Schwartz, M. S., & Fischer, K. W. (2003). Building vs. borrowing: The challenge of actively constructing ideas. Liberal Education, Vol. 89(3), pp. 22-29.

Building vs. Borrowing: The challenge of actively constructing ideas in post-secondary education

Marc S. Schwartz
Harvard-Smithsonian Center for Astrophysics

Kurt W. Fischer
Harvard Graduate School of Education

Introduction:

The importance of actively constructing knowledge has influenced many generations of elementary and secondary educators, but this constructivist view rarely extends into post-secondary classrooms. College educators often harbor the opinion that their students, now adults, have overcome the need to build their own knowledge. This assumption is seductive because it easily justifies the use of an older more traditional pedagogy where knowledge is transferred from authoritative sources to ready but naïve recipients. However, the problems generated by this traditional view of education are no less significant at the collegiate level than they are in elementary and secondary education.

This article explores the tension between passive and active learning among master's degree students working on their teaching certificate in science at the Harvard Graduate School of Education. These students were convinced that the traditional pedagogy was sufficient until they confronted problems concerning floating and sinking that they could not solve by listening to lectures or watching demonstrations. Our students' struggle highlighted the importance of a principle of learning that assumes that building knowledge at any age is an active and step-wise process where new knowledge is built upon less complex understandings. This hierarchical process supports all learning, and has been explored in a number of theories in cognitive science. We will introduce one model of development to re-conceptualize the challenge of learning and teaching. Building on this view, we will emphasize that constructionist pedagogies need to be clearly integrated in university courses (and especially those focusing on teaching). Constructivism emphasizes that new knowledge is a personal creation that is socially mediated [1]. University courses that over emphasize didactic approaches risk perpetuating a method of teaching that is neither useful nor empowering; and furthermore, they inadvertently undermine the value of the constructivist approach for future student teachers and their students.

For five years the first author worked with over 100 graduate students in a course designed to explore the role that models play in science[1]. Without exception students shared the same exasperation with the central message of the course, that "answers" are only as good as the models and contexts for which they were designed. They regarded this view of science as unsatisfactory, incomplete, or just another form of sophism.

Their frustration and story is familiar to science educators. Our students' experience was often our experience. Their story is embedded in our story. How then can faculty break this cycle, and rewrite a story that too often concludes with the very best and brightest students heading towards a trajectory of defeat and disillusionment when facing science as scientists, or more generally, when facing the unknowns in any discipline? How do recent insights in cognitive science illustrate how important, powerful and necessary it is for students to construct their own understanding?

The Nature of the Problem

Sally, Rasheed, and Robyn participated in a science activity exploring the nature of floating and sinking. Later they shared their thoughts about the experience.

> Sally: "I didn't think I would understand, so I didn't see why I should get involved."
> Rasheed: "I'm not sure we got anything out of this activity. We haven't been given the answers yet."
> Robyn: "I was enjoying the experience of trying to calculate the density, but my group asked me, 'Why I was doing this'. I didn't know why I was doing it, so I stopped."

Middle and high school teachers are accustomed to these kinds of comments from their students; but they seemed unusual for students who had Bachelors Degrees in science. Perhaps even more curious was that our students were also working on Master's degrees in science education as well as state certification to teach science. One could not have had a brighter more motivated group of students; however, Sally, Rasheed, and Robyn's reactions were not unique. They, like their peers, struggled with a topic they believed they had mastered years ago, with a view of science they didn't understand, and a way of teaching they thought they believed in. Although they could talk articulately about the value of actively constructing knowledge, they did not realize how much importance they had placed on lectures and other strategies where they passively received information. Their success in high school and college science courses had been based on evaluations of how well they recalled this received knowledge, not how they made sense of this information. The constructivist approach had intellectual appeal, but offered little comfort or guidance in their own learning.

Their consternation began after an activity where they compared their answers on two different questionnaires dealing with the nature of floating and sinking (Table 1). After students completed the first questionnaire, the instructors displayed the distribution of student answers for each question, which suggested that most students recognized the correct answers. No one asked for an explanation. Students seemed satisfied. We then circulated the second questionnaire; however, this time both the distribution of answers and the students' reactions differed. The distribution of answers appeared to be driven by chance, and thus students could not determine which answers were "right". Even students who answered the questions correctly were unsure. They immediately wanted to know which answers were correct. (Perhaps you do as well?)

Instead of passing out the answers, the course instructors offered students the equipment to find the answers. Some students commented that they would have preferred the answers; however, they all were willing to test their ideas through experimentation[2]. They were motivated, self-directed and successful. They were also unhappy with their effort. Now they wanted to know why the "answer" was the answer.

Their unhappiness highlighted a central feature of science– the use of models and the nature of answers. Our students had grown accustomed to algorithms (e.g., D= M/V or F=ma) and situations where they solved for one or more variables, which the results and reactions to Questionnaire I confirm. They were uncomfortable in contexts where formulas were not useful. They hadn't thought about the significance of the variables, or recognized the relationships embedded in the algorithm's structure. As a real world model, the density algorithm had limitations, but none that students had confronted, as Questionnaire II revealed.

The students and their teachers confronted three issues. The first was the need for new models to handle the second questionnaire. The second issue was the meaning of models, including their complex relationship with "answers". But the most important issue, and the one that should concern all educators, is the lack of patience our students displayed in *building* a personal understanding of the models they needed to make personal sense of complex phenomena. They preferred to *borrow* relationships from their instructors, and expected that these *borrowed* relationships would provide the insight. Their view conflicted with the central idea of constructivism that “learning is a social process of making sense of experiences in terms of what is already known” [1].

Missing Models

Models are conceptual structures scientists and scholars use to tell stories about observed phenomena and to predict story lines for those uninvestigated parts of the phenomenon. In class, our students discovered that some models were more difficult to use than others. They could verify changes in water level, but could not explain why the level had changed. They realized that without the appropriate model they could not create a compelling story about their experiences or with the relationships they had discovered.

Given this situation, the course instructors felt that the students were ready to explore a version of Archimedes Principle: an object that floats displaces a volume of water equal to the object’s weight; and, an object that sinks displaces a volume of liquid equal to the object’s volume. Some students claimed that they knew this principle, but only one student in five years demonstrated any competence using it. The students asked us to explain how the principle worked, which as an exercise in traditional pedagogy we did. We also demonstrated how to generate a solution with one of the floating/sinking problems. Two students nicely summarized their experience (and the class’s):

> Helen: Although I understood what you (the instructor) said, it didn't help me in the long run because it didn't answer any questions I had.
> Leah: I think I understood the lecture enough to know better than lecture.

Despite student confusion, we concluded the exercise in traditional pedagogy by asking students to practice using the principle with the other problems on Questionnaire II as homework. Students agreed and at our next meeting they shared their answers. They worried that they still had difficulty applying the principle in new contexts, and that they could not follow their classmates’ explanations. Thus, we invited our students to continue practicing with the model with our support in an additional lab period. They balked. They claimed that this work would not be productive. Some argued that the principle did not count as “an answer” because they still couldn’t explain why objects float or sink; however, they no longer asked for explanations. Students were in a quandary. They had lost the initiative to explore, and they had lost confidence that they could make sense of a difficult model. Perhaps worse, they no longer had the patience to see through a problem even with the offer of time and support.

Models Are Often Sophisticated Mental Tools

Archimedes principle looks straightforward, and is easy enough to recite; however, for nearly all our students it seemed more like a mysterious incantation. Initially they could not use the principle to explain their observations, much less predict what would happen in unexplored problems. The principle required students to coordinate a number of experiences and concepts: some objects float, some sink; to understand why objects sink, one must focus on the object's volume, however you must shift your focus to the object's weight if it floats; volume is different than weight (which is different than mass); all three quantities are measured in different ways, with different tools and are described with dissimilar units; (and the list is far from complete).

Such coordination requires time and effort, much like learning to juggle. Archimedes principle is a complex conceptual juggling act. A student must initially learn to juggle a smaller number of the essential experiences before being able to assemble them into pertinent concepts, which can then be coordinated into a usable principle. A closer examination of this learning process reveals a pattern of evolving complexity in understanding that mirrors human cognitive development. Learning in the short-term appears to unfold in a fashion similar to the changes in understanding observed in the long term as infants mature into adults, a process called microdevelopment [2-3]. The important difference is the time frame. The educational implications of this claim depend on a closer examination of our learning experiences with a Neo-Piagetian model of cognitive development– skill theory [4]. A brief exploration of this model will serve as a framework for understanding changes in understanding that occur in shorter time frames, and ultimately our student's difficulty with questionnaire II.

Skill Theory

According to skill theory, people develop toward maturity by building an evolving and hierarchical framework of skills over many years, and they use the same general structure to build new understandings in the short term, working from lower to higher-level skills. Learning, inspired by new problems, involves movement through a portion of one's developmental framework, and analysis of this process is the basis of a strategy for studying learning called microdevelopment [2-3]. Unlike earlier debates about whether development to new stages allowed the individual to display the new ability in all contexts [4,11], skill theory allows educators to view each new context as an opportunity for students to build and coordinate skills using the framework of prior skills that is their developmental legacy. However, this process is neither automatic, instantaneous or guaranteed and often requires extensive construction of new lower level skills to create new understanding. This process frequently requires lengthy time and specific experiences, and it is context sensitive [10-12].

Long-term development and microdevelopment involve movement along the same scale for growing skills, and Piaget's framework of development provided an important starting point for establishing that scale [5]. According to Piaget, development moves through three major stages. In the sensorimotor stage, infants coordinate and execute numerous actions to interact with and learn about the world. Toddlers and children later take advantage of this foundation by internalizing these interactions as mental representations. Broadly speaking, this second stage became known as the Concrete Operational stage. Children might need as much as ten years before they could coordinate operations (or representations about their world) into the final stage of development– Formal Operations. In this last stage of human development, adolescents use their concrete representations to form abstract ideas

Each stage becomes a qualitatively new way to understand the world because it incorporates and consolidates the accomplishments of earlier stages into a more efficient mental structure. For example, any operational understanding (or representation) assumes that a child has mastered appropriate and related sensorimotor understandings. The word "water" would have little meaning if the child had never tried to pick up water, taste it, or splash around in it. All of these (and similar) actions are necessary underpinnings to the concept, "water". As children become teenagers they become increasingly more capable in coordinating representations, such as the similarity and differences between water, ice, and steam. During adolescence, the maturation process accommodates one last transition in understanding.

The final Piagetian stage is abstract understanding, which depends on the coordination of many representations, and permits a new way to integrate concrete operations, which is more than just another representation. Buoyancy, for example, is an abstraction that emerges from the organization of a number of relevant representations about water and the objects that float in water: the weight of the object; the difference between weight and mass; that weight is a measure of force; that the water can exert a force on the object; and, that whether an object floats is the result of forces on the object being in balance.

Neo-Piagetian models have focused on characterizing the developmental scale behind Piaget's original stages and specifying the processes of developmental change and construction of understanding [6-7]. Skill theory [4] addresses both issues. Fischer specifies a scale for developmental change and learning – a series of 13 levels defined by specific empirical criteria for abrupt or discontinuous (stage-like) change. The levels group into four tiers or "stages"– Piaget's three, plus one more early in infancy: (1) Reflexes (to describe development in the first couple of months of life; (2) Actions (or Sensorimotor), (3) Representations (or Concrete Operations), and (4) Abstractions (or Formal Operations).

Mastery in each tier progresses through the coordination of less complex skills into more complex ones, with four levels documented in each tier [4]. For example in the representational tier, understanding begins as "single representations" (e.g., Imagine that all you knew about the clear liquid in a glass was that people called it "water". In this case the word "water" carries no additional understanding or insight about the liquid in the glass.). With further maturity single representations can be coordinated with other single representations (e.g., water can be a liquid or a solid). This new level of understanding is a more complex representation, or "mapping". Here the observer is able to compare and contrast object(s) from the perspective of one dimension (e.g., the physical states of water) [8]. Mappings, in turn, can be coordinated with other mappings about water or liquids or the objects placed in water to form a new level– "representational systems". The transition to the last tier emerges when multiple representational systems are successfully coordinated together. This fourth level becomes the transition step to abstract thought, because it forms the first level of the next tier– single abstractions.

The levels specify a scale for not only long-term cognitive development but also short-term learning, including specific processes of constructing skills. Researchers and educators can use this general framework to model how understanding evolves as students confront new problems [8-9]. Students take advantage of their cognitive framework to solve problems. Depending on support and context, students move through their framework to more complex understandings. Consequentially, in short time frames (seconds, minutes, hours or days), students use their cognitive framework in new contexts and domains to build new understandings [10,13]. The trajectory of this path of learning leads to the most complex level that the framework will accommodate due to its state of maturation (the optimal level – the upper limit on skill complexity).

To understand Archimedes Principle, the number of experiences that need to be coordinated into single representations which in turn need to be coordinated into mappings and then systems is substantial. Even though our master's students are very capable of creating abstract ideas in areas where they have extensive experience, they still need time to explore, build, and coordinate appropriate relationships in the "floating and sinking" domain in order to take full advantage of their developmental legacy. There are no short cuts to the kinds of abstractions that we want our students to understand. Attempts at shortcuts lead to rigid and inadequate skills. Although our students are capable of building their own understanding of Archimedes principle, their professors cannot directly give them their understanding.

Building versus *Borrowing* Representations:

The issue that we confronted, and that teachers need to face, is that we build our understandings out of our efforts to coordinate our experiences. In most traditional educational experiences we teachers unconsciously ask students to borrow our representations (or Archimedes' representation) to make further sense of the world. The complexity of Archimedes' representation requires that teachers let go of the temptation to supplant the students' need to construct their own understanding of the concept. This challenge does not mean that students have to reconstruct Archimedes principle on their own without guidance. They must make personal meaning of the principle in a variety of contexts, guided by teacher and text. Archimedes' model serves as a construct that organizes properties of the world, but it cannot substitute for the process of making sense of the model as students actively put it use. This operation is an ongoing and dynamic process because new problems will challenge the student's understanding of the principle and the stability of this abstraction across contexts.

Thus teachers should resist the instinct to immediately answer student questions because quick answers create new educational problems. The first problem is that providing answers -- a transaction typical in traditional educational settings -- cannot replace the coordination that students need to perform on their own. Authoritative interventions can undermine the patience necessary for creating complex representations and abstractions, and ultimately student confidence that they can do this kind of work. Our students were too easily satisfied by ideas that they could repeat back, but had not processed.

Second, quick answers downplay the important fact that all answers depend on the model instructors emphasize. Why an object floats can be understood from Archimedes principle as a special situation where the weight of water displaced by the object equals the weight of the object. But students can ask why is this so? Newtonian physics might address this question from the perspective of forces. The force of gravity on the object is balanced by the force exerted by the column of water under the object. Once again students can ask why, and once again there is another model (the atomic model) that helps organize necessary observations and representations into a coherent story. The stories are difficult to tell because if parts of the story are changed, then the task of creating an alternative conclusion requires a thorough understanding of the model.

What made questions on Questionnaire I so popular was that students could borrow and quickly use the density algorithm. The problems were designed so that only the lower levels of representational understanding were required and only recall of the algorithm or simple facts was needed (e.g., water has a density of 1gm/cc). Students did not need to know the meaning of this ratio, only that it was the water's density (as such, this understanding illustrates a single representation). The problems in Questionnaire I allowed students to use the borrowed algorithm to solve for a missing variable. They did not need to know what the variables meant or if the context mattered as long as they had the variables. Moving past these initial levels into representational systems and abstractions required more effort. The floating and sinking activity wound up irritating our students because building knowledge beyond the initial levels was more difficult and time consuming than borrowed knowledge would accommodate. In terms of skill theory students were unable to progress quickly beyond the initial levels of representations with knowledge that was not their own.

Skill theory provides a framework for understanding the cognitive challenge students face when confronting new (and abstract) knowledge such as Archimedes principle. Constructivism provides a context for supporting this unfolding challenge. Tobin and Tippit identify four essential factors in all variations of constructivism: New knowledge is a personal construction that is socially mediated. New knowledge is dependent on personal experience. New knowledge must provide reliable and predictable information about the world. New knowledge is built on existing knowledge. Together both constructivism & skill theory help explain why Archimedes principle can only become meaningful to students through their own construction [1].

In order for students to profit from the active construction of knowledge, teachers must focus on several issues in their classrooms. We recommend including discussions to clarify what students believe and why. Any attempt to amend, enhance, or change student views must account for the experiences that generated their representations. They are intimate and foundational constructions. This foundation will help educators identify new, anomalous, or follow-on experiences that can become personal representations available for further coordination as abstractions. This perspective helps teachers target with greater precision the experiences and discussions that need to occur if their students are to create the abstract concepts demanded by the discipline they are studying. Although the capacity of abstract reasoning is present in adults, this skill can only emerge when students can capture and coordinate the appropriate sensorimotor and representational understandings.

If teaching at the university level does not emphasize the nature of learning discussed, by embodying its principles, then the university experience risks perpetuating a view of learning that only focuses on the manipulation of borrowed concepts and schemas. Since students do not build these representations themselves, the “knowledge” is not long-lived and is more difficult to coordinate into the kinds of abstractions that are valued in university discourse. We invite our colleagues to consider seriously the need and impact of a constructivist approach, which requires students to build instead of borrowing representations. Traditional teaching practices with sophisticated students can easily mask any deep understanding of topics. For colleges of education the problem is even more insidious in that we risk convincing another generation of teachers that the didactic approach has more value then it actually has.

Table 1: Two questionnaires claiming to test student understanding of density

Questionnaire I
1. What is the density of water? A) 0 gm/cc B) 1 gm/cc C) 5 gm/cc
2. If an object's density is 2 gm/cc, will it float? A) Yes B) No C) Can not tell from this information
3. If an object has a mass of 2 grams and a volume of 4 cc, what is its density? A) 8 gm/cc B) 2 gm/cc C) .5 gm/cc

Questionnaire II
1. You come across a canoe in a swimming pool. There is a large anvil in the canoe. You wonder if the level of water in the swimming pool will change if you take out the anvil and throw it in the water. First you closely mark the level of water in the swimming pool and then throw the anvil in the water. You notice that: A) The water level goes up B) The water level goes down C) The water level remains unchanged
2. One hot summer afternoon your loved one brings you a glass of ice water filled to the brim. You look at the glass but do not drink it immediately. It only takes a few minutes for all the ice to melt. After all the ice has melted, what happens to the water level? You notice that: A) The water level goes up B) The water level goes down C) The water level remains unchanged
3. Compare two containers filled to the brim with water. One container has a piece of wood floating in it. Which of the following is true? A) The container with just water weighs more. B) The container with the block of wood weighs more. C) Both containers weight the same.

Note: Each questionnaire contained ten questions that were similar in style and content to these questions

<u>Footnotes:</u>

[1] The course was entitled the Nature of Science and taught by three members of the School of Education and the Faculty of Arts and Sciences: Irwin Shapiro, Bruce Gregory, and Marc Schwartz.

[2] Initially, students struggled to produce results everyone could accept. The instructors were pleased that students were discovering (or re-discovering) the problem of creating unambiguous experiments. This issue can easily be reduced to a tedious lecture in methodology in science courses.

References:

[1] Tobin, K., & Tippins, D. (1993). Constructivism as a referent for teaching and learning. In K. Tobin (Ed.), The practice of constructivism in science education (pp. 3-21). Hillsdale, NJ: Lawrence Erlbaum Associates.

[2] Wertsch, J.V., & Stone, C.A. (1978). Microgenesis as a tool for developmental analysis. Quarterly Newsletter of the Laboratory of Comparative Human Cognition, 1(1), 8-10.

[3] Fischer, K.W., & Granott, N. (1995). Beyond one-dimensional change: Parallel, concurrent, socially distributed process in learning and development. Human Development, 38, 302-314.

[4] Fischer, K.W., & Bidell, T.R. (1998). Dynamic development of psychological structures in action and thought. In W. Damon (Ed.), & R. Lerner (Series Ed.), Handbook of child psychology: Vol. 5, (pp.467-561) Theoretical models of human development. New York: Wiley.

[5] Piaget, J. (1983). Piaget's theory. In P. M. Mussen (Ed.), Handbook of child psychology (Vol. 1, pp. 103-128). New York: Wiley.

[6] Case, R. (1998). The development of conceptual structures. In D. Kuhn & R. S. Siegler (Eds.), & W. Damon (Series Ed.), Handbook of child psychology: Vol. 2. Cognition, perception, and language. New York: Wiley.

[7] Siegler, R.S. (1981). Developmental sequences within and between concepts. Monographs of the Society of Research in Child Development, 46(2,Serial No. 189).

[8] Parziale, J., & Fischer, K.W. (1998). The practical use of skill theory in classrooms. In R. J. Sternberg & W. M. Williams (Eds.), Intelligence, instruction and assessment (pp. 96-110). Hillsdale, N.J.: Lawrence Erlbaum Associates.

[9] Dawson, T. L. (2002). New tools, new insights: Kohlberg's moral reasoning stages revisited. International Journal of Behavior Development. 26, 154-166.

[10] Fischer, K.W., Bullock, D., Rotenberg, E.J., & Raya, P. (1993). The dynamics of competence: How context contributes directly to skill. In R. Wozniak & K.W. Fischer (Eds.), Development in context: Acting and thinking in specific environments (pp. 93-117). Hillsdale, N.J.: Erlbaum.

[11] Rogoff, B. (1990). Apprenticeship in thinking. New York: Oxford University Press.

[12] Salomon, G., & Perkins, D.N. (1989). Rocky roads to transfer: Rethinking mechanisms of a neglected phenomenon. Educational Psychologist, 24(2), 113-142.

[13] Granott, N. (1998). We learn, therefore we develop: Learning versus development--or developing learning. In C. Smith & T. Pourchot (Eds.), Adult learning and development: Perspectives from education psychology (pp. 15-34). Mahwah, NJ: Lawrence Erlbaum Associates.