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Introductory Paper on Critical Explorations in Teaching Art, Science, and Teacher Education

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The authors of the three papers in this issue discuss and analyze the practice underlying "critical exploration," a research pedagogy applied in common within their separate art, science, and teacher education classrooms. Eleanor Duckworth developed critical exploration as a method of teaching by involving students so actively and reflectively with a subject that they have "wonderful ideas" that arise from their own questioning. Teachers who encourage critical exploration support their students in encountering complex materials, experiencing confusion, considering multiple possibilities, and constructing new understandings. Teachers refrain from providing answers, or even implying that there is an acceptable answer or technique, and instead facilitate the personal process of development that Jean Piaget, Bärbel Inhelder, and others documented and analyzed. Applying Piaget's findings requires teachers

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to sustain what David Hawkins described as "triangular relationships" of trust and respect among teacher, learners, and subject matter. The three classroom studies that follow narrate these exploratory qualities in the contexts of middle school girls learning Chinese brush painting, undergraduates investigating mirrors, and teacher education students exploring seeds, pendulums, and the moon. In teaching art and science via critical exploration, curiosity and a sense of beauty reinforce one another, and open a window into the processes of—and connections between—art and science.

INTRODUCTION, OUR BACKGROUNDS, ART AND SCIENCE

Commonplace things get overlooked. Routine contact fools us into supposing we know about things like brushes, mirrors, and seeds. Situations seldom arise that put us at risk of realizing that we do not know what we think we know. Artists and scientists may hazard that risk, cracking the surface of the familiar to expose its meanings and workings. Leonardo sketches sunlight and shadow on a staircase or a face; Galileo investigates how a weight swings in space and time. New understandings about humanity and nature arise for them and a widening community.

Classrooms have potential to be places for taking the risk of discovering how much is unknown within what we thought we knew. Yet, incongruous with this potential is a pervasive assumption that classrooms are places for dispensing well-defined knowledge by adhering to a predeterminable order of exercises. That packaging of knowledge and its exchange by transmission discourages the kind of risk-taking that might show up inadequacies in the knowledge, the order of its presentation, or the thinking of classroom members. Bringing about a classroom where even everyday things can be seen as curious and worthy of questioning means letting the packaging unravel, tolerating spontaneity in what students notice, wonder about, and discuss, and finding grounds in those responses for further activities and study. Doing this compounds the risk that teacher and students experience. Not only do they, like artists and scientists, use commonplace things in provoking contemplative and investigative acts that may reveal failings in everyday knowledge, but also they do disrupt structures of human relationships that become ingrained in people through conventional schooling.

We are teachers of art, science, and teacher education seeking to develop classrooms that are resonant with curiosity. These would be classrooms where students look closer at everyday things, do something in response, and wonder about what they observed and did, while associating together with respect and critical outlooks. The articles that follow describe classroom activities and reflective work by which our respective students reinvented strokes and expressiveness of traditional Chinese brush painting, investigated light's reflection off mirrors, and watched

a seed sprouting over time and swung weights from string. Complementing these classroom experiences and productions run accounts from the interactions, thoughts, and inquiries of each of us as the teacher. As our students found themselves on new ground with seemingly familiar materials of brush and ink, mirrors, or seeds, weights, and string, so we as teachers accessed untapped educational possibilities in these same materials, and in relationships that bring together students and materials with an equally curious teacher. Thus what arose for us by way of our teaching provides a resource for others in considering how teaching and teacher education can develop.

The three of us taught and studied art and science in instructional formats more conventional than those presented here before becoming doctoral students of Eleanor Duckworth. As related separately below, our personal experiences as students in her course "Teaching and Learning" moved us each to rethink what we do as teachers and to conduct our teaching as critical explorations, drawing on the research pedagogy she has developed (Duckworth, 1973/2006a, 1987/2006c,1991/2006d, 2005/2006e). Together we find that critical exploration brings about conditions that engage students in art and science as creators in their own right who undergo development in the course of their explorations.

CRITICAL EXPLORATION IN THE CLASSROOM

Critical explorations are experiences in teaching and learning which a teacher conducts so as to engage learners in a subject matter that is real and may be physically present in the classroom. With its fullness of detail, the reality of such a subject accommodates plenty of leeway across which learners may exercise curiosity, actions, observations, conjectures and thought. Theirs are the eyes noticing something about that subject they had never seen before; theirs is the mind perturbed enough by it to ask a question, or want to try something out, or express a spontaneous reaction; theirs are the hands constructing something or modifying an apparatus or wielding a paintbrush. By their own agency on and with the subject, learners develop in their awareness and understanding of it, and in their capacity for action.

Both the name, "critical exploration," and the methodology it represents were introduced to classroom practice by Eleanor Duckworth from the research methodology that Jean Piaget (1926/1960) and Bärbel Inhelder (1974) evolved while investigating how children come to new understandings and capacities in relation with the world. Early in this work, Piaget (1926/1960) interviewed children about night, dreams and other phenomena not under the child's control. Piaget foresaw that children's inclination to say whatever they suppose an adult wants to hear would impede his effort to reveal their underlying thought. To work around such tendencies to please, he probed the depth of their beliefs and watched their behavior for clues that confirmed or disconfirmed what they said. Piaget evolved

further means of investigating children's actions while following his own infants' growth (1936/1952, 1936/1954), and in his later collaborative studies where intriguing problems or experiments were presented to school-aged children (Piaget, 1932/1965a, 1941/1965b, 1948/1967, 1960/1981; Inhelder & Piaget, 1955/1958). Across this extensive research heritage, a methodology is developed which Inhelder (1974) named "critical exploration," emphasizing that both the adult researcher and the child participants are involved in exploring.

An exploratory outlook is essential for a researcher who seeks to elicit, document, and understand children's emerging actions and thoughts, as Inhelder observed:

> Development is an unknown territory that can only be charted by studying children, whose actions and ideas will continue to surprise us. (Inhelder, 1974, p. 22)

Over the course of much teaching and research, Duckworth realized that a teacher who seeks to support learners' developments in action and thought is intrinsically an explorer who learns about students' thinking, activities, and potential by taking up the curiosity, questions, and hunches of a researcher. The conditions and practices that Piaget and Inhelder worked out as researchers to facilitate development among the children they studied also pertain to teaching and learning. Just as Inhelder sought the unanticipated "surprise" of children's spontaneity, valuing it for research, Duckworth associates the "essence" of teaching with providing opportunities by which students may "have wonderful ideas" that are expressions of their learning (Duckworth, 1973/2006a, p. 1). Wonderful ideas carry surprise for both teacher and learner, as Duckworth conveyed in imagining the inner ruminations of a boy in her class who was on the verge of a new understanding about ordering the sizes of soda straws:

> … he picked [the straws] up and said to me, "I know what I'm going to do," and proceeded on his own to order them by length…He meant, "I have a wonderful idea about what to do with these straws. You'll be surprised by my wonderful idea." (Duckworth, 1973/2006a, p. 1)

The genuine depth at which such change transpires for learners becomes evident in many ways. Each wonderful idea is an intellectual achievement for its inventor, freighted with the emotions of struggle, delight, or discovery by which it came to be. The process becomes self-sustaining. Learners' new "wonderful ideas" grow on their past "wonderful ideas," at times critiquing, changing, dismantling, inverting the earlier offerings while bringing about learnings that are emotionally compelling and intellectually ever-enriching.

In being attuned to watch for wonderful ideas and hold open space for their tentative emergence, a teacher of critical exploration has broken with the role of providing answers to students or telling them what to do. As a counterpoint to

conventional instruction which proceeds through answers to produce closure and certainty about a topic, a critical exploration proceeds through the raising or unmasking of questions, tensions and ambiguities in it. For students and teachers whose education has ingrained in them an expectation of answers and identifiable endpoints, it is disconcerting to participate in a critical exploration. Unaccustomed to exploring as an ongoing process, they suspect that there are answers after all, withheld by the teacher. Part of the work of any class involves building the trust to move beyond the shadows cast by assumptions that bind education to answers.

Critical exploration puts learners into experiences like those faced by explorers in history, such as Galileo, Leonardo, or Ming Dynasty artists. By going into areas unknown, they take risks, meet up with dead-ends and unexpected discoveries, and gain knowledge about both what they have seen and how they got there. Yet, they are not alone. Their classmates are along, making their own personal and interrelating journeys which may coalesce as a classroom community.

The teacher is there too as an explorer. The teacher has to learn to see wonderful ideas that are unexpected or expected, familiar, original, or mistaken. The teacher needs to gain skills and sensitivity in looking for, identifying, and supporting them. What that productive work looks like often runs counter to the types of behavior that teachers are traditionally trained to spot and reward. For example, learners' confusion is often a prelude to their keener involvement and the making of connections or analyses that deal with significant puzzles in the subject and the learners' grasp of it (Duckworth, 1979/2006b).

In carrying out their work as explorers, teachers and learners have a shared and mutual responsibility to build an environment in the classroom that is safe for taking risks about knowledge. In order to voice a tentative idea or test an experimental hunch in the shared space of the classroom, a student—or a teacher—needs to feel that others will respect his/her offering. Respect comes about gradually through continual ongoing efforts—many of which may fail and fall short—to hear and show genuine interest in the thinking and doings of others. The netting of mutual respect not only makes the "having of wonderful ideas" possible, but it also ties classroom participants together as a community where each is invested in each others' undertakings, no matter how divergent these may appear.

We found for ourselves as new teachers of critical exploration that it was easy to start to take over, tell learners about the subject, guide them along established routes toward generally accepted outcomes. However, we are assisted in refraining from these practices by several factors. First, all the teaching we have done repeatedly confirms that many students gain minimally from teachers' telling and guidance. More positively, once we began to see wonderful ideas in action, and students' accompanying energy in pursuing them, we became caught up in their educational potential and drama. We then wanted to know more about how to keep that level of student involvement going.

The research aspect of critical exploration addresses this very desire. By researching what goes on during our students' explorations of the subject we strive to plunge enough into where they are in it to offer responsively some materials, questions and experiences that may stretch, unsettle, and extend their thoughts and actions. Thus, we are as much engaged in trying things out, meeting dead-ends, stumbling upon surprises, and forming new knowledge that bears on teaching and learning, as our students. And, the diversity, tangledness, and depth of students' multiple explorative paths are meaningful as knowledge about teaching that can inform our future practice.

As our research puts ourselves, the teachers, into the role of being learners, it takes self-reflection and critique to sustain in our own learning the explorative qualities we seek to enlarge for our students. Duckworth sees this self-watchfulness as a tool in opening up a subject matter to our own explorations and preparing for those of our students:

> We try to be tuned into areas or encounters in which our subject matter surprises us, puzzles us, excites us, intrigues us; these are precious indicators to us of ways our students might connect with the material. We try to catch ourselves in moments when we make what we might consider a "foolish" misjudgment, quickly corrected; we want to understand what led us to think this even for an instant, as a way of understanding what some of our learners' ideas might be. (Duckworth, 2001b, p. 182)

These self-reflective activities expand our resources for responding to wherever students are in their explorations. The teaching responses we then make may take many forms that are associated with good pedagogy anywhere: providing new materials, tools or activities; posing questions, problems and readings; asking students to discuss and share their work with each other; setting aside time for reflection and writing; introducing new experiences. Underlying this diversity is the teacher's concern to ever-widen the possibilities by which students may engage the subject and come to apprehend its characteristic behaviors, properties, or patterns. Relationships among teacher, learner, and subject, along with the history of what goes on in critical explorations, are inseparable from this work and from the new (for them) knowledge—"wonderful ideas"—that students generate.

In support of our research, we continually document, reflect, and collect materials that carry evidence of the explorations as these occur. On the students' part, the act of documenting science observations or making successive paintings on paper, supports them in understanding the grounding aspects of natural phenomena in science, and of paint and painting in art. Through their involvement with materials and record keeping, our students form meaningful personal connections with the subject. They become aware of how their understanding develops over time. On our part as teachers, the act of documenting helps us to look closer at what our students

are doing and thinking. This provides us with useful feedback for planning the next activity or instructional intervention. Our reflective journal writing is a beginning phase of analysis of the developments that go on in critical explorations.

In presenting critical exploration research, we try to render dynamically evolving events and understandings that occurred in our classrooms and teaching experiences. Drawing on documentary evidence—such as student work, recordings of class sessions, photos, and teacher journals—we look for confusions, uncertainties, and observations that interrelate students' thinking and actions with the subject matter and the teacher's interventions. Narratives are a means for reconstructing students' creative acts in process and for following their wonderful ideas as these develop into original productive work branching in many areas while deepening in understanding. The resulting classroom stories can expand other teachers' awareness of the myriad explorations and teaching responses that may arise in a specific subject area, such as floating and sinking (Duckworth, 1986/2001a); batteries and bulbs (Cavicchi, 1999; Hughes-McDonnell, 2000); paint and brushes (Chiu, 2003); teacher education (Duckworth, 1987/2006c; Magau, 2001); a poem (Schneier, 2001); nineteenth century butter molds (McKinney, 2004).

ORIGINS IN PIAGET'S ANALYSES OF DEVELOPMENT THROUGH MULTIPLE POSSIBILITIES

If others have already codified techniques for producing Chinese brush painting, figured out how mirrors reflect, charted seeds sprouting over time, would it be more "efficient" to educate by presenting those formalizations to students? It appears "slow" to teach by involving students in explorations by which they may, or may not, generate understandings that are consistent with those already formulated. Such objections to exploratory learning privilege a certain type of efficiency and uniformity in information transfer while ignoring the processes by which anyone's learning becomes sufficiently deep as to be usable in new, evolving situations. Eleanor Duckworth learned to observe those processes in real time while she engaged children in problem-solving activities during clinical interviews that she conducted as part of her studies with Piaget and Inhelder. We discuss here some features of the interviewing and analyses by Piaget and Inhelder that pertain to critical exploration.

Observant teachers recognize that students can say the "right answer" without knowing what it means, how it was determined, or how to proceed on a somewhat different problem. Piaget's findings suggest that to go beyond such superficial compliance, students need to "construct" for themselves knowledge that is new for them. This construction depends not on adopting correct language or formalisms, but on working out, for one's self, relationships that are at play in the situation under study. When thoughtfully done, working out these relationships brings about changes

in how an individual comprehends those relationships and how he or she deals with anything partaking in them. This reorganization in thinking and action can be put to use in a range of situations, giving rise to further opportunities for re-examining relationships and thus continuing the constructive process.

The constructive process is personal, yet externally observable and open to input from external sources. Piaget's studies of his own infants illustrate how it goes on even where language is not yet available (1936/1952, 1937/1954). Showing his watch to his year-old daughter, who was always fascinated by it, Piaget closed his fingers around it, put his hand under a blanket (secretly depositing the watch there), then lay his fist before her (1937/1954). She opened his fingers seeking the watch, but did not next raise the blanket. At eight months, once his hand closed around the watch, putting it out of sight, she forgot it; at a year and a half, she looked for it in all the hiding places his hand had been. Adapting his hiding games in response to these observable changes in the child's behaviors, the father posed additional tasks. Experimenting along with her, he looked for how she reacted to new games that tested his inferences about how she viewed things he hid (Cavicchi, 2006).

From this observing and testing, Piaget inferred that real development was going on for his daughter, both in what she could do and in how she construed objects. These two aspects—actions and the outlook associated with them—interrelated dynamically. He observed her innovate actions—such as using her fingers to open his—that had attributes of previous actions and some new elements. He characterized this type of repeatable action as a "schema," a capacity that, once generated by a person, the same individual could call on again and again. Together with these innovations in actions were innovations in how extensively she searched for something hidden. When, eventually, his daughter searched until she found it, Piaget surmised that she had constructed an understanding which she had not held before: an object persists even when obscured.

In these expanding capacities for action, Piaget espied transitions to new "stages" in the structure by which she acted on things and concurrently understood herself in relation to those objects. A stage was a phase where, temporarily, what happened when she did something cohered with her expectation. Unexpected occurrences and outcomes destabilized this coherence. Being destabilized, which Piaget termed disequilibrium, put her in a state of trying out new ways to act, taking in what transpires, and synthesizing that with her previous actions. Piaget described this active process, which he probed and documented across the childhood years in many subsequent studies, as analogous to the means of generating experiment and theory in science (Piaget & Garcia, 1989). For the child, as for the scientist, collaboration with a community of peers—as well as investigations of the natural world—can give rise to the personal and collective experiences of disequilibrium that propel vibrant development (Piaget, 1932/1965).

Being in disequilibrium is fluid and uncertain, yet something comes of this ambiguity that enables those partaking thoughtfully in it to act and understand in

ways that were not evident before. Disequilibrium opens up the participants' access to what Piaget called "possibilities": potential actions, plans or thoughts that are conceived in advance of their execution. The act of generating intellectual possibilities is, for Piaget, "essentially invention and creation" and it demonstrates the constructed, not-preformed, nature of our emergent capabilities (Piaget, 1981/1987, p. 4). The whole range of possibilities is never taken in at once; instead it is by delving into the problem and its initial appearances that other variations come into view. Experiences of disequilibrium come to a temporary but not definitive end; they give rise to further opportunities for discovering unanticipated possibilities whose evaluation plunges us into fresh disequilibrium.

Development depends crucially on our capacity for making multiple possibilities available for consideration at the same time. It is not a step-by-step procedure of going from one prediction defined in isolation to another. Through putting their mind to work on evaluating multiple possibilities, participants come up against characteristics of the problem at hand that may be distinctive and by which its underlying relationships can be inferred or tested. All the possibilities considered—not just the "successful" ones—contribute to the development that is underway.

A person's access to the full range of possibilities pertaining in a situation may be blocked by internal convictions or external conditions that improperly limit or over-specify what can be, thereby closing off from consideration some viable possibilities. It may seem that things have to be in a certain way, whereas the reality is otherwise—and more open. Part of the task of development is to sort out these false limits and liberate ourselves from preemptive restrictions so as to be willing to ever-widen the scope of what our conjectures may be. Piaget's finding was that this liberating process of generating possibilities that may be infinite in extent is the means by which we form new structures of thought and action that are flexible, reusable, and abstract. Someone who has developed to the point of being able to conceive infinite possibilities has, by means of that very development, the intellectual tools to begin to evaluate, critique, and analyze them.

Connecting Piaget's analyses to teaching is a disequilibrating undertaking in itself. Conventional exercises in education privilege such nonconstructive activities as producing an answer, being certain, following prescribed steps, limiting options, building directly on precedent, and avoiding "failure." To give space for students and teacher to work seriously in disequilibrium means disrupting these ingrained but seldom-questioned practices that, like the false limitations on possibilities discussed above, curtail what is thought and done. Giving multiple possibilities a productive role in the classroom involves such everyday teaching actions as catching ourselves before we cut off a student's expression whose reasoning we do not yet grasp, or opening a class discussion without directing it towards a particular conclusion. Realizing that our teaching is, in itself, ever-evolving through disequilibriums, grounds us in awareness of what our students face during their explorations in our classrooms.

TRIANGULAR RELATIONSHIPS AND COMPLEX SUBJECT MATTER

If, as Piaget's studies suggest, each learner constructs knowledge through his/her own experience and engagement, then, as Eleanor Duckworth asks in her introductory course, "what can a teacher do to help?" Under conventional outlooks on acquiring knowledge, this dilemma might resolve through assigning the responsibility of learning to the learner, as a solitary act in which the teacher has no operative role. Philosopher David Hawkins (1969/2002) expressed an alternative, where teacher, learner, and subject matter make up a triangular relationship of continual interaction and shared trust. Practitioners of critical exploration find Hawkins' analysis germane to their efforts to bring about classrooms where learners actively extend what they notice, do, and come to know.

In describing the relationships that pertain in education as triangular, Hawkins adopted the pronouns "I," "Thou," and "It."[1] Hawkins associated the personal pronouns "I" and "Thou" with teacher and learner (in either order) and the impersonal pronoun It with the subject of study. Hawkins' triangle puts "I," "Thou," and "It" in a nonhierarchical relation. No one element dominates and the effort to keep balance among these three parts compensates if one part becomes over-stressed. In a classroom with many learners (and teachers), each of these relationships takes on plural inputs.

The "It," the subject matter, can be known in various ways and depths, of which the learner is mostly unaware. While the teacher knows "It" more fully, in this triangular relationship, the teacher is not there to pass that knowledge to the student. Instead, the teacher seeks to bring about a relationship between the learner and the "It," by which the learner develops both in understanding "It," and in capacity to carry on in relationship with it after the teacher's participation with that learner ends. In looking to engage learners with the subject matter, the extent to which the teacher has a relationship with "It"—and not merely factual or summary information about "It"—is mirrored in the possibilities for learners' engagement that the teacher can envision and perhaps facilitate. The teacher, having developed awareness of multiple possibilities in the subject matter through her own past and ongoing explorations of "It," now offers these possibilities for learners to explore. This mechanism makes it important for teachers of critical exploration to have experienced critical exploration as learners who have moved through personal confusion to appreciate how diverse outlooks and possibilities enhance understanding. In addition it confirms the teacher education truism stating that teachers must have learned in the way they aim to teach.

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[1] Hawkins' essay implicitly referred to the relational analysis of Martin Buber's work *I and Thou* (1923/1970). Buber adopted the pronoun pair "I-Thou" to represent relationships where the participants interrelate by their whole being, transforming each other. With the pronouns "I-It," Buber designated relationships where the other is treated as an object, an external entity. See McDonnell (2008) for an expression of Buber's analysis in discussions of classroom teaching. Stillwaggon (2008) applied the thinking of Buber and Hawkins to the context of pedagogical relationships.

Hawkins' triangle, in putting the teacher into relation with the learner as well as with the subject matter, does not intend that the teacher simply opens up those possibilities and then stands back. In elucidating the teacher's relationship with the learner, Hawkins uses the analogy of a diagnostician who watches what is happening, takes input, and makes conjectures as a prelude to responding. To fulfill these functions, the teacher needs to see as much of each learner's particular actions and fascinations as possible. A teacher sees much less when everyone in a class does the same thing, compared to when each engages in a self-chosen pursuit. To get beyond an educator's conventional dependence on words and writing, Hawkins, in referring to teaching young children, underscored the value of eliciting a child's whole being and body using "the big muscles and not just the small" (p. 57). It is then that the teacher espies "inklings of interest …[of] what might prove absorbing" (p. 58), a pedagogical form of evidence that the teacher uses in making thoughtful responses that may prove provocative for that child.

When that diagnostic effort succeeds in the sense that the learner takes up a new and sustaining activity with the subject matter, the triangle completes among "I," "Thou," and "It." As the learner "comes alive" for the teacher, the learner gains from the teacher a basis for having and giving respect—the conduit of a viable, multi-participant relationship. Teacher and learners are involved together in something other than either of them—in a subject matter of the world.[2]

That the subject matter remains whole and of the wider world is an insight about curriculum which Duckworth (1991/2006d; 2005/2006e) finds essential for conducting critical explorations. Only where the subject has many facets and problems veining through it from within as well as threading out to other equally multiform subjects beyond it, is there matter substantial enough to support extended classroom exploration. Duckworth refers to this condition of a subject matter as its "complexity." Complexity characterizes the raw materials of any field of study: poems, paintings, seeds, mirrors, objects in motion, numbers, rocks, water, the moon, historical documents, maps, or the field of teaching and learning. By contrast with these materials that can be explored endlessly and still give rise to new ways to act, observe, and reflect, much educational curriculum has projected the subject matter into a space of lesser dimension, which accommodates only one way to proceed.

Most educators and students view it as the educator's task to prepare in advance explanations and lessons that direct students through the material by a clear and efficient route. Duckworth sees an educational role in not simplifying the subject matter or mapping it out with routes and explanations:

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[2] A subject matter for a critical exploration is not considered the discipline, such as painting or physics or botany, but rather the actual fodder that supports the exploration—brushes and paint; mirrors; seeds. A discipline's formalization of certain techniques, interpretations, and solutions tends to narrow the scope for study to the extent that genuine choices, alternatives, and possibilities are not readily available to students and teachers.

> a teacher who presents a subject matter in all its complexity makes it more accessible by opening a multiplicity of paths into it." (Duckworth, 1991/2006d, p. 135)

That multiplicity of paths, which a complex subject matter can sustain but a simplified one cannot, is a means at the teacher's disposal for accommodating diverse learners in noticing for themselves its multiple possibilities. Learners' acts of noticing and responding to multiple possibilities motor their own development, as Piaget understood it.

Dealing with complexity and its multiple possibilities can destabilize what sense a learner currently makes of the subject matter, bringing about confusion. Finding that learners become aware of confusion as their engagement with the material deepens, Duckworth (1979/2006b) supports them in taking time and space to delve into previously unexamined assumptions and issues. By staying with their confusion long enough to see it through to a next resolution or equilibrium, learners change in their relation to the subject matter, the "It," and to their own exploratively driven insights and perplexities. Over time, the process of engaging with complex materials builds learners' trust in themselves as explorers, a trust that can sponsor future explorations in areas more overlooked or unknown.

VISUAL ART AND SCIENCE

Visual art and science are often treated as disjoint domains, where the skills, outlook, and participants in one have little to do with, or to offer, the other. This disparity breaks down when we pursue art and science exploratively. Both art and science involve exploring something outside ourselves, whether, for art, materials like brushes and paint; or, for science, natural phenomena like light's reflections and seedlings' growth. This external matter resists our interventions, showing forth its own properties and behaviors, thus goading us to take into account something we do not expect or fully control. Both modes of exploration enhance our capacity to act and reflect on these things of the world, to be observant and flexible in response to whatever happens, to apply what we notice about the particular and general features of things, and to share our work in community.

The creativity that arises in artistic and scientific explorations—in generating and searching after possible expressions and understandings—is of a piece with the process of developing through disequilibrium that Piaget identified. These analogies across the practice and process of art, science, and development motivate us as teachers in attempting classroom explorations with art and science materials. Yet the commonality we share goes beyond that of teaching our respective subject matters through exploration. Due to the spontaneous processes that we encourage, art comes up in the science classroom; science comes up in the art classroom. Art and science cross-fertilize, and we as teachers encourage these emergences in our art, science, and teacher education classrooms.

For example, everyday materials like water, wax, string, and seeds have an immediacy that invites us to hold, shape, open them up—responses that are intrinsically both art and science at once. College student Carolina Gomez described this unity of art and science in reflecting on her childhood play with candles: "I would gently touch…and observe the liquid in my hands… turn[ing] into wax once I removed it from the heat" where she formed it in shapes (Gomez, 2007). From long ago, the working of materials by hand and tool entailed doing art and science together in ways that show up under close study of historical artifacts. Metallurgist Cyril Stanley Smith identified this art-science concurrence in analyzing how a treasured Classical Greek bronze, the life-sized Poseidon sculpture now in Athens, rests on delicate ankles having crucial welds whose craft, permanence, and precision remain as much a marvel as the artistry of the figure (Steinberg, 1973; Smith, 1981). Similarly, in the multilayer microstructure of Japanese samurai swords Smith discerned signs that the metal was worked, welded, and forged in cycles that impart visual beauty, design, and strength to the resulting blades (Smith, 1981). That materials retain so deeply in their structure the concurrence of art and science suggests their potential for enticing learners into doing art and science. Physicist Philip Morrison observed:

> The artist shares the most basic problems with the scientist…There needs to be paper and pigment, or catgut and horsehair, or clay and chisel. To work in art is always to solve some problem of handling a portion of the real world… Here is a fundamental kinship of science and art… (Morrison, 1964/1970, p. 106)

As well as bringing us into responsive contact with the material world, both art and science sustain exploration. The French filmmaker Henri-Georges Clouzot (1956/2003) photographed Pablo Picasso by timelapse and film as he painted. The film reveals Picasso's process of painting a horse in layer upon layer all superposed onto a single canvas. Each layer expresses yet another possibility for the horse, changing its color, shape, emphasis, contrast, light and dark, gesture… The final painting is, in the artist's experience, all of these layers and not only the outmost one that the public receives. An analogue in science, to Picasso's successively redrawn, ever-changing horse, lies in the lab notebooks of scientists. Unlike the step-by-step order we are led to expect of science, these notebooks trace out transitory findings, observations, and hunches in evolving disarray, where an investigation may digress, reverse, and write over its previous assertions. The exploratory face of science emerges when these notebooks are closely studied along with other evidence (Holmes, 2004, 2003; Cavicchi, 1997; Steinle, 1996; Settle, 1996).

Beyond these analogies in the materials, uses, and exploratory processes of art and science is the integrated practice of art and science together, manifested in Leonardo da Vinci's notebooks (da Vinci, 1973-1975; Chiu, 2000). Drawings of a waterwheel in motion, a floral spray, optical diagrams, or studies of a human hand

neighbor each other on manuscript pages edged with cursive mirror-writing. Leonardo's exquisite drawings are at the same time investigations into structures and patterns of nature and renderings of proportion, balance, craft, and sensitivity. The curiosity to understand light and shadows in a crumpled drapery is of a piece with the drawn evocation of that form.

In the examples provided in the articles to follow, as we try to make exploration possible for our art, science, and teacher education students, these analogies and concurrences of art and science flow into their experience. Art students delight in the distinct textures of ground pigments and learn to regulate their brush's uptake of water and pigment to produce a fluid effect. Looking closely at chrysanthemum blossoms to sketch them, these students in the process grasp the petals' symmetric structure (Chiu, this issue). A science student constructs a curved mirror device that is at once elegantly crafted and precisely aligned to demonstrate light's equal angle reflection. As science students interpret a problem in mirror reflection, they play, improvise, argue, disassemble, and rebuild their set-up in an evolving process that remains observant to the behaviors of light and appreciative of its visual fascination (Cavicchi, this issue). Teacher education students follow a seed from a hard kernel in their hands, to a fragile sprout, to a fruiting plant, with drawings, photos, measurements, diagrams, and reflective writing that encompass responses of art, science, and deep emotion (McDonnell, this issue).

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