ISEE's Inquiry Framework: Six Elements to Guide the Design, Teaching, and Assessment of Inquiry Lab Units

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We acknowledge the work of many past PDP collaborators.

Inquiry is called for in many national reports on improving science and engineering education[1,2,3,4], and the terms "inquiry" and "inquiry-based" are often used in STEM education circles. However, the definitions of these terms are varied, ranging from a literal description of learning motivated by questions, to a more nuanced understanding of simultaneous learning of STEM[a] content and practices, where the PDP definition is closer to the latter view. Because inquiry is a cornerstone of our work in the PDP, we have developed a framework of six key elements that are essential to our definition of inquiry in the PDP.

This document includes a tan box at the end of each section that articulates key accomplishments that PDP participants are expected to achieve by the end of their PDP experience.

1. Cognitive STEM practices

Within ISEE, we use the phrase "cognitive STEM practices" to describe the reasoning processes that scientists and engineers use to understand the natural world and solve problems. Examples of practices include: generating explanations, designing experiments, or defining requirements. Practices (which in the literature are sometimes called processes, competencies, or reasoning skills) are emphasized in essentially all STEM education standards. For example, the Next Generation Science Standards (NGSS) calls for the integration of their identified eight core practices in K-12 science curriculum (see Box 1). Learning STEM practices is increasingly a key component of *undergraduate-level* standards. For example, in biology, "applying the process of science" is a core competency expected of all biology undergraduates [5] and is considered foundational for future physicians ("pre-meds").[6] STEM practices are also highly valued in the STEM workforce because they enable an individual to become a

Box 1: Understanding How Scientists Work

The idea of science as a set of practices has emerged from the work of historians, philosophers, psychologists, and sociologists over the past 60 years. This work illuminates how science is actually done, both in the short term (e.g., studies of activity in a particular laboratory or program) and historically (studies of laboratory notebooks, published texts, eyewitness accounts). Seeing science as a set of practices shows that theory development, reasoning, and testing are components of a larger ensemble of activities that includes networks of participants and institutions, specialized ways of talking and writing, the development of models to represent systems or phenomena, the making of predictive inferences, construction of appropriate instrumentation, and testing of hypotheses by experiment or observation.

…a focus on practices (in the plural) avoids the mistaken impression that there is one distinctive approach common to all science—a single "scientific method"—or that uncertainty is a universal attribute of science. In reality, practicing scientists employ a broad spectrum of methods, and although science involves many areas of uncertainty as knowledge is developed, there are now many aspects of scientific knowledge that are so well established as to be unquestioned foundations of the culture and its technologies. It is only through engagement in the practices that students can recognize how such knowledge comes about and why some parts of scientific theory are more firmly established than others.

Excerpted from "A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas" (2012) National Research Council

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[a] STEM = science, technology, engineering and mathematics

more independent investigator and problem solver.[7]

There are a number of lists of “core”, or foundational, STEM practices, and though there is some variation in the lists, there is also a great deal of overlap. Each of the lists shares a focus on STEM practices that are used broadly across disciplines and embody a subset of skills that scientists and engineers build upon and become increasingly more sophisticated with, as they progress from novice to expert. For example, core science practices often include:

- Generating questions and/or hypotheses
- Designing investigations
- Generating explanations

“Using models” is broken out as a core practice by some, but in other cases it is considered within the context of another core practice -- for example, using models to design experiments, or using models to generate explanations.

Core engineering practices also have been identified, and often include:

- Defining problems
- Brainstorming solutions
- Justifying solutions

As with science, there is variation and overlap. For example, “defining requirements” is an important engineering practice, and in some cases is considered part of defining problems, and in other cases is broken out separately. A good argument could be made for either way of viewing this extremely important practice, which is a key part of engineering, and less a part of science.

In the PDP, the differentiation between science and engineering is made in relation to the sets of practices used, not which discipline one is working within. Scientists regularly use engineering practices (whether or not they identify them as such) and engineers often use science practices. For this reason, all PDP participants are encouraged to develop ways of teaching both science and engineering practices.

Teaching and learning STEM practices: Practices are difficult to teach, and are rarely taught formally in the classroom. Within the PDP, a well-designed inquiry activity may engage learners in many STEM practices, but there is an explicit focus on teaching and learning one core practice in particular. That is, PDP participants do not attempt to teach in depth about generating research questions, designing experiments, and explaining results all in a six-hour lab. Instead, a PDP team chooses one core practice to focus on that is important and relevant to the disciplinary area that their activity is part of. The team delineates aspects of the practice that their learners can engage in and improve at (often drawing from education research), and they make sure the inquiry activity they design provides opportunities for learners to engage in that practice.

Box 2: Four criteria for assessing students' understanding of *scientific argumentation*:

- **Causal structure:** Science is aimed at understanding causes of nature. Consequently, scientific argument should contain causal claims
- **Causal coherence:** Many if not most scientific arguments advance chains or networks of causal inferences. These chains cohere into a sensible overarching narrative.
- **Citation of evidence:** Claims are made about data; consequently, a good argument cites the data that claims are meant to explain.
- **Evidentiary justification:** A crucial element of an argument is the relationship between claims and evidence. Good arguments explicate and justify these relationships.

Adapted from Ryu & Sandoval (2012) “Improvements to Elementary Children's Epistemic Understanding from Sustained Argumentation”

Education researchers have made significant contributions to the teaching and learning of STEM practices in recent years. Because STEM practices are not often formally taught, it is not necessarily easy for scientists and engineers to articulate what they are doing when they engage in practices. Research has focused on making aspects of core practices more explicit, so that both instructors and learners can talk about and apply practices in the learning environment.

For example, without identifying what makes a good scientific argument, it is very difficult to teach, learn and assess what makes a "good" scientific argument or explanation. A large body of work supports the idea of a scientific explanation including a claim, evidence, and reasoning (CER) – this has lead to a "CER framework", which at various points has been used in the PDP. A variation on the CER framework that has also been identified[8] for assessing students' scientific understanding is shown in Box 2. Armed with the four criteria listed, it become much easier to teach and learn the practice of scientific argumentation. For example, an instructor could identify that a student does not have a coherent chain of inferences, and then find a way to help the student find and fill gaps in reasoning.

Another contribution that education researchers have made in relation to teaching and learning STEM practices, is to identify the difficulties that students have with particular practices. For example, a number of researchers have identified difficulties that undergraduate students have with experimental design[9] (see Box 3). Though it is not a complete set of all the specific aspects of experimental design, this list of five elements could be very useful in diagnosing student difficulties with the practice, and several of these aspects could be a nice focus of a PDP activity.

Box 3: Five difficulties that undergraduate biology students have with *experimental design*:

- Identifying **variable property of an experimental subject**
- **Manipulating variables** (treatment groups, combinatorial reasoning, controlling outside variables, etc.)
- **Measurement of outcome** (categorical variables, quantitative or continuous variables, etc.)
- **Accounting for variability** (random samples, randomized design, replication of treatments, etc.)
- **Scope of inference of findings (**recognizing limits, cause-and-effect conclusions, etc.)

Adapted from Dasgupta et al. (2014), "Development and Validation of a Rubric fo Diagnosing Students' Experimental Design Knowledge and Difficulties"

A recent ISEE study has looked at difficulties that undergraduate students have as they complete a summer engineering project in an internship program.[10] The practice of defining requirements was an ongoing challenge for the interns; this was made evident through the various ways in which they were asked to formally communicate the results of their project. A lack of clearly articulated design requirements could be traced to numerous deficiencies in how and what interns presented, including possible gaps in understanding their project at a deeper level.

Box 4: Difficulties college students have in *defining requirements* of an engineering problem:

- **Identifying constraints as requirements** (and not identifying requirements)
- **Identifying non-functional requirements as functional requirements** (failure to state what the solution must do)
- **Not stating functional requirements in a way that is verifiable**

Adapted from Arnberg, N. (2014) Ph.D. Thesis, U.C. Santa Cruz

Teaching and learning STEM practices includes both doing the practice, and understandings about the practice. One study of the practice of "modeling"[11] points out that it is important for students to engage in the practice of modeling (e.g., incorporating evidence or theory into a representation, using a representation to predict or explain something), as well gaining an understanding of how models are used (how and why models are used, what their strengths and limitations are, etc.). They argue that the doing of the practice and the underlying knowledge about a practice should not be viewed as separate learning goals -- it is the integration that creates a powerful and meaningful learning experience.

ISEE does not advocate that PDP participants attempt to disentangle the doing of practices from understandings about practices, nor spend a lot of time trying to distinguish doing/understanding them. However, we strongly encourage participants to round out an inquiry activity with a component in which learners reflect on their understanding of the core practice the activity focused on. In that component, learners may reflect on how they used the practice, what they learned about it and/or may need to learn more about, and how they might apply it in different contexts. This requires that learners disentangle the practice from the content or concepts that they learned, so that they can see the generalizable aspects of the practice they engaged in, that apply beyond the activity. For this reason, we make sure that PDP participants are also able to disentangle content and practice, so that they can in turn help their learners.

PDP participants will design and teach an activity in which learners not only engage in STEM practices, but also:
- Gain proficiency with challenging and assessable aspects of one core practice
- Gain knowledge about how the core STEM practice applies in different contexts

2. Foundational STEM content

All STEM fields have core, or foundational, concepts – concepts that have broad explanatory power (can explain many phenomena) and are tied to “big ideas”. In the K-12 arena, the Next Generation Science Standards (NGSS) are intended to guide science curriculum nationally (and include both content and practices) and identify core concepts across STEM disciplines. In higher education there has been an increasing movement to establish “standards,” which are the core concepts expected to be learned. For example, five core concepts in undergraduate biology have been published as a result of a long process of building consensus from faculty members across the country (see Box 5)[12]. These core concepts are intended to be used to establish learning outcomes for courses, and also to tie “units” of study (such as a PDP activity) within a course to a larger framework of important concepts. This can be achieved through a flow-down from course learning outcomes to activity-level learning outcomes.

Box 5: Five core concepts to guide undergraduate biology education:
- Evolution
- Structure and function
- Information flow, exchange, and storage
- Pathways and transformations of energy and matter
- Systems

From “Vision and Change in Undergraduate Biology Education” (2009)

In ISEE’s definition, a well-designed inquiry activity has an intended learning outcome that includes (or is tied to) a core concept. This “content goal” challenges learners to explain a phenomenon or to design an engineering solution using that concept.

Identifying a core concept, and what it looks like when a learner understands it, is challenging for all educators. However, there are many resources that may be helpful. There is a significant body of research on how learners gain deep understanding of challenging STEM concepts, for example through a developmental process of “conceptual change” [13] over the course of an individual person’s lifetime. Some schools of thought focus attention on “misconceptions” or “alternative conceptions.” A newer theoretical perspective includes the identification of “threshold concepts” that, once

Box 6: Some identified difficulties students have related to core concepts in biochemistry:
- **Equilibrium:** Learners refer to the everyday use of the word -- everything is “just right” or “happy” – when they apply the concept of equilibrium to biological systems.
- **Intra- and Intermolecular Interactions:** Learners can name the types of intermolecular interactions but in explanations about the basis of them, use proximity of molecules rather than electrostatics.

understood, transform perception of a given subject. Some threshold concepts overlap with "troublesome knowledge" that may be counterintuitive or particularly difficult to master. An instructor can look to both threshold concepts and troublesome concepts to identify what a curriculum should focus on.[14]

There is also rapidly growing research that combines knowledge about teaching and learning in general with discipline-specific knowledge, through what is now called Discipline-Based Education Research (DBER).[15] For example, one study surveyed 75 faculty members and 50 undergraduates to identify core concepts in biochemistry and the particular difficulties that students have in understanding them.[16] Many researchers have also developed "concept inventories" – validated tests, typically a set of multiple choice questions with one correct answer and several answers that are based on common misconceptions ("distractors").

ISEE does not endorse a particular theoretical perspective, and the limited time period of the PDP excludes the possibility of discussing learning theory around conceptual understanding. However, participants are encouraged to explore this literature, and will find it very useful in identifying concepts that make appropriate learning goals. Scanning the literature for misconceptions, alternative conceptions, troublesome knowledge, etc., can be very helpful because PDP participants, like all educators, will need to identify how to distinguish between when a learner understands a concept versus when learner does not. Additional details on assessing learners' understandings are provided in the ISEE Assessment Theme document.

As PDP participants design an inquiry activity, they identify a core concept that they will teach their learners. They consider what it means for learners to demonstrate a deep understanding of that concept – an understanding that will allow them to apply it in a new context. PDP participants create an authentic setting in which their learners use a concept to explain a phenomenon, make a prediction, or design and/or support a solution. PDP participants plan for the varied amount of experience their learners may have with the concept. They anticipate potential misconceptions and/or non-intuitive aspects of the concept, and are prepared to facilitate learners as learners construct their own way of understanding the concept.

PDP participants will design and teach an activity in which learners not only engage with STEM content, but also:

- Gain an understanding of challenging and assessable aspects of one core STEM concept
- Gain an understanding of specific aspects of a core STEM concept that may be applied to different contexts

3. Intertwined content and practice

In ISEE's definition of inquiry, learners' engagement in cognitive STEM practices is motivated by conceptual understandings, and vice versa – core concepts are learned by engaging in STEM practices. Teasing apart content and practices (as described above) is an important part of teaching and assessing STEM. However, in the actual learning experience they are interwoven. As in authentic research or engineering design, STEM practices are employed to learn or design something.

The intertwining of content and practice learning is an important element of effective teaching. Some studies[17] demonstrate that engagement in "active" and "problem-based" learning can enhance long-term retention. Furthermore, instructional strategies that involve learners in collaborative projects and STEM practices can improve learners' motivation, self-direction, and their ability to transfer concepts to new problems.

ISEE has defined several points in an inquiry activity that are key to weaving together content and practices. A well-designed PDP inquiry activity starts with a component in which learners raise "how" or "why" questions that are related to a core concept and that can be further addressed by engaging in STEM practices (we call this component a "starter"). Learners then investigate or design something in order to explore an answer or solution to their question – specifically to learn about, or apply, the core concept. Content and practices are woven together throughout the activity, and the three main phases of the activity (starter, investigation, explanation of new results/understandings) are linked. More depth on this topic is included in the "design" aspects of the PDP.

PDP participants will design and teach an activity in which learners:

- Raise questions that are related to concepts they later explore or apply
- Engage in STEM practices (focal practice and others) to come to their own understanding of content
- Explain findings or solution using content understandings

4. Mirroring authentic research and design

A PDP inquiry activity reflects authentic research and/or engineering design, concentrating not only on the subtle and challenging cognitive practices of scientists and engineers, but also on social norms, values, and ways of thinking that are prevalent in STEM. Furthermore, inquiry activities mirror the way that knowledge is generated and revised in the research environment. For example, an inquiry activity on marine ecology could focus on the practice of generating a scientific explanation, giving students experience with using the particular types of evidence used to support explanations in this field. The inquiry could also include a discussion of the norms for giving feedback or asking questions during presentations in this field, and give learners practice in a context that is close to how this is done in professional settings. A learning experience that makes these aspects of STEM explicit and/or gives students practice with them builds their competency in STEM and helps them to become a part of the STEM community.

Even though there is consensus across educational communities that a major goal of STEM education is to develop learners' ability to reason scientifically, student laboratory experiences are largely "cookbook" labs that essentially tell students how to engage in practices. This style of lab bears very little resemblance to the way in which scientists and engineers employ reasoning practices to conduct original research. In a study often referred to within the PDP, Chinn & Malhotra[18] reviewed a large sample of science curricula, looking at the reasoning practices students were engaged in (in the PDP we say "cognitive STEM practices" rather than "reasoning practices"). Most curricula Chinn & Malhotra reviewed engages students in what they called "simple tasks" rather than the reasoning employed in authentic settings. Their findings are presented in a framework that can be used to evaluate authenticity of the way that learners are engaged in STEM practices. The full table is very useful, and a few highlights to demonstrate the spectrum of authentic to simple, along with an example created by ISEE, are shown in Table 1.

Table 1 (below): Engaging in STEM practices: authentic versus simple

The following table includes examples of how specific aspects of core STEM practices are carried out in authentic contexts, versus the simple way they are often carried out by students in classroom activities. It should be noted that this table shows two ends of a spectrum of authentic-to-simple, and that there is a continuum in between.

Aspect of practice	As used in authentic contexts	As used in simple context often experienced by students
Core practice: Designing experiments		
Controlling variables*	• Scientists often employ multiple controls • It can be difficult to determine what the controls should be or how to set them up	• There is a single control group • Students are usually told what variables to control for and/or how to set up a controlled experiment
Planning measures*	• Scientists typically incorporate multiple measures of independent, intermediate, and dependent variables	• Students are told what to measure, and it is usually a single outcome variable
Core practice: Generating explanations		
Transforming observations*	• Observations are often repeatedly transformed into other data formats	• Observations are seldom transformed into other data formats, except perhaps straightforward graphs
Indirect reasoning*	• Observations are related to research question by complex chains of reasoning • Observed variables are not identical to the theoretical variables of interest	• Observations are straightforwardly related to research questions • Observed variables are the variables of interest
Core practice: Analyzing Tradeoffs		
Optimizing a system	• Requires developing a scientific understanding of system • Requires iterations of improving and re-characterizing • Requires providing reasoning / justification for new iterations • System variables/components are interdependent and not easily co-optimized, with complex tradeoffs	• System is treated as a “black box”, or science behind how the system works is given • Procedure is given • A single system element or variable requires tuning to maximize performance, or at most two variables are easily co-optimized

*Excerpted from Chinn & Malhotra (2002)

Learners at the undergraduate level have likely experienced a number of “cookbook”-style labs, but more authentic experiences will better prepare them for further education and careers in STEM. ISEE identifies a number of ways in which inquiry activities can mirror authentic research and design, including engaging learners in self-directed (but supported) investigations, and providing opportunities for learners to explain and justify their work to peers and instructors while they investigate and after they come to a conclusion or solution.

PDP participants will design and teach an activity in which learners:

- Investigate their own questions about given phenomena and/or design their own solutions to problems they help to define
- Contribute, explain and justify their ideas to peers
- Are assessed as they explain findings in a way that is similar to authentic STEM reporting

5. Ownership of learning

A key component of ISEE's definition of inquiry includes learners' ownership of their learning pathway, both in relation to a STEM practice and to conceptual understanding. Other definitions of inquiry include similar elements. For example, some definitions consider "elements of inquiry" (where here they consider question raising, investigation, explanations to be inquiry elements) and the amount of learner self-direction in each element[19], or whether each particular element (e.g., a research question) was "provided" by the instructor[20]. The Education Development Center considers how each element of inquiry provides student responsibility for learning, active thinking, and motivation[21]. These definitions resonate and overlap with ISEE's conception of ownership but can be very difficult to evaluate in a concrete way. ISEE has found that *choice* and *challenge* are key ingredients in establishing learner ownership, and are more practical to observe.

For a learner to have ownership, there must be choice and opportunities for figuring out one's own path to understanding. A PDP inquiry activity provides multiple possible pathways to understanding core concepts and multiple ways to engage in practices. PDP participants are charged with the difficult task of designing and teaching an activity that has very specific intended learning outcomes, yet has multiple entry points, multiple ways to investigate or design something, and multiple solutions or ways to explain one's findings. While teaching, PDP participants facilitate learning in a way that maintains learners' ownership, without simply giving answers or instructions. PDP participants employ strategies that help them find out how a learner is thinking about or approaching a problem, and model collaboration that respects and embraces the diverse ways that learners work and learn.

PDP participants will design and teach an activity in which learners:
- Have choice and must figure out how to use a STEM practice
- Come to their own understanding of content
- Have choice in how to investigate their own question and/or design their own solution
- Have choice in the reasoning pathway used to explain their findings

6. Explaining using evidence

Supporting explanations with evidence is at the heart of science and engineering. Scientists use evidence and reasoning to generate explanations of natural phenomena, and engineers use evidence to support design choices. Constructing scientific explanations (or "arguments") is part of formal scientific communication, as well as part of the informal daily practices of scientists and engineers. They use explanations to make sense of things, justify their actions, or persuade others of the importance of their results.

Explanation is similarly foundational to *learning* science and engineering. Many studies emphasize the importance of explaining in constructing new scientific knowledge[22], and others have found that teaching students about explaining can improve their ability to learn science[23]. Furthermore, the social aspect of talking with others to build understanding together has long been known to be an important aspect of the learning process[24]. ISEE therefore considers explanation a key element of inquiry.

In a well-designed inquiry activity, learners work with existing data, materials, or simulations, or generate their own. They decide how to use this information as they develop a new scientific understanding or engineering solution. For example, learners may need to analyze data, weight measurements, and/or determine errors. Learners then decide how to refer to this evidence as they share their new understandings with others via explanation.

In an inquiry activity designed by PDP participants, learners are encouraged to go beyond simply noticing a data trend or pattern to constructing an understanding of what a trend implies or why it may have arisen. In engineering contexts, learners must justify their design choices rather than simply "guessing and checking." Each PDP inquiry activity offers an opportunity for learners to explain their new understandings in a culminating activity (e.g., reporting findings through a poster presentation or written abstract) in which learners use evidence to justify their findings.

PDP participants will design and teach an activity in which learners:
- Generate their own evidence and/or define what counts as evidence
- Use their own evidence to support an explanation of their new understandings

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References

[1] AAAS Project 2061, Rutherford, F.J., and Ahlgren, A., 1989. *Science For All Americans*, Oxford University Press, http://www.project2061.org/publications/sfaa/online/sfaatoc.htm

[2] National Research Council, National Committee on Science Education Standards and Assessment, 1996. *National Science Education Standards*, National Academies Press, http://www.nap.edu/readingroom/books/nses/

[3] National Research Council, Olson, S., and Loucks-Horsley, S., *eds*., Committee on the Development of an Addendum to the National Science Education Standards on Scientific Inquiry, 2000. *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning*, National Academies Press, http://fermat.nap.edu/html/inquiry_addendum/

[4] President's Council of Advisors on Science and Technology, Feb. 2012. "Engage to Excel: Producing One Million Additional College Graduates With Degrees in Science, Technology, Engineering, and Mathematics." http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_2-25-12.pdf from http://www.whitehouse.gov/administration/eop/ostp/pcast/docsreports

[5] American Association for the Advancement of Science, 2011. *Vision and Change in Undergraduate Biology: A Call to Action*, Washington, D.C. http://visionandchange.org/files/2011/03/Revised-Vision-and-Change-Final-Report.pdf.

[6] American Association of Medical Colleges and the Howard Hughes Medical Institute, 2009. *Scientific Foundations for Future Physicians,* https://www.aamc.org/download/271072/data/scientificfoundationsforfuturephysicians.pdf

[7] Seagroves, S. and Hunter, L. 2010. "An Engineering Technology Skills Framework that Reflects Workforce Needs on Maui and the Big Island of Hawai'i", in *Learning from Inquiry in Practice*, L. Hunter & A.J. Metevier, eds., ASP Conference Series 436: 434, http://www.aspbooks.org/a/volumes/article_details/?paper_id=32541

[8] Ryu, S., and Sandoval, W.A., 2012. "Improvements to Elementary Children's Epistemic Understanding From Sustained Argumentation", *Science Education*, 96: 488-526, http://onlinelibrary.wiley.com/doi/10.1002/sce.21006/abstract

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[9] Dasgupta, A., Anderson, T.R., and Pelaez, N., 2014. "Development and Validation of a Rubric for Diagnosing Students' Experimental Design Knowledge and Difficulties", *CBE-Life Science Education*, 13: 265, http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1005&context=pibergpubs

[10] Arnberg, N., 2014. "Science & Education: Genetic Analysis of Winter Social Structure and Social Trats in a Migratory Sparrow & Teaching Argumentation in STEM Education", Ph.D. Thesis, University of California, Santa Cruz, http://escholarship.org/uc/item/9q7118z1

[11] Schwarz, C.V., Reiser, B.J., Davis, E.A., Kenyon, L., Acher, A., Fortus, D., Shwartz, Y., Acher, A., Hug, B., and Krajcik, J., 2009. "Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners", *Journal of Research in Science Teaching*, 46:632, http://onlinelibrary.wiley.com/doi/10.1002/tea.20311/abstract

[12] AAAS and NSF, 2009. *Vision and Change in Undergraduate Biology Education: A Call to Action*, C.A. Brewer and D. Smith, eds., http://visionandchange.org/files/2013/11/aaas-VISchange-web1113.pdf

[13] See for example:

> Posner, G.J., Strike, K.A., Hewson, P.W., and Gertzog, W.A., 1982. "Accommodation of a scientific conception: Toward a theory of conceptual change", *Science Education*, 66: 211, http://onlinelibrary.wiley.com/doi/10.1002/sce.3730660207/abstract
>
> Duit, R., and Treagust, D.F., 2003. "Conceptual change: A powerful framework for improving science teaching and learning", *International Journal of Science Education*, 25: 671

[14] Meyer, J.H.F., and Land, R., 2003. "Threshold Concepts and Troublesome Knowledge – Linkages to Ways of Thinking and Practising", *Improving Student Learning – Ten Years On*, C. Rust, ed., Oxford Center for Staff and Learning Development, Oxford, https://www.dkit.ie/ga/system/files/Threshold_Concepts_and_Troublesome_Knowledge_by_Professor_Ray_Land.pdf

[15] See for example: National Research Council, 2012. *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*, Washington, D.C., http://www.nap.edu/catalog/13362/discipline-based-education-research-understanding-and-improving-learning-in-undergraduate

[16] Loertscher, J., Green, D., Lewis, J.E., Lin, S., and Minderhout, V., 2012. "Identification of Threshold Concepts for Biochemistry", *CBE Life Sciences Education*, 13: 526, http://www.ncbi.nlm.nih.gov/pubmed/25185234

[17] See for example:

> Kvam, P.H., 2000, "The Effect of Active Learning Methods on Student Retention in Engineering Statistics", *The American Statistician*, 54:136, http://amstat.tandfonline.com/doi/abs/10.1080/00031305.2000.10474526#.VN_6396waMM
>
> Norman, G.R., and Schmidt, H.G., 1992. "The psychological basis of problem-based learning: a review of the evidence", *Academic Medicine*, 67: 557, http://journals.lww.com/academicmedicine/Abstract/1992/09000/The_psychological_basis_of_problem_based_learning_.2.aspx

[18] Chinn, C.A., and Malhotra, B., 2002. "Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks", *Science Education*, 86: 175, http://onlinelibrary.wiley.com/doi/10.1002/sce.10001/abstract

[19] National Research Council, 200. *Inquiry and the National Science Education Standards: A Guide for Teaching and Learning*, National Academies Press, http://www.nap.edu/openbook.php?record_id=9596

[20] Buck, L.B., Bretz, S.L., and Towns, M.H., 2008. "Characterizing the Level of Inquiry in the Undergraduate Laboratory", *Journal of College Science Teaching*, 38: 52, http://www.chem.purdue.edu/towns/Towns%20Publications/Bruck%20Bretz%20Towns%202008.pdf

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[21] Education Development Center, Inc., 2006. “Conceptualizing Inquiry Science Instruction”, Technical Report 2 from Inquiry Synthesis Project, *Has Inquiry Made a Difference? A Synthesis of Research on the Impact of Inquiry Science Instruction on Student Outcomes*

[22] See for example: Knorr Cetina, K., 1999. *Epistemic Cultures: How the Sciences Make Knowledge*, Harvard University Press, http://www.hup.harvard.edu/catalog.php?isbn=9780674258945

[23] Nussbaum, E.M., Sinatra, G.M., and Poliquin, A., 2008, “Role of Epistemic Beliefs and Scientific Argumentation in Science Learning”, International Journal of Science Education, 20: 1977, http://www.tandfonline.com/doi/abs/10.1080/09500690701545919#.VOGFjN6waMN

[24] Vygotsky, L.S., 1978. Mind in Society: *The Development of Higher Psychological Processes*, Harvard University Press, http://www.hup.harvard.edu/catalog.php?isbn=9780674576292