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Paul J. Wendel

Otterbein University

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PAUL J. WENDEL
Department of Teaching, Leadership, and Curriculum Studies
Kent State University Kent, OH 44242

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Abstract: In *Modeling Theory in Science Education*, Ibrahim Halloun (2004) adopts the word 'paradigm', but his use of the term is radically different from that of Kuhn. In this paper, I explore some of the differences between Kuhn's paradigms and Halloun's paradigms. Where Kuhn's paradigms are public, community-defining exemplars of practice, Halloun's paradigms are private, individualized ways of thinking. Where Kuhn writes of the paradigm shift as a revolutionary, vision-altering conversion experience, Halloun writes of a gradual evolution from one way of thinking to another and an easy back-and-forth switch between paradigms. Since Kuhn's paradigms are self-enclosed and incommensurable, there is no objective standard by which one paradigm can be shown to be superior to the other. But Halloun uses 'viability' as a standard for paradigm choice. Underlying all of this is the more basic question of whether the history of science is an appropriate metaphor for student progress in the classroom. I conclude with some brief thoughts on this question.

Introduction

Through two decades, 'modeling' has evolved as an epistemology as well as a physics pedagogy (Arizona State University 2005; Halloun 1996a, 1998; Halloun & Hestenes 1987; Hestenes 1987, 1996; Wells, Hestenes, & Swackhamer 1995). In *Modeling Theory in Science Education*, Ibrahim Halloun (2004) assembles these two decades of thought into a coherent theory. Leaning heavily on the philosophy of Bachelard (1968/1940) as developed by Mortimer (1995) as well as Halloun's studies of the personal epistemologies of physics students (Halloun 1996b; Halloun & Hestenes 1998), Halloun suggests that with respect to scientific thinking, the human mind can be represented by three types of paradigms. The first of these is the naïve realist paradigm (NR), characterized by a reliance on sense experience and straightforward measurements. A naïve realist will tend to take a strictly inductive, Baconian view of scientific knowledge. For example, a naïve realist will regard mass as little more than an observed or measured quantity. The second type of paradigm is classical scientific realism (CR), characterized by the use of theoretical constructs. A classical realist will take a more deductive approach to scientific knowledge. For example, a classical rationalist may treat mass as a ratio between two other constructs, force and acceleration. The third type of paradigm is modern scientific realism (MR), characterized by the insights of relativity and quantum theory. Concepts such as space and time are no longer absolute, and classical causality is replaced with the probabilistic world of quantum physics. To a modern scientific realist, mass depends on speed and other factors.

Halloun does not claim that anyone is a ‘pure’ naïve realist, classical realist, or modern realist. Instead, consistent with Bachelard, Mortimer, and his own surveys of students (Bachelard 1968/1940; Halloun 1996b; Halloun & Hestenes 1998; Mortimer 1995), Halloun suggests that each person combines various paradigms into a unique profile. Following Bachelard and Mortimer, Halloun illustrates this concept as follows:

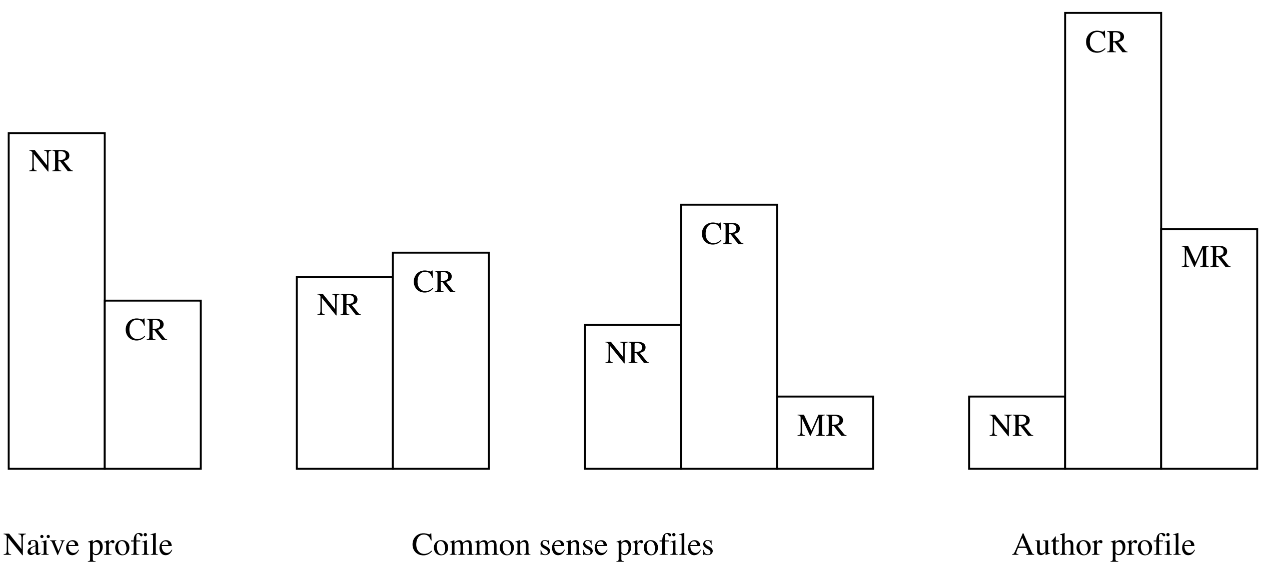

Figure 3.2. Paradigmatic profiles

Bars are not to scale in the above bar charts, and bars’ relative heights reflect an ordinal and not a proportional order of magnitude.

My own natural paradigmatic profile is currently dominated more by classical scientific realism (CR) than by modern scientific realism (MR) because my professional experience has so far been concerned more with CR than MR. The naïve realism (NR) dimension is mostly about physical realities that are the object of scientific fields outside my domain of expertise, and which I casually contemplate. (Halloun 2004, p. 97)

As one progresses in science, NR paradigms are applied less frequently and in fewer domains, while the CR and MR paradigms are applied more frequently and in a greater number of domains. Note that in the caption to Figure 3.2 (above), Halloun explains his own incomplete suppression of NR paradigms as the result of his incomplete experience in science. Therefore by Halloun's account, a complete experience of all domains of science would eliminate his NR paradigms. This is one of several significant departures from the Bachelard/Mortimer account, in which naïve realism would persist for a different reason:

> No one can survive without common sense. Even a professional scientist uses phrases such as 'shut the door and keep the cold out'. There is evidence to show that physicists use naïve notions to make predictions in everyday life (McDermott 1984) . . . . This way of viewing the world is largely incorporated as a cultural feature of everyday life. A person can acquire the capacity to criticize its meaning in the light of more sophisticated ways of thinking. However, to suppress the alternative conceptions sometimes means suppressing common-sense thought and its mode of expression, everyday language, which is the most comprehensive way of sharing meaning in a culture and permits communication between all the various specialized groups that share the same mother tongue. To suppress it means suppressing the possibility of different groups sharing meaning within the same culture. (Mortimer 1995, p. 276)

For Mortimer, naïve realism is built into our language and is therefore inescapable, whereas for Halloun, NR paradigms persist because of incomplete experience. Halloun modifies the Bachelard/Mortimer account in other ways as well. He reduces Bachelard/Mortimer's number of categories from five to three, and he renames each type of paradigm as a 'realism' instead of Bachelard's 'realism', 'empiricism', and 'rationalism'; or Mortimer's 'concretism', 'empiricism', 'rationalism', and 'idealism'. Perhaps most significantly, Bachelard and Mortimer do not refer to 'paradigms' at all, but 'ways of thinking'. The use of the word 'paradigm' in the context of a personal epistemology is Halloun's invention. As we will see, this use of the word represents a significant departure from that of Thomas Kuhn.

Personal Paradigms

Although the use of the word ‘paradigm’ in philosophy of science can be traced to Georg Christoph Lichtenberg of the late 18th century and Ludwig Wittgenstein of the early 20th century (Cedarbaum 1983), the present popularity of the term originates in Thomas Kuhn’s (1970) *The Structure of Scientific Revolutions*. For Kuhn, paradigms are exemplars of scientific practice:

> I take [paradigms] to be universally recognized scientific achievements that for a time provide model problems and solutions to a community of practitioners. (p. viii)
>
> By choosing [paradigms], I mean to suggest that some accepted examples of scientific practice—examples which include law, theory, application, and instrumentation together—provide models from which spring particular coherent traditions of scientific research. (p. 10)

In Kuhn’s use of the term, a paradigm is a model of scientific practice. This model is shared and accepted by a community of scientists, and the model defines the community. Those who accept the paradigm can be part of the community, and those who reject the paradigm cannot. Therefore a paradigm is a *public* entity. There are no private paradigms any more than there are private languages.

Although a paradigm is public, it has private consequences. By Kuhn’s account, acceptance or rejection of the paradigm determines how scientists see the world. For example, he writes that Aristotle did not see pendulums, whereas Galileo and the medieval scholastic Oresme did:

> To the Aristotelians, who believed that a heavy body is moved by its own nature from a higher position to a state of natural rest at a lower one, the swinging body was simply falling with difficulty. Constrained by the chain, it could achieve rest at its low point only after tortuous motion and a considerable time. Galileo, on the other hand, looking at the swinging body, saw a pendulum, a body that almost succeeded in repeating the same motion over and over again ad infinitum . . . At least in Oresme’s case, and almost certainly in Galileo’s as well, it was a view made possible by the transition from the original Aristotelian to the scholastic impetus paradigm for motion. Until that scholastic paradigm was invented, there were no pendulums, but only swinging stones, for the scientist to see. Pendulums were brought into existence by something very like a paradigm-induced gestalt switch. (Kuhn 1970, pp. 118-120)

By Kuhn's account, the impetus paradigm brought pendulums into existence. Kuhn goes so far as to say that 'though the world does not change with a change of paradigm, the scientist afterward works in a different world' (p. 121). Yet we must avoid a temptation here—although a paradigm profoundly affects the work and the private thought life of the scientist, the paradigm remains a public entity. Although I may speak to myself, the language with which I speak to myself remains public (Ryle 1949/1984, p. 27). In the same way, I may view the world through a specific scientific paradigm, but the paradigm is meaningful only as it is shared with others. Like languages, paradigms are community property.

Yet Halloun describes paradigms as private, individual affairs:

> No two people can ever share exactly the same paradigm, whatever the nature of the paradigm or the profession that the two people might have in common, and this, because of biological and cultural differences in people's history. For paradigms of a particular nature, differences are significantly more pronounced within the lay community than within a professional community guided by such paradigms. . . . In fact, a scientific paradigm may be delimited in a specific field in such a way that we can practically ignore paradigmatic differences among scientists working in this field, and say that all those scientists share virtually the same paradigm. (Halloun 2004, pp. 14-15)

Halloun places the paradigm within the person, so like fingerprints or DNA, no two paradigms can be exactly alike. Under this trait-like account of paradigms, we can group people according to the similarity of their paradigms. The personal paradigms of scientific communities are notable because they are 'virtually the same'. Presumably we could determine whether or not a scientist was a Newtonian by estimating his or her degree of Newton-ness along a continuous Newtonian scale.

Halloun's concept of the paradigm contrasts sharply with the Kuhnian paradigm. As noted above, a Kuhnian paradigm is an exemplar, a theoretical or experimental model which guides the practice of individual scientists. Since this exemplar is a specific event or practice, it lies outside of the individual. Therefore under Kuhn's theory, there are no degrees of Newton-ness. Either one accepts and works under the Netwonian paradigm or one does not. In this regard, Kuhn's is a quantum epistemology. Halloun has moved the paradigm from an exemplar outside the individual to a trait within the individual; he has broken a single paradigm shared by many scientists into many personal paradigms which overlap to varying degrees; and he has changed membership in a scientific community from a question of participation to a comparison of degrees of similarity along a continuum. In short, he has inverted, atomized, and de-quantized the Kuhnian concept of paradigm.

Paradigmatic Evolution

Among the crucial (and controversial) concepts in *The Structure of Scientific Revolutions* is the incommensurability of paradigms:

> [T]he proponents of competing paradigms practice their trades in different worlds. One contains constrained bodies that fall slowly, the other pendulums that repeat their motions again and again . . . Practicing in different worlds, the two groups of scientists see different things when they look from the same point in the same direction. (Kuhn 1970, p. 150)

Because the two groups of scientists practice in different worlds, they cannot perceive the world in the same way, and therefore they are unable to communicate fully with each other: '[c]ommunication across the revolutionary divide is inevitably partial' (p. 149). Consequently, compromise is impossible. When someone switches from one camp to another, it is like entering a new world:

> [Paradigmatic crises] are terminated, not by deliberation and interpretation, but by a relatively sudden and unstructured event like the gestalt switch. Scientists then often speak of the "scales falling from the eyes" or of the "lightning flash" than "inundates" a previously obscured puzzle, enabling its components to be seen in a new way that for the first time permits its solution. (Kuhn 1970, p. 122)
>
> Like a gestalt switch, it must occur all at once (though not necessarily in an instant) or not at all. (p. 150)

The scientist experiences a gestalt switch, a sudden and complete paradigm shift. Although it may occur over time, it isn't a gradual change; it is a scientific *revolution*. Yet Sharrock and

Read (2002) point out an important limitation to Kuhn's gestalt switch metaphor. In the classic gestalt images, one's perception can switch back and forth between a duck and a rabbit or an old woman and a young woman. Yet by Kuhn's account, scientific revolutions are one-way—once the scientist has switched paradigms, there is no going back to the old way of seeing (Sharrock & Read 2002, pp. 45-46).

However, Halloun's inversion/personalization of the paradigm concept enables incommensurable paradigms to peacefully coexist within the same person. For Halloun, a student's scientific maturation is not characterized by an apprenticeship into a community of practice, but in learning to employ different paradigms in different situations:

> A physicist may use a Newtonian model (CR-type . . .) to study a typical transition . . ., and then shift to a relativistic model ([MR]) to study the same transition or a similar one, should s/he desire to significantly improve the precision of the outcomes. In contrast, paradigmatic profiles of ordinary people, science students included, do not have their scopes and limits of viability well delineated, and various paradigms often overlap in conflicting ways. A student might have recourse to a particular model with one particular instance of a given pattern (say, a positivist, [NR] model . . .), and then a contradictory model (say, a Newtonian, CR one) with another instance of the same pattern considered under the same rational and empirical conditions as before. (Halloun 2004, p. 95)

By atomizing and personalizing paradigms, Halloun has reduced the vision-altering, community-defining character of the Kuhnian paradigm to a matter of choosing the appropriate paradigm for the situation at hand. Instead of a crisis over how scientists see the world, we have an epistemological supermarket. The one-way gestalt switch, the 'conversion experience' (Kuhn 1970, p. 151) of the Kuhnian revolution is replaced by a regular and perhaps easy back-and-forth switch from paradigm to paradigm.

From a Kuhnian perspective, the novice student described above would be *pre-paradigmatic*, participating in no paradigm at all, and education would be a matter of initiating the student into a paradigm. But Halloun's wholesale change of the paradigm concept enables him to describe the education process not as a matter of paradigmatic initiation, but as a matter of transformation from a naïve paradigm to a scientific paradigm. This transformation is not a matter of revolution for Halloun, but a matter of paradigmatic evolution:

> Paradigmatic evolution involves the *transformation* of existing constituents of a person's initial paradigmatic profile, as well as *formation* of new paradigmatic constituents. Transformation extends from the refinement to the rejection and replacement of existing conceptual structures and processes. (Halloun 2004, p. 113, emphasis original)

A Kuhnian paradigm may develop over time, but it doesn't evolve into a new paradigm. Instead, the pressure of anomalies builds within the paradigm until a paradigm shift occurs. It is a discontinuous process. By contrast, Halloun's personal paradigms can gradually evolve from one to another. As an educator, one hopes that the student will eventually choose scientific paradigms more often than naïve paradigms:

> [T]eachers can only hope that in any conceptual profile possessed by individual students some but not all of its naïve components become modified. Thus, one can never expect an integral paradigm shift, from naïve to scientific realism, but only a partial, though significant, change of the paradigmatic or conceptual profile in the positive direction. (Halloun 2004, p. 130)

Whereas Kuhn is a catastrophist, speaking of a sudden shift in perspective, Halloun is a gradualist, speaking of a slow transition from domination by naïve paradigms to domination by scientific paradigms.

Viability

A consequence of the incommensurability of Kuhnian paradigms is that there exists no external standard by which one can compare one paradigm to another. A paradigm is a self-enclosed system, setting the standard for appropriate questions as well as satisfactory answers:

> Like the choice between competing political institutions, that between competing paradigms proves to be a choice between incompatible modes of community life. Because it has that character, the choice is not and cannot be determined merely by the evaluative procedures characteristic of normal science, for these depend in part upon a particular paradigm, and that paradigm is at issue. When paradigms enter, as they must, into a debate about paradigm choice, their role is necessarily circular. Each group uses its own paradigm to argue in that paradigm's defense.
>
> The resulting circularity does not, of course, make the arguments wrong or ineffectual. The man who premises a paradigm when arguing its defense can nonetheless provide a clear exhibit of

> what scientific practice will be like for those who adopt the new view of nature. That exhibit can be immensely persuasive, often compellingly so. Yet, whatever its force, the status of the circular argument is only that of persuasion. It cannot be made logically or even probabilistically compelling for those who refuse to step into the circle. (Kuhn 1970, p. 94)

Since practitioners of competing paradigms reason from within the paradigm, the competing paradigms stand on equal footing. Each paradigm is equally able to answer its own questions. Therefore paradigm choice is not a matter of evidence, but a matter of persuasion.

As mentioned above, a novice does not participate in a Kuhnian paradigm, but is rather pre-paradigmatic. Although Halloun acknowledges that the novice's thoughts are neither systematic nor self-consistent (e. g. p. 118), his individualization of the paradigm concept enables him to elevate the novice's untutored thoughts to the status of paradigm. Consequently, Halloun deals with education as a matter of paradigm shift (or more accurately paradigm evolution) rather than paradigm initiation. In doing so, he deals with NR 'paradigms' in a decidedly non-Kuhnian way:

> [S]tudent conceptions about physical realities consist more of mixed beliefs and knowledge of vague correspondence to the real world than of *viable* knowledge about physical realities. (Halloun 2004, p. 89, emphasis added)

And,

> [M]ost of what students think they know about the course actually consists of mixed beliefs, naïve or *viable*, about science and to a lesser extent about physical realities. The relative amount of knowledge and the proportion of naïve knowledge to *viable* knowledge vary from course to course, and from one student to another in a given course. (Halloun 2004, p. 116, emphasis added)

For Halloun, CR and MR paradigms are viable, whereas NR paradigms are not viable. In making such statements, Halloun is forgetting or disregarding the self-enclosed, circular nature of the Kuhnian paradigm. If we insist on describing novice beliefs as paradigms, then the viability of those beliefs should not be in question. They work very well within the everyday world of the student. If an outfielder wishes to catch a fly ball, an everyday, naïve way of thinking will be more useful than a CR or MR paradigm. Halloun forgets that when he demonstrates to the student that her naïve conceptions are not viable, he also introduces new standards for viability. The scientific paradigm provides the new questions as well as the new answers.

The Adaptability of the Paradigm Concept

Now that I have pointed out that Halloun and Kuhn use the word ‘paradigm’ in radically different ways, Halloun or anyone else might very well respond with a shrug. After all, language constantly evolves (McWhorter, 2002), so an evolution of the word ‘paradigm’ is to be expected. Citing Margaret Masterman (1970), Halloun points out (Halloun 2004, p. 15) that ‘paradigm’ was never well defined in *The Structure of Scientific Revolutions*. Critics such as Kenneth Caneva (2000) and Michael Matthews (2004) have criticized Kuhn for imprecision in key issues cited above, such as Kuhn’s failure to adequately account for the relationship between the individual scientist and the community and his failure to explain how a gestalt switch can occur over an extended period of time. Kuhn has many critics (see, e. g., Lakatos & Musgrave 1970). Perhaps Halloun has simply taken a flawed paradigm concept and transformed it into a useful one.

In response, I would begin by noting the necessity of precision in scholarly work. If Halloun’s use of ‘paradigm’ differs from the conventional use of the term, he should point this out. Early in *Modeling Theory in Science Education*, Halloun makes an effort to do so:

> Our position regarding paradigms, and especially scientific paradigms, converges in part with Kuhn’s position. We do not fully subscribe to Kuhn’s work (1970), or any other work in the philosophy of science for that matter . . . (Halloun, 2004, p. 16)

Yet following this disclaimer, Halloun lays out an essentially Kuhnian definition of ‘paradigm’, beginning with: “We thus define a *scientific paradigm* as a natural paradigm shared by members of a particular scientific community, of well-defined scope in the real world, and consisting of . . .' (p. 16, emphasis original). Here and in the extensive definition that follows, we see no hint of the inverted, atomized, gradualist use of the term that characterizes Halloun's subsequent use of the term. Furthermore, Halloun cites Kuhn nearly 20 times throughout the book, including at least 9 quotations. Apparently, Halloun is unconscious of his extensive redefinition of the term.

Halloun notes that Masterman (1970) lists 21 uses of the word 'paradigm'. Yet Masterman's point isn't that the word is 'up for grabs': 'It is evident that not all of these senses of "paradigm" are inconsistent with one another: some may even be elucidations of others' (Masterman 1970, p. 65). As I read the list, it appears to me to be a list of metaphors in the development and explication of the paradigm idea rather than a list of conflicting definitions. To borrow Ludwig Wittgenstein's phrase, Kuhn's various uses of 'paradigm' bear a close family resemblance. Masterman concludes, and many philosophers would agree, that the concept of paradigm is crude. Yet Masterman counts the 'crudeness' of the paradigm concept as a strength rather than a weakness! She asserts that if it were defined too precisely, it would no longer be a useful concept (pp. 79-81). Although the concept is crude, Masterman would agree that it is not without boundaries. However, Halloun's use of the word falls outside of Kuhn's boundaries.

Conclusion: Historical vs. Cognitive Development

Halloun looks to Kuhn for guidance because he assumes that the historical development of the sciences bears some relationship to the learning of science by individual students:

> [W]e believe that Kuhn's account of the development of scientific paradigms provides significant insights not only into those paradigms, but also into the natural paradigms of science students. In this respect, the cognitive implications of Kuhn's work bear for us a special value . . . (Halloun 2004, p. 16)

Piaget (1970) championed the idea that the development of individual students recapitulates historical development, and the idea plays an important role in conceptual change theory as well (see, e. g., Hewson 1981; Posner, Strike, Hewson, & Gertzog 1982). However, I have come to doubt that 'cognitive ontogeny recapitulates scientific phylogeny' (Matthews, 1994, p. 208). For example, Aristotle's beliefs about falling objects and the impetus theories of the medieval scholastics are sometimes cited in support of the thesis. Yet Aristotle and the medieval scholastics were highly systematic thinkers who strived for self-consistency. By contrast, Halloun points out that novice thinking is often *ad hoc* and inconsistent (e. g. p. 118). How are ancient natural philosophers comparable to novices? Or as other critics have noted:

> The naïve astronomical theories of students are certainly not so complex and observationally accurate as the Ptolemaic theories that Copernicus confronted. And the current naïve astronomical theories certainly do not include assumptions about the immutability of the heavens or the existence of crystalline spheres surrounding the earth. Thus, a case by case study needs to be made of the dominant naïve theories in various domains . . . (Duschl, Hamilton, & Grandy 1992, p. 40)

Again, how are ancient experts, steeped as they were in a particular paradigm, comparable to modern pre-paradigmatic novices? Like many others before him, Halloun assumes that history is an appropriate metaphor for cognitive development. Soon the personal paradigm becomes an appropriate metaphor for the workings of the human mind. The Kuhnian paradigm, however, does not lie within the student. Therefore the Kuhnian paradigm is an inappropriate metaphor for the working of the human mind.

References

Arizona State University.: 2005, *Modeling Instruction Program*, from http://modeling.asu.edu/

Bachelard, G.: 1940/1968, *The Philosophy of No: A Philosophy of the New Scientific Mind* (G. C. Waterston, trans.), Orion Press, New York.

Caneva, K. L.: 2000, 'Possible Kuhns in the History of Science: Anomalies of Incommensurable Paradigms', *Studies in History and Philosophy of Science* **31**(1), 87-124.

Cedarbaum, D. G.: 1983, 'Paradigms', *Studies in History and Philosophy of Science* **14**(3), 173-213.

Duschl, R. A., Hamilton, R. J., & Grandy, R. E.: 1992, 'Psychology and Epistemology: Match or Mismatch when Applied to Science Education?'. In R. A. Duschl & R. J. Hamilton (eds.), *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice*, University of New York Press, Albany, NY, pp. 19-47.

Halloun, I.: 1996a, 'Schematic Modeling for Meaningful Learning of Physics', *Journal of Research in Science Teaching* **33**(9), 1019-1041.

Halloun, I.: 1996b, *Views About Science and Physics Achievement: The VASS story*, from http://modeling.la.asu.edu/R&E/Research.html

Halloun, I.: 1998, 'Schematic Concepts for Schematic Models of the Real World: The Newtonian Concept of Force', *Science Education* **82**(2), 239-283.

Halloun, I.: 2004, *Modeling Theory in Science Education*, Kluwer Academic Publishers, Boston.

Halloun, I., & Hestenes, D.: 1987, 'Modeling Instruction in Mechanics', *American Journal of Physics* **55**(5), 455-462.

Halloun, I., & Hestenes, D.: 1998, 'Interpreting VASS Dimensions and Profiles for Physics Students', *Science & Education* **7**(6), 553-577.

Hestenes, D.: 1987, 'Toward a Modeling Theory of Physics Education', *American Journal of Physics* **55**(5), 440-454.

Hestenes, D.: 1996, *Modeling Methodology for Physics Teachers*. Paper presented at the International Conference on Undergraduate Physics Education, College Park, MD.

Hewson, P. W.: 1981, 'A Conceptual Change Approach to Learning Science', *European Journal of Science Education* **3**(4), 383-396.

Kuhn, T. S.: 1970, *The Structure of Scientific Revolutions* (2nd ed), University of Chicago Press, Chicago.

Lakatos, I., & Musgrave, A. (Eds.).: 1970, *Criticism and the Growth of Knowledge*, Cambridge University Press, Cambridge, UK.

Masterman, M.: 1970, 'The Nature of a Paradigm'. In I. Lakatos & A. Musgrave (eds.), *Criticism and the Growth of Knowledge*, Cambridge University Press, Cambridge, UK, pp. 59-89.

Matthews, M. R.: 1994, *Science Teaching: The Role of History and Philosophy of Science*, Routledge, New York.

Matthews, M. R.: 2004, 'Thomas Kuhn's Impact on Science Education: What Lessons can be Learned?', *Science Education* **88**(1), 90-118.

McDermott, L. C.: 1984, 'Research on Conceptual Understanding in Mechanics', *Physics Today* July 1984, 24-32.

McWhorter, J. H.: 2002, *The Power of Babel: A Natural History of Language*, W. H. Freeman & Company, New York.

Mortimer, E. F.: 1995, 'Conceptual Change or Conceptual Profile Change?', *Science and Education* **4**(3), 267-285.

Piaget, J.: 1970, *Genetic Epistemology* (E. Duckworth, trans.), Columbia University Press, New York.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A.: 1982, 'Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change', *Science Education* **66**(2), 211-227.

Ryle, G.: 1949/1984, *The Concept of Mind*, University of Chicago Press, Chicago.

Sharrock, W., & Read, R.: 2002, *Kuhn: Philosopher of Scientific Revolution*, Polity Press, Cambridge, UK.

Wells, M., Hestenes, D., & Swackhamer, G.: 1995, 'A Modeling Method for High School Physics Instruction', *American Journal of Physics* **63**(7), 606-619.