Constructivism in Physics Education
– Philosophically Problematic, but Pedagogically Successful

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The famous work of Thomas Kuhn (1970), *The Structure of Scientific Revolutions* sparked a new philosophical analysis and critique of science: constructivism (Glaserfeld, 1995). Presented as a counter to empiricism, which places facts outside of theory, and emphasizes prediction and validation of theory as determined by facts, constructivism tends to give facts much less honor of place, regarding them as only one component in validating theory. Indeed, some versions of constructivism question the existence of facts in the common sense of the word.

Constructivism as a alternative to empiricism is nicely described in Encyclopedia Britannica. Empiricism claims that "…the facts justifying changes in scientific ideas are both intellectually prior to the theories…developed to explain them and also capable of being recognized…in advance of all theory construction.....Given this presupposition, [empiricists] regard prediction and validation as the crucial and distinctive steps in scientific procedure". For example, the measurement of the aberration of starlight during the 1919 solar eclipse empirically validated the predictions of Einstein's General Theory of Relativity. But the General Theory also explained the previously known fact of the advance of Mercury's perihelion.

Constructivism claims that "…the essential test of a science it that it should provide coherent, consistent, and wide-ranging theoretical organizations. Empirical facts will then be recognized as scientifically relevant only to the extent that they exemplify these interpretations and make them more discriminating…Thus, no single factual observation can ever serve as a logically crucial experiment". For example, the question, "Is light a wave or a particle?" turned out to be an inappropriate theoretical construction. Experiments confirmed both, forcing reconsideration of the question, and the replacement of classical theory with quantum mechanics and its own newly constructed theoretical categories.

Britannica claims that "Both Empiricist and constructivist philosophers oversimplify…" . Examples of this are not hard to find. The *empirical* tests of the theory of relativity depend on a prior *reconstruction* of classical notions of time and space, and replacing of the force concept with the idea of a spacetime metric. On the other hand, the *constructivist* reorganizing of the body of physical knowledge into the theory of quantum mechanics is subject to *empirical* tests of its validity: e.g., Bell's Inequality demonstrated that the predictions of Bohr's interpretation of quantum mechanics accorded with experimental data, while the predictions of Einstein's interpretation did not.

There are various subsets within constructivism, each with its own assumptions (See e.g., Gautreau & Novemsky, 1997; Solomon, 1994):

-**Constructivism**: "a complex philosophical approach to the conceptualization of phenomenological world within the head of the observer". "Facts" depend on theory construction.
-**Personal constructivism**: "Students come into our classrooms as amateur scientists" not as "empty vessels." Students must therefore be "active learners", since they *construct*, rather than merely *absorb* meaning, as they are taught.

-**Social constructivism**: "…as social beings we need to legitimate the world picture we are continuously constructing…these conversations profoundly affect both the world picture we are creating and our view of ourselves".

Physics teachers tend to be philosophical empiricists, but many of them have become pedagogical constructivists. They believe in facts, but also believe that learners construct knowledge, in which facts play an important but not exclusive role. Constructivist science pedagogy has become widespread, especially in teacher education (Fensham et al., 1994; Matthews, 2002 and references therein). The burgeoning field of physics education research [PER] (McDermott and Redish, 1999) has based its pedagogical initiatives on constructivist assumptions.

Danish physics teachers have been in the forefront of constructivist pedagogy (e.g., Jensen, 2001; Paulsen, 1994; Nielsen and Paulsen, 1991). Beyer (1992) has argued for a close connection between constructivist science pedagogy and reduction of science anxiety, especially in females. Roskilde University has pioneered group research projects, a particularly powerful form of this pedagogy.

There is, however, considerable concern regarding the validity of constructivist philosophy. Solomon (1994) has argued that such claims as "children are natural scientists" and that "group investigations will lead to correct answers" are not in fact valid. Matthews (2002) has provided a strong critique of much of the constructivist enterprise, arguing that it is a misinterpretation of Kuhn, that its assumptions are flawed, and that it places barriers in the way of science learning. (He also has produced in that paper, an hilarious chart of constructivist-speak and its normal English translation).

Of special concern are those aspects of the constructivist critique contained in what Matthews (2002) refers to as the "radical constructivist paradigm" where it is argued that science (especially physics) as currently constructed is a Eurocentric male enterprise, and therefore alien to women (e.g., Harding, 1991; Keller, 1985). There have been intense discussions and analyses of this paradigm (e.g. Harding, 1998; Mallow, 1998) as compared with other models for women's participation in science (e.g. Fuller et al., 1985). Hake and I have developed a database of references in Gender Issues in Physics/Science Education [GIPSE] (Mallow and Hake, 2002), in which we summarize the various arguments, and offer our own and others' critiques. Kastrup and I (Kastrup and Mallow, 2003) have embarked upon a project to elucidate why constructivist pedagogy seems to work, despite its problematic philosophical underpinnings.

But what in fact is the evidence that it *does* work? Constructivism's most common manifestation in physics pedagogy is what is called "interactive engagement" (IE), the substantial departure from lecture mode to student-teacher and student-student interaction. Most traditional physics lecturers argue that the time spent on such interaction is time taken from coverage of essential material. They can point to numerous studies in which researchers have demonstrated an improvement in students' *attitudes* towards science, or in which students performed well on exams designed to test IE learning, but they claim that in traditional exams testing coverage of standard material, the IE students would perform more poorly than those in standard lecture courses.

There are two possible answers to this question. The first is to ask, "Do the standard lecture courses actually teach understanding of physics? Do the standard exams actually test understanding of physics?" PER researchers have demonstrated conclusively that more often than not, the answer to both questions is "No". They have done this by devising tests of conceptual understanding, as opposed to strict numberheavy problem solving, and shown that the two correlate very poorly. In particular, good problem solvers are frequently very bad at understanding just what the underlying concepts are. Thus, an appropriate study should be one in which students in IE courses and students in traditional courses are given the same *conceptual exams*, and the results compared.

The second answer is to see whether in fact IE produces students whose performance is as good or better *on traditional exams* than that of students who take traditional lecture courses.

Almost a decade ago, both answers were provided: the first by Richard Hake, the second by Ronald Gautreau and Lisa Novemsky.

Hake (1998) demonstrated that physics courses with IE emphasis led to significantly higher *conceptual learning* than traditional "chalk-and-talk" lectures. He acquired data from 62 introductory physics courses, with 6542 students, from American secondary schools, four-year bachelors' degree-granting colleges, and universities. Fourteen of the courses were taught using traditional lecturing; the others all employed one or more forms of IE for a substantial portion of the course. All of the students had taken a pre-test in mechanics concepts at the beginning of the course, and a post-test at the end. The tests were either the Mechanics Diagnostic test [MDI] (Halloun and Hestenes, 1985) or the Force Concept Inventory [FCI] (Hestenes et al., 1992).

Hake designed a measure of students' gain in conceptual understanding, based on the difference between pre-and post-test performance. He found that the students in IE courses consistently outperformed the students in traditional courses. These students ranged from those who had chosen to make physics or engineering their career, to elementary education students. Indeed the latter in IE courses understood mechanics better than the former in traditional courses.

Hake's study has been scrutinized for error over almost a decade, and it has stood the test of time.

But conceptual understanding on the MDI or FCI is one thing; passing a typical physics exam which comprises mostly problem solving is quite another. A less well-known, but equally important work (Gautreau and Novemsky, 1997) tested students in IE and traditional learning situations, under controlled conditions in separate sections of a single introductory mechanics-based physics course at one institution, the New Jersey Institute of Technology (NJIT). The IE sections used a particular form of instruction: Alan Van Heuvelen's *Overview, Case Study* [OCS] methodology (Van Heuvelen, 1991), coupled with small-group interactions. The same teachers were switched between traditional and IE sections in successive semesters, to control for instructor bias.

Gautreau and Novemsky found in this micro-experiment what Hake had found in his meta-analysis: IE students consistently out-performed traditional students. But in this case, the performance of the two groups of students was measured by their scores on the same traditional problem-solving based physics exams. Thus, IE was shown to produce students whose performance on *standard physics exams* was superior to that of students in the standard lecture courses.

Gautreau and Novemsky also showed that disadvantaged minority students in New Jersey Institute of Technology's special pre-college summer program outperformed the traditional NJIT students, if the summer program used the IE methodology.

In summary, students who learn introductory physics with interactive engagement acquire both a stronger understanding of physics concepts and a better ability to solve traditional physics problems. That the two are coupled is not surprising.

Has there been a massive revolution in physics pedagogy since these two revolutionary papers? Sadly, no. Hake himself predicted that educational inertia would take its toll of IE innovation, as it had done with so many earlier advances. Gautreau and Novemsky noted that even a teacher who had been one of those in their IE experiment and had seen the remarkable change in performance, went contentedly back to lecturing. Students themselves have sometimes objected to IE. In our experience at Loyola University, we have found that pre-medical students in particular often complain about IE in physics courses. "Just teach me what I need to know for the Medical College Admissions Test" is their mantra.

Well, maybe there has not been a massive revolution, but there has been a small one. Constructivist pedagogy is a primary focus of every meeting of the American Association of Physics Teachers. PER researchers employ it in their various studies; instructors report on its efficacy in their teaching. The same is true in Denmark, and increasingly in other countries. The international physics teaching community has evolved, and there are more and more classes in which lecturing is blended with a range of IE pedagogies: group projects, Socratic dialogue, peer instruction and more. IE is, happily, developing its own inertia, and will not easily give way to old methods—although someday, new ones may well overthrow it.

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