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"*I wonder how this little seed can have so much potential*": Critical Exploration Supports Preservice Teachers' Development as Science Researchers and Teachers

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A teacher educator and student of Duckworth's critical exploration approach to teaching shares three episodes taken from science methods courses she teaches for preservice teachers in graduate and undergraduate programs in elementary education. The episodes reveal the pedagogy of critical exploration to be particularly well suited to the preparation of teachers. Classroom episodes are reconstructed using data extracted from student journals and field notes made during and following teaching. Consistent with the pedagogy, the students explore a phenomenon the teacher presents to them: the development of a seed, the swinging of an object on a length of line, the path of the moon in the sky, etc. The teacher, in turn, explores what students respond to, notice, and question; curriculum grows from these mutually reciprocal explorations. The teacher's exploration of what students are seeing, feeling, and thinking, and the connections they are making, creates an environment that supports further development in what students notice, which enriches the teacher's understanding of the phenomenon. Students' exploratory experiences with the subject matters they will teach in the public setting provide a framework for assimilating the experiences and

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thinking of young children. Teaching, learning, and research go hand in hand. The liberatory and transformational aspects of critical exploration for learners and teacher alike emerge.

INTRODUCTION

I am a teacher educator at a small college in southern New Hampshire, where I design and teach science methods courses for students in programs leading to certification in elementary education. The students I teach typically have minimal preparation in science and do not have a vision of themselves either doing science or teaching science. Teaching science (or any other subject) requires deep familiarity with the subject matter one is teaching and of the various and diverse paths learners take in and make sense of it. Such knowledge and familiarity helps a teacher to use her expertise and authority on behalf of children—to make choices that respect each child's sense-making capacities and nurture each child's interests and development as an individual—rather than acting out of fidelity to implementing a programmed curriculum. Designing environments and experiences that help aspiring teachers to develop the understandings they will need to teach in ways that are responsible and accountable to children—their interests and their development—is my particular challenge as a teacher educator. For this reason, the teaching-research pedagogy of critical exploration is the foundational pillar of my work with preservice teachers. For a description of critical exploration, see Duckworth (2001c, 2005, 2006b, 2006c) and our introductory paper in this issue of *The New Educator* (Cavicchi, Chiu, & McDonnell, 2009).

In critical exploration both students and teacher engage in exploration. Students explore a subject matter that the teacher presents to them—the swinging of a pendulum, the sprouting of a seed; the teacher explores the various and diverse ways that students "apprehend" (Schneier 2001) and make sense of it, thus extending her knowledge of the subject matter itself and of the nature of human development and learning (Duckworth 2005, 2006b). In this way, teacher and students are engaged in a reciprocal relationship, the explorations of one supporting the learning of the other. Critical exploration creates a classroom environment that provides preservice teachers with access to the "knowledge" and "insight" that David Hawkins[1] had in mind, I believe, when he considered the challenges of teaching science to young children. Hawkins wrote,

> To understand mathematics, or physics, or geography well enough to know ways of structuring them, of rooting them so to speak in the child's garden, is a major intellectual undertaking for the best minds

[1] **David Hawkins in the early 1960s, along with Jerrold Zacharias and Philip Morrison, helped to organize the Elementary Science Study in Newton, Massachusetts, and served as its director until 1964. Throughout his essays on learning and teaching, Hawkins acknowledges the influence of John Dewey.**

> we have. Only a good and reflective physicist can see the beginnings of his own basic schemes and abstractions nascent in the experience of childhood, and only an inventive teacher, supported by such knowledge and insight, can undertake the [necessary] reconstructive process. (1965/2002a, p. 172)

Critical exploration is, at root, a nonoppressive and liberatory enterprise for teacher-educators and their students, and thus introduces a Freirean approach to teacher education. Rather than equipping aspiring teachers with an arsenal of instructional strategies and lesson plans to unleash in the educational setting, critical exploration helps teachers to see and apprehend the individual in each student by preparing them as "diagnosticians" of development and learning (Duckworth 2006a). Curriculum emerges from the reciprocity between and among teacher and students.

Critical exploration, as the episodes that I share from my classroom and those of others show (see Cavicchi, 2009, this issue; Chiu, 2009, this issue; Duckworth, 2001a; Ramsey, 2002), puts "profound trust" in subject matter to reveal structures of the world (both physical and social), and in "people and their creative power" (Freire, 1973/2005 p.75) to make sense of those structures. This trust in the world as subject matter and in people as sense-makers drives and sustains the development of an authentic community in which teacher and students come to see and know each other as individuals through observing their interactions in the world, with the world, and with each other. As Freire has written,

> Through dialogue, the teacher-of-the-students and students-of-the-teacher cease to exist and a new term emerges: teacher-student with student-teachers. The teacher is no longer merely the one who teaches, but who is himself taught in dialogue with the students, who in turn while being taught also teach. They become jointly responsible for a process in which all grow. In this process, arguments based on 'authority' are no longer valid; in order to function, authority must be *on the side of* freedom, not *against* it. Here no one teaches another, nor is anyone self-taught. People teach each other, mediated by the world, by the cognizable objects which in banking education are 'owned' by the teacher. (Italics in original) (Freire, 1973/2005, p. 80)

Freire continues,

> The students—no longer docile listeners—are now critical co-investigators in dialogue with the teacher. The teacher presents the material to the students for their consideration, and reconsiders her earlier considerations as the students express their own. (p. 81)

BACKGROUND

I was introduced to critical exploration by Eleanor Duckworth, following more than ten years of teaching secondary science, when I was a beginning doctoral student and took a course that she was teaching titled *Teaching and Learning*. Critical exploration (Duckworth 2001c, 2005, 2006b, 2006c) rests on the notion that learning is more about developing understanding than it is about the accumulation of facts; and teaching is less about delivering information than it is about helping each learner in his or her effort to construct understanding of a subject matter they are engaged with. Critical exploration requires a teacher to observe how students interact with materials she has presented to them and to "listen" to how students "explain" their interactions with the subject matter (Duckworth, 2001a, 2001c). The idea of teachers "listening" while students do the "explaining" represented a radical and intriguing departure from what I had been doing during my years as a high school teacher!

Teaching secondary science in a large suburban public high school exposed me to a variety of teaching "innovations," some of which were helpful. Nonetheless, I felt a deep dissatisfaction with myself as a teacher and the learning I observed in my students. My overarching purpose and responsibility, it seemed, was to maintain an orderly classroom and reduce student confusion by implementing and delivering a curriculum that consisted of a carefully prescribed sequence of activities, rather than promoting the growth and development of each student. This curriculum did create what some might consider an organized and well-managed science classroom (two criteria on which I knew I would be assessed as a teacher); yet I questioned my students' understanding of the subjects I was teaching. I recognized, too, that the school curriculum did not adequately reflect the creativity, spontaneity, and inventiveness of what scientists do or the responsiveness with which scientists interact with phenomena. Consequently, my teaching and the activities of my students lacked spontaneity, responsiveness, originality, and authenticity. Today, as a result of critical exploration, I am more able than I was in my years as a high school science teacher to use my subject matter expertise and my authority as classroom teacher to support my students' growth and development.

THE CONTEXT

The episodes that I share are taken from science methods courses I have taught for graduate and undergraduate students over the last few years. Some of the courses spanned a 14-week period, others just 5 weeks. The episodes are constructed out of students' journal entries and field notes I made either during or immediately following teaching. Each episode focuses on a moment in which the students were working out some complexity related to the subject matter in question. (The seed story, for example, focuses on developments observed within the first 2–3 weeks of growth. The moon story is taken from the last class session of several weeks of observing.) In constructing the accounts, I illuminate how I went about exploring the understanding of the thoughts and perspective of my students and how I used this insight to help me have ideas about what I might do next to support each student as they sought their own coherence.

The episodes involve student explorations of three different subject matters: seeds, pendulums, and the moon. When selecting a subject matter, I am mindful of the curriculum areas that my students will teach when they become educators in the public setting (physical science, life science, earth-space science); and, within those mandated curriculum areas, I select those subject matters (phenomena, materials, etc.) that contain within them the structures (both physical and conceptual) that students are expected to learn. Always I seek out subject matters that contain within them structures, systems, and regularities that can be noticed by the student. I choose those subject matters that I know “in the most flexible ways possible” (Duckworth, 2001c, p. 182), as it is this familiarity that will enable me to follow and attend to the actions and thoughts of my students, as opposed to following an automatic or programmed response. Like other students of critical exploration (Duckworth 2001), I look for subject matters that I can present to students in the most natural, complete, and unadulterated form, as it is this complexity and richness of the material that generates student interest and provides multiple openings through which students might enter the subject. I select subject matters that my students can experience first-hand and which are responsive to the actions of my students as it is the responsiveness of the materials and phenomena that allows my students to try out the different ideas they might have. And it is the responsive nature of the subject matter that opensup even more possibilities. Sometimes the object of study is not immediately responsive to an action of the student, in which case the student seeks other ways to try out his or her idea, such as by engaging in extended observations of the object. Lastly, I seek out subject matters that have an initial appeal to my students, although this is not always possible. In these instances, I trust the subject matter itself will arouse interest and that the interest will grow with and through each authentic interaction involving student and subject matter. Not all subject matter is equal in terms of its value to and meaning for students; so I try to choose subject matters that have enduring value and “critical” meaning for my students beyond the classroom walls and which are worth our time thinking hard about. For example, depending upon the backgrounds of the students I am currently teaching, a critical exploration of silkworms may have greater value than other choices I could make. I find this aspect of critical exploration particularly challenging.

A SEED STORY

Launching

Launching a critical exploration requires "first and foremost" eliciting and arresting the learner's interest in the phenomenon (as explained by Duckworth in her course documents). Accordingly, I have experimented with a variety of approaches to pique students' genuine curiosity in seeds and their development. On one recent occasion, I launched the exploration by placing a seed in the hand of each student with the direction that they provide it with what they think it needs to sprout. (On another occasion I passed around a tray of assorted seeds.) Sometimes, as the essay by Cavicchi (2009, this issue) shows, recreating an exploration from the history of science is a productive way to launch students into explorations of their own and to connect them to the wider community of science researchers. Not all openings work for all students, but, from experience, I know that people of all ages and walks of life typically enjoy planting seeds. And so, this opening is, I find, broad enough to invite the participation of all students. A long table held a supply of containers of various sizes, hand lenses, rulers, potting soil, plastic bags, squares of felt and cotton, paper towels, colored pencils, paper, and a pitcher of water. Typically, most students plant their seed into a small pot of soil, which is, of course, a sure way to get a seed to sprout! Why would a person do anything else?

I teach adults. Finding an authentic way to encourage exploratory behavior and prompt genuine interest in the phenomenon of "sprouting" is always one of the difficult tasks that I face when teaching this class. Without some action from me, most adults would be content to let their potted seed sit in a window or some other spot. Without careful attention to the nature of the directions and questions that I pose at the outset, this session could soon become a traditional teacher-centered science class. And so, whatever my chosen starting point, my aim always is to initiate my students' exploratory behavior with the intent that the seedling and its behaviors will become the primary director and motivator of student explorations. The decisions that I do make are critical as it is only through observing their spontaneous exploratory behavior that I can grasp how my students are truly thinking about seeds and their growth. Each decision I make either compromises or opens up the possibilities for my students. And so, to stimulate further involvement with the phenomenon of seed growth, I have, on occasion, presented the challenge of figuring out the minimum requirements for sprouting. On other occasions I have shared my observation that people responded to my direction by planting their seed in a pot of moist soil, which they then placed in the classroom window. On those occasions, I might say, "So you might wonder, does your seed need all of these things?" Or, I might try asking, "Did you have anything in mind when you placed your seed into a pot of soil?" I might say, "I notice that all of the pots are lined up along the window sill. Tell me about that."

Sprouting

The excerpts below are taken from a class session in which the students had worked together in small groups to figure out the minimum requirements of seed sprouting. Different groups were testing a seed's need for moisture, sunlight, soil and air. The classroom was adorned by the various setups the students had invented to create the specific environmental condition they were hoping to replicate. Some arrangements were designed to investigate the need for moisture, others the need for soil, and others were designed to explore the need for light. One student devised a way to explore a seed's need for "air" by enclosing a seed in plastic wrap and removing the air using a seal-a-meal device, which she kept at home. Students placed their seeds inside storage cupboards, shoeboxes, pocket books, and small capsules made out of two plastic drink cups sealed together, one cup inverted on the other. A few students, testing the need for soil and water, left their seeds resting in the open air on the window sill. One group of students placed seeds onto moist cotton squares which they placed inside small plastic sandwich bags, some of which they taped to the window, and others they placed inside a tightly sealed shoebox.

In the same way that the environment my students supplied to each dormant seed provided the seed with what it needed to sprout, the sprouting seeds sparked the wonder and curiosity that lay dormant within my students. Diana gasped in surprise when she found that a seed she had wrapped in moist paper towel, in an effort to provide the seed with water but not soil, and placed inside a shoe box on the top shelf of a metal storage cabinet to "keep out any trace of light" had produced a long white root. Across the room, Barbara puzzled over the extensive growth of a seed that she had kept in a brown paper lunch bag compared with the much more limited growth of a seed she had put inside a plastic sandwich bag and taped to the window "to be sure it gets enough light." The extensive growth of seeds that had been kept in the dark as compared with seeds that had been sprouted in the light became a shared fascination. Another student, Kim, shrieked with surprise when she unwrapped a seed from moist paper towel to find that it had produced a long, white root. She poked the tiny structures with her finger, gingerly, noting her surprise that "they're not at all soft and fuzzy." Across the room, a student commented on the strength of the root, which, to her surprise, had become "completely webbed" into the cotton pad on which it had been resting. "It's anchored itself," she remarked. In her journal, she pondered the growth and development of the seed, reflecting, "I wonder how this little seed can have so much potential" (see Figure 1).

I took note of the behaviors and conversation happening among my students, awed by the potential of a small bean seed to produce such wonder and curiosity among my students. My primary responsibility at this time was, I decided, to create the occasion and space for each student to share with the class the details of what she or he was seeing. I made the decision to focus on observations and surprises

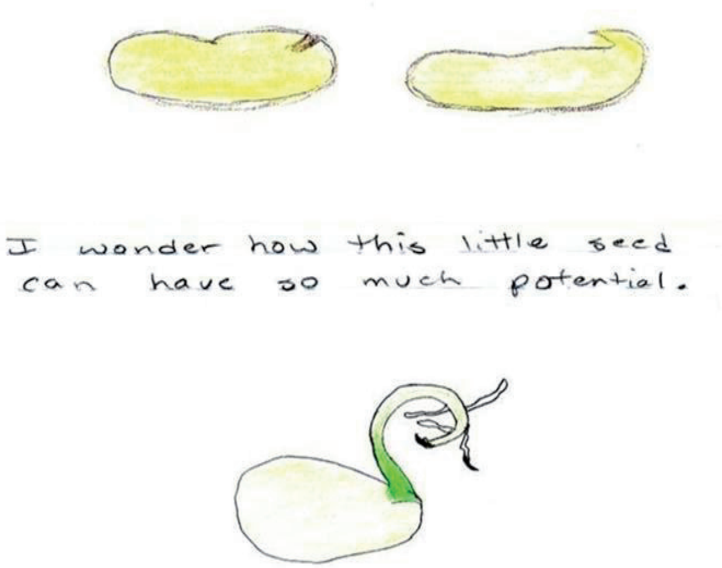

Figure 1. A page from a student's journal in the second week of the study. Observations of rapid growth, prompt the question, "I wonder how this little seed can have so much potential?"

rather than questions. This proved difficult as each observation raised a question about sprouting.

Light

The growth of seeds which had been kept in the absence of light seemed to be the source of greatest fascination and intrigue. Students who had placed seeds inside brown lunch bags, which they had then placed in a shoebox, wondered if, despite their efforts, light had managed to enter the container. Barbara asked the class, "Do you think that the seeds that have been kept in cupboard have grown better than those taped to the window?" The puzzle about light proved a fruitful exploration for many students throughout the semester.

Laura offered the possibility, "I'm just brainstorming, but maybe, in the beginning at least, seeds need warmth more than they need light." Patty, intrigued by Laura's idea that maybe a seed does not requires light to sprout, decided to make her own "small experiment." That night she wrapped three seeds in moistened paper towel which she placed carefully underneath her daughter's bed, where there was a heat vent and it was dark! LaDelle also tested the "warmth versus light theory," albeit "not very scientifically," she acknowledged, by putting one new seed, also wrapped in moist paper towel, next to the hotplate on her coffee pot! I took Patty's "small experiment" as evidence that the bean seed, and the puzzles it was presenting to them, was now the motivator and director of students' activities and thinking.

Soil

The sprouting of seeds without soil was as compelling to students as the finding that a seed can sprout without light. Amid a discussion about the need for soil, Kim conceded, "Maybe it is possible to sprout a seed without soil, but, is it possible to grow a *plant* without soil?" The tone of the questions suggested that the answer is no, a seed cannot grow into a plant without soil. From a corner of the room, another voice, in apparent support of Kim, added, "After all why do they sell potting soil?" I decided that this was an appropriate moment for a 15-minute break. I prefaced the break by saying something like, "There are lots of questions about sprouting and plant growth. What might you want to look at more closely? There are plenty more seeds." I noticed how the act of close observation elicited feelings of care. Students who had sprouted their seed without soil on cotton squares, convinced that their seedlings would not develop further and might even die if they were not put into soil, quickly transferred their seeds into small pots of soil with all the urgency of a medical team! Kim approached, turning her back to the class, and asked me in a very quiet voice if she could keep her sprouted seed in its tiny plastic bag. She said, "I'm curious to see how long I can keep this thing going without soil." I had the impression that Kim assumed that the seedling would not develop into a plant without soil. Kim and Patty's small experiments constitute a "critical experiment" (Duckworth 2001b) in that the investigations they made, resulted from their own thinking and the desire to gather what they perceived would be credible evidence to illuminate the question of what a seed needs to sprout.

Meditating Upon the Origin of Structures Observed

Rachel, a student in a five-week summer class, looked at her potted seedling with what I interpreted to be a look of grave concern. She looked first to her tiny seedling, and then she looked to the potted seedlings resting on the desks of other students. She looked at the pages of her journal. When the hum of activity stopped, I looked toward her, creating an opening for her to say what was on her mind. She looked up from her potted seed and said, "Well, I'm puzzled by my bean tonight." I listened and did not speak. After a moment or two, she quickly added, "I'm puzzled because it seems to be sprouted facing downwards." She pointed our attention to a hook-like structure above the soil (see Figure 2).

Given my knowledge and experience of growing seeds, I appreciated the significance of the structure she was noticing. Rather than delivering the botanical account, I encouraged her to "tell me more" (Duckworth 2006).

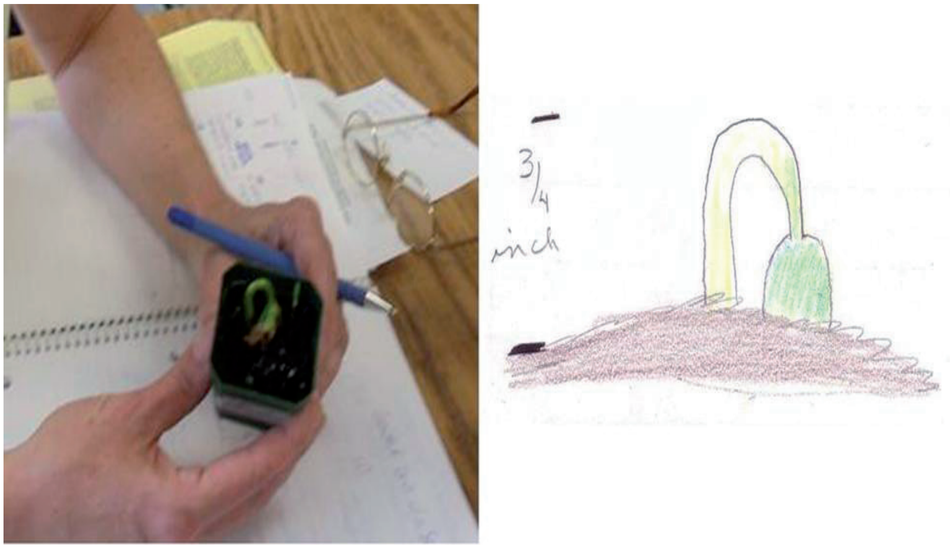

Figure 2: A student examines the “hook-like” structure that Rachel and others have noticed.

> Teacher: I wonder if you could show us what you are seeing and puzzling over.
> Rachel: Well, my seed, it’s bent over; I don’t know. My seed seems to be sprouting downwards
> Teacher: What is bent over?
> Rachel: The stem is hugging the inside curve of the bean, and is trying to unfold and reach toward the sun.

I did not want the moment to pass by too quickly. The mechanics and beauty of how a seed manages to do what it does often go by without notice; and so, in part to slow things down so that we might gaze upon the structures, and in part to understand her thinking and puzzle (a puzzle that is well worth thinking about), I asked Rachel if she would approach the board and make a drawing of what she was seeing. As she made her drawing on the board, I had a moment to think of how I might explore and openup her thinking in a way that conveyed my genuine curiosity without creating the sense that she had said something either wrong or amusing. Students, especially in the beginning of a critical exploration, are not accustomed to having their thoughts and confusions considered by the group, and can mistake the attention to their thoughts as an “error” in thinking. It is essential that any probing originate from a genuine curiosity in understanding more about the observations, ideas, or questions expressed. I decide that the best approach would be to simply ask Rachel to tell us about what she had drawn. After her description, which illuminated her puzzle, I asked her to tell us what she thought we would all see the next time we meet. Rachel described her drawing as a “whitish-greenish stem with a nub on the end, which,” she said, now speaking in a very small voice, “I think is the seed.”

Rachel: I think that next week the *seed will have gone down into the soil* and the other part [the whitish-green stem] will have straightened out and will go up towards the light.

I observed another student nodding her head in agreement with the explanation she had heard, and asked her to share what she was agreeing with. I saw this as both support for Rachel who had the courage to share her thinking about what she saw as the most plausible explanation for what she was seeing (as opposed to avoiding the issue by saying, "I don't know") and as another opportunity for other students to articulate and elaborate on their ideas about plant growth.

Teacher: I see that you are nodding your head?

K.R: Yup. I agree.

Teacher: What part of what Rachel said are you agreeing with?

K. R. It's [the nub] definitely, the seed. And I do think that it will go downwards; it has to!

Motivated by the class discussion, Rachel observed her seedling closely over the next five-day period. The next week, she arrived to class carrying her potted seedling. I asked her for a follow-up report. Rachel explained that the seed had done the *opposite* to what she had predicted it would do! The "nub," which she now referred to as the "seed," rather than going back down into the soil, had been "pushed up toward the sun." Not only did Rachel reconstruct her original idea of what seeds do (namely that seeds remain in the soil), she appears to have worked out a mechanism that could explain how a seed could find itself at some distance above the soil! In her journal, she wrote,

> The bean plant has grown approximately 5 inches in 3 days, and has sprouted 4 leaves at the top of the stalk. Interestingly, the bottom right leaf still has the seed casing attached to it . . . [and] the lower two leaves are still in the shape of the bean seed. It appears that the plant grew downwards, pushing the seed up toward the sun. This is opposite to what I predicted.

This student now contemplated the mechanics and energy required to raise the "seed up toward the sun."[2] She considered the role of the roots in facilitating the process, and continued,

> This is puzzling because I imagine the seed casing is heavy. I think the roots grew down first, and then the 'seed' became the plant."

[2] It is unclear how Rachel distinguishes "nub," "seed casing," and "seed." Students use a variety of words when referring to the paired structures they observe on the side of the stem. It is as if the structures can be anything but the seed they planted!

Opening Up a Seed

Deciding if and when to introduce a new activity is always a challenge for me. However, later in that same class, I found what I thought was a good opportunity to suggest that we open up a seed to see what we find. We do not always do this. The activity requires some teacher direction and, if not presented with an appropriate tone or at an appropriate moment, could shift the class momentum and be interpreted by students that I have the answers to questions that they are puzzling over, which is not to say that the students believe me, the teacher, to be naïve of the subjects we are studying. On this occasion, I felt that seeing the inside of a seed was what was on everyone's mind. As the students reached for new seeds, I posed the question of what they thought they might find once they managed to open one up. Rachel speculated, "It'll be all gray, with no green or visible plant matter." Opening up the seed, she gasped when she observed a tiny structure with two tiny leaves (the "embryo") lying along one side of one of the two seed halves. Later in the class, rather than disposing of the two seed pieces, which had become separated, she planted each seed half alongside her potted seedling. This mini-investigation gave Rachel insights into the "whitish nub" she had observed several days before and helped her to figure out how a seed sprouts and manages to emerge from the soil. This is how she wrote about her experiment in her journal:

> Exciting seed developments today! On 5/30 I planted the two seed halves in the dirt to see if either would sprout. After about 1½ weeks the seed began to sprout, and the side of the seed with the "casing" began to sprout and curl *upwards*.
>
> When my original seed was in this position, I had thought the seed casing end would grow down into roots, but now I see that the opposite happens, and the seed casing grows upwards. The other side grows downwards into roots. (Italics added)

"It looks like the bean, sort of"

Two weeks following the planting of seeds, I arrived to find students fully engaged in making drawings and measurements of their developing seedlings. Students were awed by the rapid growth of the seedlings. Responding to the obvious interest and delight in seedling height, I devoted a good portion of the class gathering data for the questions that had emerged, "Whose seedling is the tallest?" "Whose seedling had grown the fastest?" "How do you measure the speed at which a bean plant grows?" Yet, the interest in height took attention from other developments that were visible to me, the teacher. Circulating the room, I observed two students, Diana and Michelle, engaged in a discussion concerning two unidentified structures

Figure 3. Two students wonder about the two lobed structures located on each side of the stem, several centimeters above the soil.

(cotyledons) located on the stem of the seedling several centimeters above the soil surface. I took notice of the interaction and saw it as a potential opening to contemplate additional aspects of development (see Figure 3).

Diana: [Pointing to a pair of lobed structures located on the stem of her seedling several centimeters above the soil.] “What are these pod things?”

Michelle: “Hmm. I don’t know. [Pause] They’re probably just leaves.”

Diana: “Oh, okay.”

Following a lengthy session in which students shared data concerning seedling height, I invited Diana to share her observations of and questions about the unidentified structures. (Students were interested in sharing thoughts about where and how to measure seedling height and had not as of yet collected sufficient data to embark on a discussion of the rate at which a seedling grows.)

Teacher: So, I’m wondering about what everyone thinks about the pod-like structures on the stem that Diana is noticing?

Karen: Well, I think they are too round to be leaves.

Pat: . . . they’re too thick to be leaves.

Andy: They’re sort of spongy; too spongy to be leaves. [Pause]

Robin: I also think they’re too big to be the seed.

Jayne: I have pods, and mine are off-white, like the seed I planted.

Robin: I’ve got them too, but mine are a little green. I think they must be leaves.

Amy: Mine are really green, look!

Erin: I want to add that the seed I grew on cotton swelled to about two to three times its original size.

I realized that Erin's observation was one that deserved attention and could be a useful contribution to our discussion concerning the possible origin of the paired structures. I paused the discussion for Erin to share data she had concerning the dimensions and size of the seed she had planted.

Jayne: I really think that it's the seed that split in two. It's the same kind of kidney bean shape.

Amy: I agree with Jayne; they just look like the bean, sort of.

Liz: But, the seed was not green!

Barbara: I've got what looks like a seed coat on the soil.

Sometimes a student will find what looks to be the seed coat still attached to the cotyledon. Yet, I try to not have this finding be the final evidence of the structure's origins and I try to keep the thinking going as long as I can without it becoming too tedious or contrived. Indeed, I believe that at some point the class recognizes that a large part of our work together is to both celebrate and find joy in the complexity of subject matter, especially that which is typically portrayed in the public domain as elementary in nature. Moreover, through watching my students over the years, I now realize that finding a seed coat on the soil surface is final and convincing evidence about the origin of the paired structures only to those individuals who have already worked out and "developed a network of ideas" (Duckworth, 2001b, p.39) to appreciate the structure and function of a seed!

Teacher: So what are you thinking?

Barbara: I'm thinking that the two pods things are the two halves of the original seed.

Teacher: Does anyone have data that will help us with this question?

Erin: I have a drawing of my seed and its sprout. It looks just like the pods that we are talking about. The pods are the seed. [Said quietly, yet emphatically]

Long Pause.

It was then that Diana posed the question that was clearly on her mind. When I listened to the question, I was surprised that I had not heard it expressed quite so clearly before.

Diana: But, how could a seed that we planted in the soil get way up there?

Teacher: So, that, to me, seems like a reasonable question to keep thinking about.

A SEEDLING IS UPROOTED!

The answer to Diana's question was, I recognized, critical to having an understanding of how a bean plant grows and was one that deserved time and space. And, if the structures are a part of the original seed, by what mechanism does the seed arrive

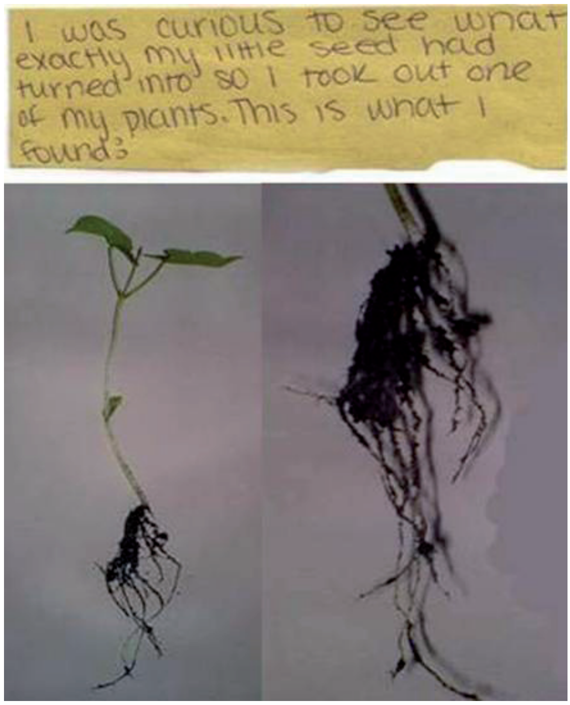

Figure 4. Diana uproots her seed and photographs what she does not find. She writes, "I was curious to see what exactly my little seed had turned into, so I took out one of my plants. This is what I found."

several centimeters up the stem? By validating Diana's question, I hoped to bring the immediate discussion to a close but not the thinking, which proved to be a good thing. That night, Diana did what she needed to do to convince herself about the origin of structures in question. She uprooted the tiny seedling she had planted. This act was, I believe, critical not just for Diana but for many other students. The next class Diana shared with us a photograph of what she had "found." The photograph showed a developed root system but no seed (see Figure 4).

Meditating Upon the Function of "Cotyledons"

Seedlings are often damaged during transport or involved in accidents of various kinds. Accidents in which structures are lost or damaged can make visible some aspects of plant growth that are more difficult to see in normal circumstances. Such accidents can create a critical experiment for those students who have been observing their seedlings closely and have already come to some understanding of events they are observing. As Duckworth (2006b, p. 39) reminds us, "[C]ritical experiments themselves cannot impose their own meanings. One has to have done a major part of the work already. One has to have developed a network of ideas, into which to embed the experiment."

In one accident, a student, Shona, told us of how her cat had knocked her potted seedlings off the window sill, spilling the seedlings onto her kitchen floor. As a result of this accident one seedling lost one cotyledon, which she called "seed pod," and a second seedling lost both structures. Shona continued her observations, now noticing differences in the rate at which the two seedlings grew relative to each other and to other seedlings grown by other students in the class. This observation required that she had already developed a network of ideas, into which to embed her observation. In her journal, she reported:

> Could Seed A not be growing as fast as some of the others in the class because only one of the seed pods remains on the stem? The other was removed when the cat got to it. Seed B has not grown at all since the cat knocked the seed pods off the stem, does this mean that the seed pod does play an important role in the growth of the plant? (Journal entry, 2/9/16)

Through making various explorations of seeds that they and others had planted, and reflecting on the possible meaning of structures and phenomena observed, these preservice teachers developed knowledge and insights necessary to root the subject matter into the experiences of children in the elementary grades.

A LEAP OF IMAGINATION: A STORY ABOUT PENDULUMS

This second story shows the depth of connections that students can make when they are given the freedom to engage in exploratory behavior. The episode follows a session in which my students made "swingers" of various sorts by tying objects onto lengths of line. The materials included keys, washers, small film canisters, fishing weights, scissors, yarn, fishing line. I asked students to observe their swinger in such a way that they could describe its behavior to another student. After a period of close observation, we shared our different observations and, together, identified those behaviors a person might follow more closely. Following Duckworth (2006b, 2006c) and Hawkins (1967/2002b) I typically have a variety of things that students might try, if it happens that nothing comes about or if students run out of ideas to try. I do not put these ideas out until it seems that they are needed, which, most of the time, they are not. (Over the course of my experiences, I have come to the realization that most students are more interested in pursuing their own questions and ideas, regardless of how small the exploration seems to me, and that they are less interested in mine!) One way that I have found to be useful is to help my students find materials that help them to take their own explorations further, which is why I put time into thinking of interesting materials to explore and devote significant class time to simply "messing about" (Hawkins 1965/2002b) for the sheer pleasure of seeing what different things do, which also involves making time to share with each other the nature of our meanderings.

In the story that I share, LaDelle, Tamara, and Shona were observing the rate at which three different pendulums were swinging. The large clock on the classroom wall was a perfectly adequate timer for the task at hand. Some pendulums had long lines with “small” objects attached; others had short lines with “large” objects attached. Prior to this, they had spent an entire class finding out the “swinging time” for pendulums with what they described as “long” and “short” strings! I remember wishing that they had found some other starting place, thinking that this might not be a “productive” use of precious class time. Yet, the explorations were important to the students in thinking about pendulums and did generate data that the students found to be both surprising and puzzling. Pendulums with long lines and short lines kept swinging for a very long time, with no convincing data that they could use to establish a difference between the “swinging time” of long and short pendulums. This lack of clear difference puzzled the students enormously to the point that they went on to another exploration. (One group in the class did work on this question.) In the class that I share here, the students (Tamara, LaDelle, and Shona) were now making a number of pendulums with lines of all the same length but with different weights attached. In this second experiment, their idea was to see if the “weight” of the object attached to the line made a difference to the total “swinging time” of the pendulum. In this instance the weights were similar in shape and, by chance, made a minimal difference to the overall length of the pendulum. Again the students became dissatisfied with not finding any difference that they could rely on between the total “swinging time” of pendulums with different weights! So now they tried a third experiment which involved counting the number of back-and-forths that different pendulums made in a fixed time period. I might have suggested this. There were many other explorations happening throughout the class.

The students began the exploration with the idea that the weight of the object attached to the line would affect the number of pendulum swings in a given time period. But Tamara and Shona each had a different idea about how the object would affect the swinging rate. Tamara speculated that the line with the greater weight attached would yield the most swings in a one-minute time period, while Shona made a persuasive argument that the pendulum with the lighter weight attached would yield the greater number of swings. Tamara had chosen an object that, while heavier than the weight chosen by Shona, happened to create a pendulum that was shorter in overall length than that constructed by Shona. The students had not begun to consider the question, “What defines the length of a pendulum?” Again, the results of the exploration were “inconclusive.” Because of difficulty keeping the pendulum swinging in a constant direction, they had reduced the time period to 30 seconds rather than one minute. They also moved to changing the weights of the objects attached by adding metal washers to lines of string that they had measured to be “exactly the same length.” The reason for using metal washers was, they told me, so they could discover the exact point at which “weight makes a difference.” They were using the washers as units of weight. The fact that the washers were of the same shape and thus did not change the length of the pendulum was coincidental! The group was now using stop watches and having what they called practice "release starts." They had also drawn a white chalk line along the linoleum floor, which they used as a "marker." Despite many trials, the data they gathered was, as LaDelle put it, "inconclusive." "It's too difficult to tell," said Tamara. "The difference [in number of swings] between the heavy and light weights is *very small*." (Groups in the class were, in this second session, making large claims about the swinging rates of pendulums with "light" and "heavy" weights on the basis of thousandths of a second. I attribute much of this to the use of stopwatches. Students who use the second-hand on the wall clock were less emphatic about differences observed.)

After several repeated attempts to find a "conclusive" difference between the swinging of "heavy" and "light" objects, LaDelle had the idea that maybe "weight does not make a difference." LaDelle asked her group if what they were seeing with their pendulums had anything to do with the dropping of objects. She asked her group, "Is it true that heavy and light objects [dropped from the same height] reach the ground at the same time?" Shona said that she thought she had heard that in her physical science class, but she was not sure that it had anything to do with what they were doing. Tamara suggested that they try it. The group rushed to the metal storage cabinet to retrieve the bucket of balls that they knew I kept there. When I inquired about the new activity (what did they intend to do with the balls they had gathered up?), Tamara responded, "Oh, nothing. We're just testing an idea we had."

The three students exited the classroom and gathered around the stairwell. For the next few minutes the group dropped ping-pong balls, tennis balls, lacrosse balls, a soft ball, a marble, a tiny earth globe down the stairwell. Initial attempts to time the fall of each ball with a stop watch were relinquished as "the balls dropped too fast" and it became "too difficult to time." The stop watches were put aside as they now timed each object by listening for the sound of the ball hitting the tile flooring. I watched as the students moved between listening for sound and trying to compare, on the basis of sound, which object hit the ground faster. After another period of dropping and listening to the sound of the ball and the flooring, the group decided to drop the balls in pairs and find the "winner" in each pair. It did not take too long for the group to decide that there was "no clear winner." The group returned to the classroom ready to set about yet another exploration. This time they would tie each ball to a length of string and watch it swing! This is how Shona wrote about the exploration in her journal.

> When we dropped different balls from the stairway we couldn't find a difference in the time they took to reach the bottom. So we decided that the weight on the end of the string doesn't really matter. So if it's not the weight, it must be string length. . . Our final experiment was to try to attach the different balls to the pendulums. (Journal entry, 4/15/06)

The group had a lot of difficulty trying to tie the tennis ball and the lacrosse ball to the line. I also saw that the question, "How do you measure the length of a pendulum?" was one that they needed to consider, but had trust that given their explorations involving weight, none of which proved that weight did make a difference, the phenomenon of length might yet become visible to them. On this occasion, I knew that another group of students was looking at swinging rate, using washers only. The data convinced them that the number of washers on the line did not make a difference to the number of swings a pendulum makes in a given time period. However, the method they used for increasing weight obscured the question, "What defines the length of a pendulum?" The group was fairly chuffed with themselves—and rightfully so—but I knew that the group discussion that followed would be critical to how people felt about what they did, and I did not want to privilege an "answer" over what might be called the "exploratory journey." Tamara, Shona, and LaDelle came to a similar insight through a journey that involved taking some risks and making a leap of imagination in connecting two phenomena that they had initially seen as quite distinct. I introduced the story of Galileo, who, like them, used sound to measure falling rate when his eye seemed inadequate for the task at hand.

A MOON STORY

I close with a short episode that involves what a teacher education student came to know about the moon through her own imagination and inventiveness, an inventiveness motivated by her desire to know "where the moon is" at any moment, especially when she cannot see it in the sky! Again, the story is taken out of a much larger story, which I do not include here. Tamara arrived carrying a large, blue beach ball, on the face of which were a number of markings and times. As we were about to begin the class I received a message from the registrar that I was expected at an admissions recruitment event. "But we can't end now," said Tamara, "I know where the moon is!" I agreed. We could not end now. Standing in the classroom, her moon journal in her left hand, the giant blue beach ball steadied by her right arm, Tamara explained the various markings she had made (see Figure 5). "So why don't we go outside," said Pat. "Let's find the moon!" I looked out of the window and saw that the sky was completely overcast. I said that I thought Tamara had given a great explanation and that we could, if they chose, add one more class meeting to follow through on this idea. I think now that I thought that I was protecting Tamara—maybe her "moon finder" would not locate the moon today. I also wondered if Tamara was thinking that the moon would always be at the same position relative to the sun as it had been in recent days. And in that moment I was overly conscious that this was to be our last class meeting. I worried that if the moon-locator did not work to Tamara's satisfaction, she might leave the course with her confidence in herself as a moon researcher shaken. In that moment I felt the weight of my responsibility as a teacher. What was I to do?

Figure 5. Tamara uses her moon journal to explain the diagrams on her beach ball moon-locater.

The students who entered the course fearful of science were now persistent, exhibiting the trust and confidence in Tamara's invention that I, the teacher, now seemed to lack, perhaps projecting my own history as a learner onto my students. I could not imagine myself inventing a moon locater! Standing outside on that grey overcast afternoon, Tamara faced the dim glow of the setting sun and planted her feet confidently. The sun's disk was veiled by clouds making it difficult for her to locate. The device required locating the sun. I heard myself interject, "It's enough; we can go in now."

But neither Tamara nor her classmates were deterred by my protestations, as the exploration had taken on a life of its own. My students had become "seized" by the power of the subject matter. (One of the wonderful aspects of critical exploration is that the subject matter and student interest in it drive our interactions. Students find themselves unable to bring their explorations to a stop simply because the course is completed or because the instructor states that the class is over!) With complete calmness and trust in her data and her invention, Tamara announced, "It should be right there, over my left shoulder." We all looked up, but the sky was swirling with clouds. Not seeing anything, I moved toward the entry, encouraging my students to move with me. They did not. They stood with Tamara and waited. "Look!" shouted Robin. "There it is!" And there above us, peeking through the swirling clouds, was the moon, just where Tamara knew it would be.

DISCUSSION

I have no doubt that the experiences of these teacher education students will carry over into their work with elementary age children. Indeed, in a final journal entry Rachel reported that she was now growing seeds with the young students in a kindergarten class for which she was a teacher's aid. She included with her final paper for the course the drawings of the seedlings that she, the teacher, and her students had made. I noticed her interest in having the children tell *her* what they were seeing; I noticed how she encouraged her students not to draw an "imaginary plant" but to draw what they are "actually seeing." I noticed that her exploration of children's understanding moved beyond the words that young children use to express their thoughts to include exploration of the things they make and do as a result of their interaction with the world. I noticed her profound trust in the seedling to reveal structures of significance in understanding how a seed grows and develops into a plant; and I noticed her profound trust in children's capacities to see and their capacities as sense-makers. I noticed her growing trust in herself as a teacher of young children. She wrote,

> I thought it would be best to just let the children *tell me* what they were seeing. I told them that they should use the crayons to show what they were actually seeing. I told them not to draw a picture of an imaginary plant, but to make drawings of what they were seeing.

The next week, which was also our last class meeting, Rachel stated with confidence, "I've decided that I'm not going to tell my students about plants. I'm going to see what they know about plants." Meaning that she was going to see what her students could learn about plants for themselves. She added, "I hope this will be okay with my supervisor. We'll see."

Another preservice student, Jane, who became fascinated with the moon, described how over the course of the class she had gone from being convinced that I, as the teacher, had an "obligation" to tell her, the student, where to look for the moon to being grateful that I did not take from her the delight in finding this out for herself. She described how in one class she had held her breath thinking that I was about to explain something she was on the verge of figuring out for herself. Jane's small divulgence reminded me of a similar divulgence made by another student several years before, who, standing with her family at a graduation event, confessed to me that she had spent the first few weeks of the course writing sticky notes to herself which she pasted in her notebook that said things like, "Do not teach this way! Do not do this." She then described to me what she took to be a pivotal event in her life as a student, telling me of how in one particular class, after a period of doing things that she had assumed to be "totally nonproductive," her group was arranging some materials (two light bulbs a battery, lengths of wire). "All of a sudden," she said, "I knew that I knew what would happen. And I was right. I learned things in that class that I never learned before all through high school."

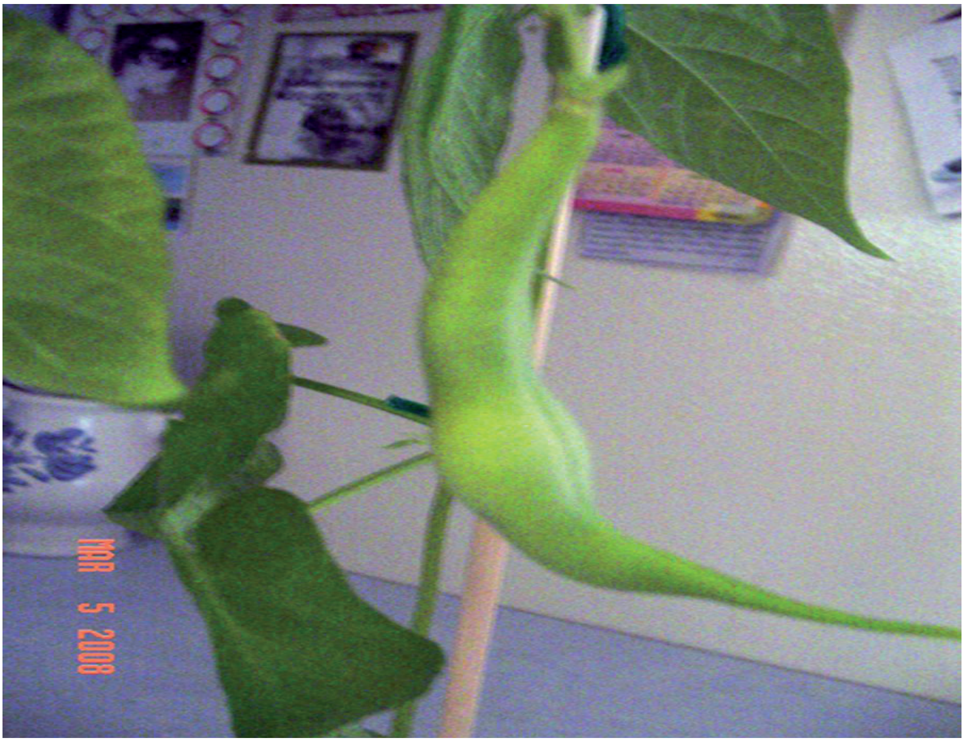

Figure 6: Michelle's "amazing" green bean**.**

The reflection below was written by a student as part of her final paper:

> Through observation and description of outcomes and predicting what they think will occur next, a person's cognitive ability is exercised as they need to interpret data and formulate hypotheses that are logical [to them]. Observation although often done in a free environment still requires logical steps and conclusions in order for the experiment to move forward. As I continued investigating the growth of my seed, I was able to discover the truth to the initial question asked and the answer was revealed to me in the freedom of my own space and time. . . .
>
> . . . Have you ever just held a bit of soil in your hand and just sniffed? Oh, the freedom that such an aroma gives a person and the imagination that stimulates the mind as the scent permeates the brain. My fingers felt the different textures that the plant had to offer in its various stages . . . The experience was invigorating, arousing . . . incredible. Such a feeling of freedom is lost in today's classrooms and must be awakened through [the child's own] experimentation and observation.

> Through experimentation I discovered that it is okay to make mistakes. At many points I did things that turned out to be a disaster. Scientists as well experience error in judgment. However, mistakes made me stronger and provided new ideas for other experiments to try. Observation and investigation opens endless doors to reality as well as imagination and it is important to somehow, no matter the circumstance, incorporate that into classrooms today so that all kids can *feel* the world around them. (Italics in original)

I close with the following episode. Late one evening I returned to my office to find two photographs that a student had slipped underneath my office door. One photograph showed a leafy bean plant. The second photograph focused on a single green bean! (see Figure 6). In an email, the student explained, "I am giving you two pictures of my plant . . . I wanted you to see them in color because the green bean looks amazing to me!"

I have no doubt that these teacher education students will observe and attend to the development and well-being of the students entrusted to them, and thus develop the same appreciation and amazement for the children they teach as did this one student for one ordinary field bean!

REFE RENCES

Cavicchi, E. (2009). Exploring mirrors, recreating science and history, becoming a class community. *The New Educator*, *5*(3), 249–273.

Cavicchi, E., Chiu, S., & Hughes-McDonnell, F. (2009). Introductory paper on critical explorations in teaching art, science and teacher education. *The New Educator*, *5*(3), 189–204.

Chiu, S-M. (2009). "The ancient master painted like me". *The New Educator*, *5*(3), 229–248.

Dewy, J. (1912/1956). *The child and the curriculum*. Chicago: Phoenix Books.

Duckworth, E. (2001a). *"Tell me more": Listening to learners explain*. New York, NY: Teachers College Press. (Original work published in 1986)

Duckworth, E. (2001b). Inventing density. In E. Duckworth (Ed.), *"Tell me more": Listening to learners explain* (pp.1–41). New York, NY: Teachers College Press. (Original work published in 1986)

Duckworth, E. (2001c). Teaching/learning research. In E. Duckworth (Ed.), *"Tell me more": Listening to learners explain* (pp.181–187). New York, NY: Teachers College Press.

Duckworth, E. (2005). Critical exploration in the classroom. *The New Educator*, *1*(4), 257–272.

Duckworth, E. (2006a). Understanding children's understanding. In E. Duckworth (Ed.), *The having of wonderful ideas and other essays on teaching and learning* (3rd ed., pp.83–97). New York, NY: Teachers College Press.

Duckworth, E. (2006b). Critical exploration in the classroom. In E. Duckworth (Ed.), *The having of wonderful ideas and other essays on teaching and learning* (3rd ed., pp.157–172). New York, NY: Teachers College Press.

Duckworth, E. (2006c). Teaching as research. In E. Duckworth (Ed.), *The having of wonderful ideas and other essays on teaching and learning* (3rd ed., pp.173–192). New York, NY: Teachers College Press.

Freire, P. (2000). *Pedagogy of the oppressed* (30th anniversary edition). (M. B. Ramos, Trans.). New York: Continuum International. (Original work published in 1973)

Hawkins, D. (2002a). On living in trees. In D. Hawkins (Ed.), *The Informed Vision: Essays on Learning and Human Nature* (pp. 171–192). New York: Algora Publishing. (Original work published in 1965)

Hawkins, D. (2002b). Messing about in science. In D. Hawkins (Ed.), *The informed vision: essays on learning and human nature* (pp. 65–76). New York: Algora Publishing. (Original work published in 1965)

Ramsey, L. (2002). *Developing curriculum in light of close attention to student thinking: An examination of selected narrative research literature by classroom teachers*. Unpublished Qualifying Paper, Cambridge, MA: Harvard University.

Schneier, L. (2001). Apprehending poetry. In E. Duckworth (Ed.) *"Tell me more": Listening to learners explain* (pp. 42–78). New York: Teachers College Press.