Wittmann (2018)). Human learning is more complex than most of the other phenomena that physicists are traditionally dealing with. This includes factors far from the closed, idealized systems that physicists tend to favor and create for themselves: within the last decade, PER started to also focus on external, sociocultural issues, in particular gender and barriers to physics learning and advancement (Brewe and Sawtelle (2016)).

2.6 Curricula and Gadgets

An important outcome of PER are research-based strategies, which are directly applicable in the classroom (Redish (2004); Meltzer and Thornton (2012)). This is a strength of DBER: researchers developing methods, curricula, and gadgets are also in a position to directly investigate them in their own classrooms.

Thus, ready-to-use curricula such as Tutorials in Introductory Physics (McDermott and Shaffer (1998)) were developed, which brought research-based strategies into classrooms with a relatively low threshold, in spite of challenges (Finkelstein and Pollock (2005)). Other strategies include peer-instruction (Crouch and Mazur (2001)), studio physics (Cummings et al. (1999)), and just-in-time teaching (Novak et al. (1999)).

Also, ready-to-use gadgets came out of PER, namely video analysis (Brown and Cox (2009)), computational lab data analysis (Thornton (1987); Sokoloff (1992)), sensors (Sokoloff et al. (2007)), and clickers (Burnstein and Lederman (2001)). Several of these, at least in the beginning, were developed in the spirit of open-source tools.

The professional societies helped spread the word about research-based teaching methods. A large percentage of new physics faculty hires in the States now participate in the series of New Faculty Workshops (American Physical Society (2019)), which are organized every year by the American Association of Physics Teachers (AAPT), later joined by the American Physical Society and the American Astronomical Society and supported by the National Science Foundation.

Awareness of research-based instructional strategies is relatively pervasive among physics faculty ($\approx 90\%$), and currently about half of physics faculty state that they use these techniques (however, not necessarily completely as intended (Henderson and Dancy (2009)), and some of them later dropping those practices again (Henderson et al. (2012b)).

2.7 Journals and Conferences

While PER had established itself as a solid field of research, there was no journal to publish this work. SoTL journals like the Journal of Research in Science Teaching were not necessarily attractive for the flavor of discipline-based research that physicists were pursuing.

Instead, for over three decades, articles on PER were hosted primarily by two practitioners' journals: The Physics Teacher (TPT) and The American Journal of Physics (AJP). While the majority of articles in these journals is dedicated to novel or intriguing ideas for teaching physics without necessarily providing empirical evidence or theoretical frameworks (these are not research journals!), in 1999, a PER supplement to AJP was created (Wittmann and Price (2018)).

Meanwhile, a large portion of traditional physics research was published in the highly respected Physical-Review series of journals, with its different flavors, e.g., Nuclear or Solid State Physics. In 2005, the Physical Review Special Topics – Physics Education Research was launched (Henderson and Dancy (2009); Beichner (2015)), and in September 2005, the first article was published (Finkelstein and Pollock (2005)). In 2016, the "Special Topics" was dropped from the name of the journal (Henderson (2016)), and PER had finally made it into main- stream physics research publishing. This also contributed to PER publications counting in hiring, tenure and promotion processes.

What started out as PER sessions at conferences of the American Physical Society (APS) and the American Association of Physics Teachers (AAPT) eventually developed into its own

Physics Education Research Conference (PERC), which is tagged on to the summer meetings of the AAPT.

2.8 Dedicated Degrees

An important question was: does the community need Ph.D.s in Physics Education? The pendulum ended up swinging mostly into the direction of simply having a Ph.D. in Physics. This was found to be important to position graduates as full physicists who happen to do research in Physics Education, just like others do research in Solid State Physics. It was also found that on the academic job market, the general degree opened up more opportunities.

While this is now widely accepted practice, it should be remarked that some departments still require "mixed" thesis projects, which also have traditional physics research components. These might for example deal with High Energy Physics, but then include sections on how to teach and communicate the underlying concepts.

2.9 Teaching Evaluations

In the States, physics faculty are now expected to use at least some activating techniques in their classroom teaching, where for example the absence of clickers in introductory courses is almost perceived as professional malpractice. Teaching Statements or Teaching Philosophies are routinely expected in faculty job applications.

The evaluation and self-reflection of teaching practice is regularly a component of the substantial packages submitted for salary determinations, tenure, and promotion. Several departments have switched away from traditional student *teaching* evaluations, which to some degree simply measure comfort-level, toward *learning* evaluations (Seymour et al. (2000)) that focus on outcomes (Henderson et al. (2014)) and attempt to reward experimentation and innovation. In addition, the practice of peer-evaluations, where faculty (sometimes not even from the same discipline) visit each other's classrooms help foster open dialogue about teaching and foster dissemination of research-based and activating teaching practices.

3 Discussion

3.1 Sub-Culture to Main Stream

Career-switchers were arguably the most influential progenitors of PER; as they were already members of the main stream community, they lent respectability to this new field. Equally important were applicable techniques, which were created, tested and proven in actual classrooms — this "hands-on" approach made PER accessible.

The PER community in the States now needs to be careful to keep this classroom link and to not move into a subculture with inaccessible theoretical frameworks, language, and unrealistic expectations. There is a danger that some methods, such as tutorials and studio physics in its purest form, put large demands on faculty energy and time, leading to possible burn-out. Student resistance, scalability challenges, demands on topic coverages, and perceived limited return-on-investment in terms of learning gains might be reasons that some departments or faculty members withdraw from research-based practices; it takes persistence and perseverance (Foote et al. (2019)), as well as at times support by science-education specialists (Wieman et al. (2013)).

3.2 Unique or Replicable?

In the United States, in several subject areas including physics, the first years of college are essentially an extension of high school. The ability to make class attendance de-facto mandatory, as well as to have formative assessment count for a significant portion of the class grade, allows instructors to enforce learner cooperation in activating teaching techniques. In other parts of the World, particularly Europe, class attendance is strictly voluntary, and passing or failing a subject area depends on examinations that are not part of the class itself (at times more than one semester later). Thus, far less emphasis and attention are invested on what happens in the classroom, both by faculty and by students. The latter oftentimes manifests itself through low student attendance, or students demanding lecture recordings, which make any activating teaching techniques impossible. Grading and examination policies would need to allow for more formative assessment during the semester, where homework, projects, and recitations count toward grades; instead, policies frequently prohibit just that.

Also in terms of teaching evaluations, the culture in European universities is vastly different, where oftentimes only “red flags” in course evaluations are considered by department und university leadership — these punitive “red flag” policies discourage risk-taking, since anything deviating from traditional transmission-style lecturing is perceived as not only potentially “raising flags”, but also as possibly being frowned upon by peers. While several universities have teaching awards, the ubiquitous teaching evaluations also need to move into the direction of evaluating learning and rewarding risk-taking and innovation, rather than as a tool to simply spot train wrecks. To make things worse, classrooms in Europe tend to be “closed door,” where faculty colleagues rarely visit each other’s lectures — peer-evaluations of teaching (not content!) might go a long way toward active dialogue.

Establishing DBER in Europe will require changes in the institutional culture of European higher education institutions and funding agencies. Over decades, in the States a culture developed in which research in PER started to pay off in the currency of faculty, namely toward tenure and promotion, through acknowledged publications and through grants. With the developments in the States having paved the way, though, it will not have to take decades for post- secondary science education research to gain foothold.

Finally, professional societies need to be on-board; currently, they are still a long way from issuing statements similar to that of the APS (American Physical Society (1999)). For example, efforts in establishing New Faculty Workshops in Germany failed due to lack of support by the Deutsche Physikalische Gesellschaft, which still appears to have a very skeptical outlook on PER. Some this skepticism appears to be unduly fueled by debates and antagonism to- ward initiatives in the K-12 realm, which strongly deviated from the traditional structures, notations, and nomenclature of physics (Herrmann (2000); Deutsche Physikalische Gesellschaft (2019); Strunk and Rincke (2019)). A strength of PER in the States is and was that it stayed within the accepted methodology, value system, and epistemology of physics, and the debacle in Germany highlights the necessity to not be “out in left field” and cause collateral damage when trying to establish PER in Europe.

Of course, academic culture is not uniform within Europe, either, as for example the German/Swiss tradition is different from the Scandinavian and British traditions. Particularly the former has a certain element of “swim or sink” during the first semesters, where some faculty members see it as part of their job to select the segment of the student population who is “cut out” for higher education. Even different institutions within the same countries will have different cultures; academia is a slow-to-change, complex, and eclectic enterprise, so establishing DBER will have to be a slow process, which has to be contextualized on many levels beyond disciplines.

4 Conclusions

A focus on student learning in higher education classrooms, combined with the evidence-based nature of physics, let to the development of a new branch of physics research: beginning with career-switching physicists, over decades, PER developed into a mature branch of physics alongside traditional branches such as Nuclear and Solid State Physics — this is where I eventually found my disciplinary home. Coming to Europe seemed like stepping back in time in terms of DBER. A similar development, however, would likely be possible at European universities, particularly while making use of the now existing infrastructure like the journals, conferences, and sabbatical opportunities, but it would require changes in examination policies and faculty reward structures.

Acknowledgements

The author would like to thank the reviewers of this journal, as well as the members of the YoungPER Mailing List (University of Maine (2020)) mailing list for their input, in particular Ramon Barthelemy, Eric Brewe, Tom Carter, Scott Franklin, David Jackson, Alexis Knaub, James Laverty, Daniel MacIsaac, Benjamin Pollard, Amy Robertson, and Michael Wittmann.

References

Adams, W. K., Perkins, K. K., Podolefsky, N. S., Dubson, M., Finkelstein, N. D., and Wieman, C. E. (2006). New instrument for measuring student beliefs about physics and learning physics: The Colorado learning attitudes about science survey. *Phys. Rev. ST Phys. Educ. Res., 2*:010101.

American Physical Society (1999). Statement 99.2 research in physics education. American Physical Society (retrieved June 2019). New faculty workshops. Bardeen, M. G. and Lederman, L. M. (1998). *Coherence in science education*.

Barthelemy, R. S., Henderson, C., and Grunert, M. L. (2013). How do they get here?: Paths into physics education research. *Phys. Rev. ST Phys. Educ. Res., 9*:020107.

Beichner, R. J. (2015). Editorial: Reflections on the origins of physical review special topics – physics education research. *Phys. Rev. ST Phys. Educ. Res., 11*:020001.

Boyer, E. L. (1990). Scholarship reconsidered: Priorities of the professoriate. ERIC.

Brewe, E. and Sawtelle, V. (2016). Editorial: Focused collection: Gender in physics. *Phys. Rev. Phys. Educ. Res., 12*:020001.

Brown, D. and Cox, A. J. (2009). Innovative uses of video analysis. *The Physics Teacher, 47(3)*:145–150.

Burnstein, R. A. and Lederman, L. M. (2001). Using wireless keypads in lecture classes. *The Physics Teacher, 39(1)*:8–11.

Chi, M. T., Feltovich, P. J., and Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive science, 5(2)*:121–152.

Crouch, C. H. and Mazur, E. (2001). Peer instruction: Ten years of experience and results. *American Journal of Physics, 69(9)*:970–977.

Cummings, K. (2011). A developmental history of physics education research. In Second Committee Meeting on the Status, Contributions, and Future Directions of Discipline-Based Education Research. Available: http://www7.nationalacademies.org/bose/DBER Cummings October Paper.pdf.

Cummings, K., Marx, J., Thornton, R., and Kuhl, D. (1999). Evaluating innovation in Studio Physics. *American Journal of Physics, 67(S1)*:S38–S44.

Deslauriers, L., Schelew, E., and Wieman, C. (2011). Improved learning in a large-enrollment physics class. *Science, 332(6031)*:862–864.

Deutsche Physikalische Gesellschaft (retrieved June 2019). Empfehlung der Deutschen Physikalischen Gesellschaft gegen die Verwendung des Karlsruher Physikkurses an Schulen.

Docktor, J. L. and Mestre, J. P. (2014). Synthesis of discipline-based education research in physics. *Phys. Rev. ST Phys. Educ. Res., 10*:020119.

Finkelstein, N. D. and Pollock, S. J. (2005). Replicating and understanding successful innovations: Implementing Tutorials in Introductory Physics. *Phys. Rev. ST Phys. Educ. Res., 1*:010101.

Foote, K., Henderson, C., Knaub, A., Dancy, M., and Beichner, R. (2019). Try, try again: The power of timing and perseverance in higher education reform. *Change: The Magazine of Higher Learning, 51(1)*:50–57.

Hake, R. R. (1998). Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics, 66(1)*:64–74.

Hammer, D. (1996). More than misconceptions: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics, 64(10)*:1316–1325.

Handelsman, J., Ebert-May, D., Beichner, R., Bruns, P., Chang, A., DeHaan, R., Gentile, J., Lauffer, S., Stewart, J., Tilghman, S. M., et al. (2004). *Scientific teaching*.

Henderson, C. (2016). Editorial: Renaming Physical Review Special Topics— Physics Education Research. *Phys. Rev. Phys. Educ. Res., 12*:010001.

Henderson, C., Barthelemy, R., Finkelstein, N., and Mestre, J. (2012a). Physics education research funding census. In *AIP Conference Proceedings*, volume 1413, pages 211–214. AIP.

Henderson, C., Dancy, M., and Niewiadomska-Bugaj, M. (2012b). Use of research-based instructional strategies in introductory physics: Where do faculty leave the innovation-decision process? *Phys. Rev. ST Phys. Educ. Res., 8*:020104.

Henderson, C. and Dancy, M. H. (2009). Impact of physics education research on the teaching of introductory quantitative physics in the United States. *Phys. Rev. ST Phys. Educ. Res., 5*:020107.

Henderson, C., Turpen, C., Dancy, M., and Chapman, T. (2014). Assessment of teaching effectiveness: Lack of alignment between instructors, institutions, and research recommendations. *Phys. Rev. ST Phys. Educ. Res., 10*:010106.

Heron, P. R. L. (2018). Identifying and addressing difficulties: Reflections on the empirical and theoretical basis of an influential approach to improving physics education. *Reviews in PER, 2*.

Herrmann, F. (2000). The Karlsruhe physics course. *European Journal of Physics, 21(1)*:49.

Hestenes, D., Wells, M., and Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher, 30(3)*:141–158.

Huber, M. T. and Morreale, S. P. (2002). Disciplinary styles in the scholarship of teaching and learning: Exploring common ground. ERIC.

Karplus, R. (1964). One physicist experiments with science education. *American Journal of Physics, 32(11)*:837–839.

Knaub, A. V., Jariwala, M., Henderson, C. R., and Khatri, R. (2018). Experiences of postdocs and principal investigators in physics education research postdoc hiring. Phys. Rev. Phys. Educ. Res., 14:010152.

Kohl, P. B. and Finkelstein, N. D. (2005). Student representational competence and self-assessment when solving physics problems. *Phys. Rev. ST Phys. Educ. Res., 1*:010104.

Kolb, D. A. (1984). Experience as the source of learning and development. Upper Sadle River: Prentice Hall.

Libarkin, J. (2008). Concept inventories in higher education science. In BOSE Conf.

Lindell, R. S., Peak, E., and Foster, T. M. (2007). Are they all created equal? a comparison of different concept inventory development methodologies. In *AIP conference proceedings*, volume 883, pages 14–17. AIP.

Lising, L. and Elby, A. (2005). The impact of epistemology on learning: A case study from introductory physics. *American Journal of Physics, 73(4)*:372– 382.

McDermott, L. C. and Shaffer, P. S. (1998). Tutorials in Introductory Physics. Prentice Hall.

Meltzer, D. E. (2005). Relation between students' problem-solving performance and representational format. *American Journal of Physics, 73(5)*:463–478.

Meltzer, D. E. and Otero, V. K. (2015). A brief history of physics education in the United States. *American Journal of Physics, 83(5)*:447–458.

Meltzer, D. E. and Thornton, R. K. (2012). Resource letter ALIP 1: Active-learning instruction in physics. *American Journal of Physics, 80(6)*:478–496.

Novak, G. M., Patterson, E. T., Gavrin, A. D., and Christian, W. (1999). Just in Time Teaching. Prentice Hall.

Redish, E. F. (2004). Teaching physics with the Physics Suite.

Redish, E. F., Saul, J. M., and Steinberg, R. N. (1998). Student expectations in introductory physics. American Journal of Physics, 66(3):212–224.

Seymour, E., Wiese, D., Hunter, A., and Daffinrud, S. M. (2000). Creating a better mousetrap: On-line student assessment of their learning gains. In *National Meeting of the American Chemical Society*, pages 1–40.

Shipley, T. F., McConnell, D., McNeal, K. S., Petcovic, H. L., and John, K. E. S. (2017). Transdisciplinary science education research and practice: Opportunities for GER in a developing STEM discipline-based education research alliance (DBER-A). *Journal of Geoscience Education, 65(4)*:354–362.

Singer, S. R., Nielsen, N. R., and Schweingruber, H. A., editors (2012).

Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering. National Research Council; The National Academies Press, Washington, DC.

Sokoloff, D. R. (1992). Teaching electric circuit concepts using microcomputer-based current/voltage probes. In *NATO Advanced Research Workshop on Microcomputer-Based Laboratories*, Amsterdam, Netherlands, pages 130–143.

Sokoloff, D. R., Laws, P. W., and Thornton, R. K. (2007). Realtime physics: active learning labs transforming the introductory laboratory. *European Journal of Physics, 28(3)*:S83.

Stewart, J., Zabriskie, C., DeVore, S., and Stewart, G. (2018). Multidimensional item response theory and the force concept inventory. *Phys. Rev. Phys. Educ. Res., 14*:010137.

Strunk, C. and Rincke, K. (retrieved June 2019). Zum Gutachten der Deutschen Physikalischen Gesellschaft über den Karlsruher Physikkurs.

Thornton, R. K. (1987). Tools for scientific thinking – microcomputer-based laboratories for physics teaching. *Physics Education, 22(4)*:230.

Thornton, R. K. and Sokoloff, D. R. (1998). Assessing student learning of Newton's laws: The Force and Motion Conceptual Evaluation and the evaluation of active learning laboratory and lecture curricula. American Journal of Physics, 66(4):338–352.

Traxler, A., Henderson, R., Stewart, J., Stewart, G., Papak, A., and Lindell, R. (2018). Gender fairness within the force concept inventory. *Phys. Rev. Phys. Educ. Res., 14*:010103.

University of Maine (2020). YoungPER mailing list.

Wieman, C., Deslauriers, L., and Gilley, B. (2013). Use of research-based instructional strategies: How to avoid faculty quitting. *Phys. Rev. ST Phys. Educ. Res., 9*:023102.

Wieman, C. and Perkins, K. (2005). Transforming physics education. *Physics today, 58(11)*:36.

Wilson, K. G. (1993). Wisdom-centered learning: Strengthening a new paradigm for education. *The School Administrator*.

Wissehr, C., Concannon, J., and Barrow, L. H. (2011). Looking back at the Sputnik era and its impact on science education. *School Science and Mathematics, 111(7)*:368–375.

Wittmann, M. C. (2018). Research in the resources framework: Changing environments, consistent exploration. *Reviews in PER*, 2.

Wittmann, M. and Price, R. (2018). Editorial: AJP and PER. *American Journal of Physics, 86(1)*:5–6.

Yasuda, J.-i., Mae, N., Hull, M. M., and Taniguchi, M.-a. (2018). Analyzing false positives of four questions in the Force Concept Inventory. *Phys. Rev. Phys. Educ. Res., 14*:010112.