Curiosity Opens Relationships of the World and with Others: Narratives from Doing Teaching and Learning Through Curiosity

Interchange
https://doi.org/10.1007/s10780-024-09529-8

Curiosity Opens Relationships of the World and with Others: Narratives from Doing Teaching and Learning Through Curiosity

Elizabeth Cavicchi[1]

Accepted: 13 May 2024

Abstract

What potentials does curiosity bear for education? Some characterizations portray curiosity as self-motivated search for answers, a drive conformable with conventional education's imperative for correct answers. For participants in this study, curiosity engages them with their relationships to the world. This article examines curiosity from along my developing in learning and teaching. While school settings limited or excluded curiosity, both for me as a student and as a teacher, it relates how I encountered the value of curiosity in examples of my father, mentors, and other experiences. Beginning with a gradual and uncertain process, I transitioned from being an educator bound by conventional expectations, to a teacher-researcher creating environments where learners' expressions and acts of curiosity constitute the educational work that I actively support and seek to extend. Curiosity in the classroom generates trajectories and engagements that differ from conventional instruction. This article demonstrates and researches the educational work of curiosity, through contextual narratives from my teaching as a beginner at accommodating students' curiosity, and from my recent teaching, where students and I more fully commit to the relational and educational possibilities of encouraging curiosity. In facilitating these experiences, I apply the research pedagogy of Eleanor Duckworth, 'critical exploration in the classroom'. In narratives from my teaching, curiosity propels exploring relationships among: floating and sinking; trees, leaves and acorns; dye in water; maple sap sweetness; bubbles in water; and permutations of objects. Provocations from historical works include: Leonardo's drawings; Hooke's and Ramón y Cajal's microscopy; Keats' "negative capability"; Dewey's reflections on interdependency among children and adults; and children's creations in Reggio Emilia preschools. As experience builds through curiosity, relations deepen in ways simultaneously unadulterated—exploring unconstrained—and unchildlike—sustaining commitment. Participants characterize our process as having "No End Goal" imposed from outside themselves, unlike formal instruction that suppresses personal curiosity in favor of pre-ordained goals. The natural world, opened by curiosity, embodies ever-emerging relationships that accommodate concurrent widening and

Extended author information available on the last page of the article

Published online: 23 June 2024

deepening of learners' involvement and realizations. Learning experiences happening through relationships are infused with emotion, aesthetic qualities, and social connections and concerns.

Keywords Curiosity · Critical exploration in the classroom · Experiential learning · Floating and sinking · Uncertainty · Maple trees

Introduction

Curiosity moves us—in body and mind—to engage actively with an "other." Whether familiar or novel, through curiosity we approach that "other" with potential for changing how we understand and relate—with whatever specifically induced our curiosity, and with the wider world (Lindholm, 2018). Coming about through relational awareness, curiosity motivates learning via the learners' own agency, which empowers change, action and reflection.

What potentials does curiosity bear for education? Some characterizations portray curiosity as self-motivated search for answers (Lamina and Chase, 2021), a drive conformable with conventional education's bias toward correct answers, or satisfiable with preexisting solutions, such as internet searches yield (Sulistiani & Waluya, 2018). For participants in this study, curiosity engages them with relationships of the world. Being dynamic and ever-evolving, the paths and possibilities opened by curiosity do not conform to conventional instruction's boundaries, goals and structures. In the ongoing evolving process, the relationships of the world, not static answers, are the matter and means of learning.

This article examines curiosity from along my developing in learning and teaching. While school settings limited or excluded curiosity, both for me as a student and as a teacher, it relates how I encountered the value of curiosity in examples of my father, mentors, and other experiences.

This article reflects from the gradual uncertain process by which I transitioned from being an educator bound by conventional expectations, to a teacher-researcher creating environments where learners' expressions and acts of curiosity constitute the educational work that I actively support and seek to extend. Curiosity in the classroom generates trajectories and engagements that look and are different from conventional instruction. This article demonstrates and researches the educational work of curiosity, through contextual narratives from my teaching as a beginner at accommodating students' curiosity, and from my recent teaching, where students and I more fully commit to the relational and educational possibilities of encouraging curiosity.

Curiosity, Learning and Education

Acting on curiosity builds awareness of relationships. Encouraging children's curiosity by posing something intriguing along with an intervening obstacle or puzzle, Jean Piaget documented their engagement, from initially being foiled, to acting

with mind and body in new ways. These new actions are an outgrowth of relational capacities and understandings not previously available to the child. For example, he repeatedly placed an attractive toy under a pillow; in successive trials, Piaget's own baby transitions from being stopped by that obstacle, to acting to remove it, even employing a stick. The child has worked out spatial and instrumental relationships in the process of investigation (Piaget, 1956, p. 227). Building on their extensive researches where children experiment with materials involving spatial perspective (Piaget & Inhelder, 1956), pendulums and balance (Inhelder & Piaget, 1958), Piaget's colleague Bärbel Inhelder adapted these activities in founding the research method of "critical exploration" to specifically support, facilitate and document children's learning (Inhelder et al., 1974). While children experimented with pouring liquid into glass funnels of differing shapes, some came to view the liquid as "conserved" throughout, although that liquid showed differing levels in the narrow funnel, compared to the wide one. For Inhelder et al., these children had worked out the relationships at play, such as liquid levels, vessel shapes, and liquid quantity (p. 58). This relational learning came about through the child's own agency acting among multiple possibilities; Inhelder emphasized that these experiences of learning were not "programmed" toward producing correct answers (p. 26).

It is otherwise with much conventional education. Learners are typically directed towards predetermined responses or behaviors in an environment that closes off access to their curiosity and investigation. Researcher Susan Engel observed such a fifth-grade science lesson that tasked students with step-by-step instructions on assembling preset materials to pull a weight. The teacher reprimanded those students who conceived and trialed original and divergent constructions. The teacher stopped this activity, just as children's curiosity came into play (2011, p. 626). In another classroom observed by Engel, the children became curious about a science material, but the teacher asked all the questions, successively narrowing around the intended answer and disregarding the children's interest. To further examine this suppressive effect of teacher and environment, Engel and colleagues posed the same provocative activity to children in differing environments: classrooms or lab settings that encouraged children to explore, and others that explicitly did not. They found that children explored this activity in settings where the environment and the teacher encouraged openness, but did not interact with it, and appeared bored, in the restrictive environments (Labella, 2009).

Relating from her childhood, parental, and classroom episodes and narratives, Engel demonstrates the productivity of environments of openness for nurturing curiosity and its power in authentic learning. She finds curiosity is facilitated where classrooms are brimming with complex materials that invite learner's interaction and fascination, instead of materials prescripted toward specific routes and outcomes. (2015). Affirming "the evidence is quite clear: when children are curious, they learn" (2011, p. 628), Engel argues for change in educational environments and teachers' roles in them, to welcome the curiosity of learners, expand and enable them in acting on, and through, curiosity.

Math students and teachers-in-training experience such a changed environment at the informal museum / do-it-yourself lab titled Cabinet of Curiosity, at Université de Bretange Occidentale, France. In a space set aside for student

experimentation, with historical and contemporary tools and materials that are there to be used, Frédérique Plantevin, Petro Milici and colleagues invite students to make, use, replicate, reconstruct and manipulate, historical mathematical instruments. Geometrical relationships become tangible and interrelated for students as they envision and construct homemade devices that trace out mathematical curves or perform other functions. Having acted with personal autonomy in doing mathematics themselves, these new teachers are excited for eliciting curiosity around mathematics with their future students (Plantevin & Milici, 2022).

Whereas from its inception, the Cabinet of Curiosity welcomed students' curious undertakings, initially there was no role for curiosity in the education practiced by three chemistry teachers and their 16-year-old students at community schools in Tanzania. Researchers Esther Kibga et al. (2021) collaborated with the teachers and students in 7 weeks of lessons where hands-on activities opened through student curiosity and initiative. In between the classroom activities, the researchers provided participants with space for questioning and reflecting upon these lessons, through doing interviewing and focus groups. Initially, teachers resisted opening space for students' curiosity; the first week's activity was teacher-dominated, and the students saw nothing different from usual. A few weeks later, students were making chemistry apparatus from everyday materials and using it in following their questions. Teachers realized the generative contributions of student curiosity. Teachers and students came to trust the process. One researcher's interview exchange illustrates students' widened curiosity in relating chemistry to what surrounds them:

> Puljet: "for me…it is good experiences …I now understand that there [are] materials which can enhance my learning which I ignored before"…. these days when I see objects they draw my attention and I won't be satisfied only by looking at them.
> Researchers' follow-up question: "can you mention some of those materials?"
> Puljet: "Yes there many things in around the school and at our home which can be used to learn chemistry"
> Kengwa: "for example…. empties bottles and tins, pegs…..and so many others" (Kibga et al., 2021, p. 8)

Corroborating with these interviews were researchers' classroom observations as well as questionnaires and tests administered on curiosity. The initially hierarchical classrooms changed:

> by making students as chief controllers of their learning … they can create an environment that begets curious students. (Kibga et al., 2021, p. 11)

Students grew in their expressions of curiosity; learning became dynamic.

Like these Tanzanian teachers, I underwent a process of transition, from being part of an educational system having no space for learning through curiosity, to doing teaching as a practice of inviting, honoring, supporting and extending learners' curiosity. Not being part of a program such as that which supported the

Tanzanian teachers in their transition, for me, this process was extended, informal and uncertain. It involved realizing, for myself, and gradually seeking to act on, the educational value, possibilities and momentum of curiosity, even while surrounding educational structures remain oblivious or closed to it.

Research Questions

In undertaking the multiple studies documented here, there were several overarching research questions that kept arising as studies proceeded:

1. How does a teacher transition from conventional education, to a practice developing through learner's curiosities, where doing and inferring relationships is the active educational work?
2. What emerges in experiences that open from and through learners' curiosities?
3. How do learners and teacher engage in opening curiosity, acting on it and responding to what develops and to each other?
4. How do learners and teachers realize, and support each other in realizing, relationships and relational understandings that arise through acting on their curiosity?

Research Pedagogical Method: Critical Exploration in the Classroom

Engel advocates for teachers to concurrently research their own teaching, to "see how much inquiry is being expressed" and expand their responses to learners' curiosity (2015, p. 192). She recommends audio and video recordings and journal-keeping, function as tools and means of doing teacher research in support of curiosity.

One research pedagogical method that puts learner's questioning and development at the heart of the educational work, is "critical exploration in the classroom", developed by Eleanor Duckworth (2006a, 2006b, 2006c) from the method that she had practiced in Geneva while participating in the researches of Jean Piaget and Bärbel Inhelder. Whereas Inhelder and colleagues interviewed each child alone, during one or few sessions, Duckworth adapted Inhelder's "critical exploration" method for the classroom, where multiple participants—students and teacher- engage together over time, such as a semester (Duckworth, 2006b).

Duckworth discovered the coaction of researching and teaching within her own experience when she applied this method as a teacher-researcher in elementary school classrooms implementing the Elementary Science Study (1965, 1970). In response to her genuine, researcher interactions—not directed by academic judgment and outcomes- children explored and wondered with genuine involvement of their own. Duckworth realized that in making their development possible by creating mutual investigatory relationship, she was simultaneously teaching:

> the Piagetian methods I used to investigate learners' understanding—that is, having them take their own understanding seriously, pursue their own questions, and struggle through their own conflicts—was at the same time a way of

> engaging people in pursing their own learning…my ways of trying to follow their thoughts were, in fact, excellent ways to help them learn.
> Later I came to realize that the circle is full: This way of helping people learn is at the same time …research about how people's ideas develop. (2006a, pp. 139–140)

To do this research into the process of learning at the same time as opening up occasions for that process with its ever-widening potentials for curiosity, the researcher must concurrently be the teacher. It is in being "both a practitioner and a researcher" that one is:

> in a position through teaching, to pursue questions about the development of understanding that one could not pursue in any other way. (Duckworth, 2006c, p. 185)

The curiosity and emergent questioning awareness of the researching teacher co-inspires and interweaves with learners' emerging curiosity. Where one study showed that a science researcher participating alongside students encourages their curious acts (2011), in cases where the teacher simultaneously researches and evolves with classroom experiences, means of enhancing curiosity can be furthered.

As the teacher's researching stance provides conditions where learning happens, learning evolves for all participants—teachers and students. Narratives of experiences that evolve as learning and teaching concurrently, inform and inspire further teaching and research—by the participants and the wider community. Critical exploration in the classroom research is presented via narratives integrating dialogue, context, evolving curriculum in diverse subject areas, participant reflections, teacher decisions (Chiu, 2009; Delaney et al., 2021; Duckworth, 2001; Hughes-McDonnell, 2000; Magau, 2001). Development is expressed and examined as an ongoing process.

In this article, I apply the method of critical exploration in the classroom in those examples that relate from my graduate studies as a novice in the practice (Relationships in Critical Exploration in the Classroom) and in the following sections relating from my recent teaching at the MIT Edgerton Center (25 years later).

During sessions, I share provocative materials, readings, experiences, and other possibilities. I encourage students' responses, experimenting and collaboration. I listen and observe what develops as students interact with these materials and each other. Frequently, what emerges as students' curiosity and inclination, comes about in an area or way that I had not envisioned. This unexpectedness for me, is positive evidence of their originality and curiosity, showing that they are not conforming to expectations from me or the academic setting. I seek out, in the moment and later, materials, tools and opportunities that could extend, deepen and confound, the curiosities and areas of the students' involvement.

My students participate in informed consent for the documentation of class sessions, including notes, student and collaborative work, photography, audio and video recordings. Between sessions, I prepare illustrative summaries of our class experiences, that I share with students at a later meeting. These summaries are one way for us to see and reflect on, what we are doing, learning and creating together. Through

doing discussions, preparing summaries, and student reflections or writings, we notice the nonlinear interrelating ways by which curiosity develops among us, and into learning experiences that are vibrant, uncertain and relational.

Our teaching and learning emerges through unfolding experiences having unforeseen or unexpected qualities. Every response, observation, detail matters. Where experiences interrelate and feed off each other, there is no merely "off-task" passage. The narratives comprising this article are grounded in these complex experiences, having input from the summaries, student work, and other documentation, and revisions produced through later readings and discussions.

Dad's Curiosity Discerns Relationships

Curiosity was a way of being for my Dad, longtime NASA aeronautical engineer Richard Harold Cavicchi (Cavicchi, 1959, 1967, 2004; Cavicchi & English, 1953). He never stopped being a kid, as his older sister had frequent occasion to exclaim throughout my memory. His unadult-like escapades included swinging on a rope suspended from a tree over a river and jumping into the river—in his 80s! Limitless in asking questions, his questions seemed preposterous under an adult outlook—being observant about the world while exposing artificial constructions in language and social convention. As an example, he questioned the prevalence of caricatures of indigenous culture by high status athletic clubs, a status denied to those peoples. His curiosity was always at play, wondering and computing—astute to whatever was going on. His curiosity's internal and mental operation came into view as he interacted with tools, us and others.

Experiences that passed others of us by were—for Dad—opportunities to count and learn. As a train blocked traffic on a grade crossing that divided our town, while we children watched, waiting, Dad was silently engaged, counting the cars. When it passed, with that number—over 100 for freight—he estimated its length, possibly over a mile. During family summer hikes in New Hampshire's White Mountains, the steps to get up a summit fire tower for the view, counted by Dad, figured into his calculation of our head's elevation above sea level. Dad counted and often recorded repetitions in his actions: runs around the track; laps in a pool, swims across a pond, pump strokes to inflate a bike tire, and pints of blood donated to Red Cross. Small beginnings, that many of us might not bother to note, accumulated to large, consequential tallies. Cumulatively those counts became thousands of miles of athletic training in water, track, field and on bike, and up to three times his bodily blood content in lifetime donation!

Where such counts of actions augmented into distances or volumes, temporal durations provide another count, reporting on experience in other ways. Dad internally counted time; with no hesitation he could give the years since his mother died, since the white car was bought, or since a heroic sports event occurred. Clock timing of anything under count, added another layer. With accordion-band wristwatch always on, Dad timed while counting—the train's passing, the runs, basketball shots—estimating speeds and rates. Other timings told of a mechanical-physical process—the time it took for the car to start, for the black and white TV picture

to come on, or for a bike to break down after he'd already fixed it—or a human one—the time a scrabble game lasted, to complete a puzzle, or to practice a musical instrument.

What something weighed offered another mode of count. Reminding us "a pint's a pound the world around", the weight of water—in a canteen, milk jug, or flooded basement—was a serious matter for Dad. The bathroom scale, while it didn't change much for his lean athletic body, when he stepped on it again holding a box of bananas, the shift in its needle's deflection gave the fruit's weight. Different instruments showed differing ranges of tolerance. While the bathroom scale might not react to the box placed there alone, the pan spring balance would; it registered a baby or the Thanksgiving turkey with equal facility. That some characteristics of materials change, in going from one such scale to another, is easily neglected—a tomato basket would collapse if loaded instead with the iron pipes I collected with it, for doing junk art sculptures.

Accessing thus number, length, time and weight (mass), Dad attained simultaneously experiential and analytic awareness of the physical quantities that are fundamental to physical science. He looked for, noticed, and called out, relationships to which I was oblivious: the delicate balance involved in turning a water faucet valve; spilled water reduces floor friction, heightening risk of slipping; the angle of a ladder's tilt against a wall and its stability are linked; or, in a lidded pot, the build-up in pressure shortens its time to boil. How the physical world works came through Dad's keen counting, watching, relating and thinking. That involvement and awareness shows curiosity active in the goings- on of everyday life, taking in observations, conceiving relationships among physical quantities and putting those to use in new ways and occasions.

With active curiosity, my dad engaged the everyday world and discerned its relationships—relationships that are consistent with and analyzed by, the field of physics. His enthusiasm for physics and math encouraged me into that study and teaching, alongside doing artwork, sculpture and sketching. Yet I encountered the formal study and instruction of physics as utterly unlike the curiosity and fun that ran throughout Dad's encounters with what goes on in the world. Already as a child, I noticed asking my dad for help with school was not efficient—he saw so much else going on than the assignment asked– and Dad's input might not match what the teacher wanted. As a physics undergraduate where I struggled on problem sets and panicked in exams, I saw in parallel and in contrast, his keen fascination for problems and quantum physics in my course books, that were not in textbooks of his era. Education eroded my personal curiosity, having me suppress it, hardly aware of the loss.

Teaching Physics, Teaching Differently

When I began teaching non-calculus physics in evening programs for adults going into engineering technology, the courses required a sequence of textbook chapters. Chapters were functionally disjoint, putting each topic into a separate compartment without revealing physics as an integrating holistic web. My role in lecture was

defining and deriving equations and using these in exercises constructed artificially around each equation. Students were to emulate that in solving example problems where confirmation came through a right numerical answer, typically provided at the back of the book. Lab activities were either nonexistent or scripted toward producing a pre-specified result. While other instructors marked numerical entries on a student's paper either correct or not, I read the entirety of what they did to produce that number, commented on that argument, and noted wherever something was missing in a calculation or analysis. As a part-time instructor, I devoted many more personal hours to reading student assignments than my colleagues did or could. I saw and responded to what students did. In all of this effort, I began to wonder: where was physics, and where was learning?

There was an inherent circularity in these wholly symbolic exercises and manipulations that routed from textbook, through us, and back to the same formalizations—unchanged if correct, and in all cases hardly grasped. Student work routinely ascribed features of principles, scale, magnitude, dimension, or context, that were ludicrous for the example at hand. Unlike my dad's observations, the physical world itself was superfluous. The absence of the physical world in physics class was inseparable from the exclusion of students' experience, minds, and bodies. The physics curriculum had no space for personal observing and action; there was no way of learning through student initiative with the world and reflection on it. It was different with my dad; his mind was in continual "back and forth" *with the world*, powered by personal curiosity.

Seeing that kind of engagement in physics missing, even missing from the expectations of what I was asked to do as a physics instructor, I aspired to introduce it. Unaware of any examples of what that might look like and what changes might be called for, my attempts were iterative and initially gradual. When presenting a physics discovery, I also presented the historical background. In place of textbook exercises, I sought out, and created problems based on, real-world examples and data that applied the physical principles of the course.

Something of my dad's curiosity and awareness was moving me into reinterpreting physics differently from its educational formalization. I redid lab writeups and assigned students to write about an everyday life example of some physics topic. For example, the design of one problem involved me in measuring the time it took my husband to slurp down a 12 oz Coke through a soda straw and working out the suction force in the straw (Cavicchi, 1992a). On performing that analysis, one student calculated the suction force applied as greater than a person's body weight, orders of magnitude off.[1]

While these modifications may have enhanced interest and challenge for my students, I still felt that physics, whatever that might be, was somehow not happening within my students. Yet the required course structure could not accommodate any further stretching. I recommended a more descriptive textbook; however dispensing with any textbook was not an option. When I asked to substitute student

[1] The estimated reduction in pressure in someone's mouth, when sucking on a straw, can balance the gravitational force on an object of a few grams mass.

presentations in place of the final exam, this was not allowed. Each instance of the physics course was expected to be functionally interchangeable with the others, taught by other instructors. By implication, the educational mission was undone by deviation in any section.

A Pilot Alternative, Leaving Physics

Noticing that I was trying to teach differently, Sukant Tripathy, Chemistry Professor at University of Massachusetts Lowell where I taught, proposed that I create a new elective course of my own design. Meeting as a small group in a lab, doing activities with science materials, with no lecture, I developed this course, "Science from our Lives", during two semesters (Cavicchi, 1992b). The experience was so powerfully transformational for me, that I sought settings and ways by which it could be extended, researched, created, evolved—as education that would be unlike what had formerly involved me.

Initially, the pilot course drew on my participation in *The Ring of Truth*, the public science TV series narrated by MIT physicist Philip Morrison (Morrison, 1987; Low et al., 1987). Through examples from history, experiment and demonstration, Morrison invites the public to see how science reasons from evidence. In my work as the researcher for this series, I learned about, and contributed to, lively portrayals of science and history that never figured in my MIT physics training. As my undergraduate physics adviser, Morrison was enthusiastic for my creative initiatives in doing visual art, physics and writing. He went on to encourage me in: becoming a physics teacher; the pilot course; next in my departure from physics forced by its exclusion of its teaching as a valid area of investigation; and then in the doctoral and postdoctoral researches by which I experimented with, and documented, an alternative practice.

Morrison's relation with physics and learning was unlike what arose for me under the roles placed on me as student and instructor. Imagination, observation, passion and wonder were openly welcomed, encouraged and expressed as the core of everything he did (Morrison, 1995a, 1995b, 1995c). By contrast, my fervor for those very qualities had recurrently been silenced under reprimands posing as definitive of academic settings. Learning was different when Morrison was involved; it was more akin to my artistic inclinations.

Watching closely, I aspired to understand what made for or encouraged this different way of being and learning. Morrison valued where my learners came to realizations through their own actions and thinking. For example, he considered that a pinnacle of the pilot course occurred when I was out of the room! My students, who were middle school science teachers, were using our classroom's overhead projector as a light source in their efforts to produce a pinhole projection. I had left to bring additional materials stored elsewhere. I returned to a dark room where excitement was palpable and ecstatic. Having surrounded the projector lamp with light-blocking shielding with just a small hole, the students grouped around the screen, discovering inversion in its images. That the students themselves turned off the room lights, was deeply compelling for Morrison. Their analysis and autonomy in doing

so constituted a generative act of experimental physics: efforts to amplify subtle signals in a noisy background.

Initially I did not perceive these realizations and agencies arising on the part of my students. Gradually I began to notice, appreciate and relate what emerged in thoughts and activities among learners, including myself. I look to encourage our being together in experiences that open to possibility. While Morrison did not look for my learners to produce results that in any way replicated the physics of instruction and textbooks, those models had long before encoded expectations in me. Only as many varied teaching and learning experiences built up for me a substantial groundwork in a different world, did I depart from how I was limited under restraints representing academic progress and formalized physics. These restraints were internalized during my education and held almost invisibly; undoing and going without them was going to be different.

My internal process, of forming different relations with learning, teaching and science, continues, gradual, uncertain and integral with my students' experiences. In the external context, my role as teacher and student in formalized physics closed abruptly. Seeking to become an investigator of the evolving of physical understanding was not commensurate with the physics instructional settings where I was. Along with educational wonderings were voices of physics students I interviewed while employed on a physics education project (Di Stefano, 1996). Where some declaimed isolation, boredom and struggle in physics class, one student's vision of a mutual relation among students and teacher was provocative for me, then and now:

> Students have to look at it as if they are experimenting along with the teacher… How are we going to do it? That's the experiment. (Cavicchi, 1995, p. 13)

As I trained to do educational research, I observed most qualitative and quantitative methods to be informative about the education happening, yet without directly transforming that education. By contrast, action research and participatory research initiate educational processes in the course of investigating and transforming them. Among these, I committed to the research pedagogy of my professor, Eleanor Duckworth, which she later named "critical exploration in the classroom" (2006b).

Relationships in Critical Exploration in the Classroom

Nonhierarchical relationships among learner, teacher, and material of study are the means of learning and teaching in this exploratory practice. The material of study has its own integrity, relational composition and potential. With pronoun 'It' denoting the study material as a participant, philosopher David Hawkins describes how "'It' enters into a pattern of mutual interest and exchange between the teacher and [learner]." (2002, p. 53) As participants change and evolve through interacting with It and each other, relationship becomes yet more mutual and dynamic.

The teacher is a researcher, in and through the relationships that continue to be made and evolve. Learners are exploring through relationships, initiating their own experiments with the material and in supportive relations among the teacher and

each other. Something like what the interviewed physics student (described above) envisioned happens as a classroom practice.

The study material, the 'It' in Hawkins' depiction, with its features and processes, emerges in relation with the participants and the experiences through which they engage together with it. Duckworth discerns that the relationships inhering in the 'It' are what provoke relationships among participants—relationships by which they investigate, wonder about, and infer more in its relational character. In referring to the school children participating with her at the time she realized the identity of teaching with researching, Duckworth wrote about how she saw that engagement to deepen:

> where children tried to explain or predict or describe relationships in something they had before them and could transform or otherwise keep returning to… The more surprises people encountered, and the more possibilities they became aware of, the more they continued to want to do and think. (2006a, p. 140)

Relationships afford diverse ways of interacting, of coming upon confounding behaviors, of questioning assumptions, of developing and evolving in our thinking and interacting with 'It'–something other. Work with and through relationships, while differing from the emphasis that dominates in much education, coheres with how my Dad sought out understandings and with Morrison's insights about my students' pinhole experiments.

In my novice attempts to engage learners through the practice of critical exploration in the classroom, I experienced wonderment in observing learners engage with, question and work out the relationships at play, without direction from instructional guides. My first such undertaking was as a requirement in Duckworth's course. As our fieldwork assignment, a classmate and I were to facilitate and document several sessions where one adult learner investigated a study material—without us saying how we understood it. Our learner, Yvonne Pappenheim, antiracist peace activist, had not been a formal learner of science. As Morrison's assistant in his *Scientific American* office, she was immersed in words about science. With us, she was eager to do science for real. We chose to engage her in exploring what floats and what sinks; Duckworth had demonstrated the fruitfulness of this curricular area within physics, with her pioneering study (2001).

I was bemused by our first session, where it seemed "everything went into that bucket of water"—peanut, apple, penny, pencil, clay, and cut-up apple. Pappenheim's questions and conjectures ranged widely. In not resembling what I was accustomed to considering "science", I began to wonder if "my training and expectations" kept me from grasping her investigatory development (1993a, p. 6).

As suggested in Duckworth's quote above, surprise offered openings. Upon putting a pumpkin into the bucket, Pappenheim exclaimed "That great big pumpkin—it floats! Amazing…I'm stumped". That reaction came to be mutual. To my surprise, first one potato sank, and then another. Our learner was surprised by my surprise—"Didn't you expect it to?" she asked. (1993b, p. 9) I didn't; I had recently made potato soup, without noticing that behavior. We and our learner were finding out what it is like to explore, by doing it together. Through having

the experience of surprise in common, our questions and curiosities were relationally shared.

With surprise comes awareness of something further in what is happening, in what we did not expect. Interleaving my reaction with hers, Pappenheim wondered "maybe a tiny piece of potato wouldn't sink". We cut slivers of apple, potato and clay; our learner conducted the tests. The apple bit floated; the potato bit floated, then dropped down, like clay and penny. Now considering that some shapes float, she proposed: "Let's cut the potato in half, and see, if you put the flat side down, it will float". Laughter, emphatic exclamation—"No Sir!", and reasoning—"it has something to do with composition", attended that half-potato's sinking (1993b, p. 10). Surprise had us wondering and acting with everyday materials—and each other—in ways that normally are ignored or not available; as Duckworth had described, we conceived possibilities and sought to keep going.

Pappenheim's question to me—"didn't you expect it?"—has a further contribution in exposing what I have come to regard as a hallmark of exploratory teaching and learning. Teacher expectations do not direct, frame, judge or certify classroom experience. By observing and researching exploratory sessions, I become yet more open to what can and does emerge, and yet more distant from applying expectations that had operated in educational settings where I studied and taught. Expectation tends to be fixed and fixating; by contrast, exploratory experience is inherently relational and fluid. My role becomes that of encouraging unexpected, fluid experience among participants in relation with each other.

At the end of the floating and sinking project, I drew on dance as a metaphor for observing relationship and development among learner, materials and teacher, in writing:

> [seeing our learner] build questions, experiments, ideas and tests was like watching a dance. At first one may only be aware there is a dance going on… As she comes back to some familiar unresolved steps "so I think the relation of weight to size has something to do with it" we begin to see rhythm… our student's ways of discerning and thinking changed, became more participatory…[with] more noticings of ambiguities "maybe I made that up to confirm my theory…that's how prejudice starts" … The materials of the experiment also have a dance…I continue to wonder… doubt, about teaching that somehow encourages us to create our own learning…(Cavicchi 1994, p 10–11)

Curiosity develops and sustains relationships in the participatory dance where teaching, learning and researching transpires continuously. Surprise made for lively and initial entries into the dance. Yet across the dance developing among teaching, learning and materials, we were enacting curiosity by many other ways, including change, ambiguity, wonder, doubt, thought, and questions. Uncertain as I was—and continue to be—the relational involvement drew me on, with curiosity for experiences of teaching, learning and researching.

Seminar Context with Historical Companions

The Edgerton Center of the Massachusetts Institute of Technology (MIT Edgerton Center, 2021), where I now teach, continues the experimental teaching of Harold "Doc" Edgerton. In his twenties, Doc invented a bright lamp that blinked on and off at a rapid adjustable rate. Hefty at 60 pounds yet still portable, he took it to industrial settings to diagnose irregularities in electric motors by matching the lamp's flash rate to the motor's spin, so as to "freeze" the motion. One day in 1932, he happened to aim this flash lamp at water running from a faucet. He was astounded by the glass-like sculptural shapes in the flowing water, never seen before! (Edgerton & Killian, jr. 1954; Vandiver & Kennedy, 2005) With his strobe prototype and its subsequent developments, Doc transformed, for himself and others, the act of observing, revealing unexpected beauty and order in everyday matters viewed at short time scales: a humming bird's wings; a light bulb as it breaks, a drop of milk landing in milk—or cranberry juice! (Edgerton, 1987; Edgerton & Killian, 1954, 1979; Sidney, 1940) Doc infused this delight in observation into open-ended project labs where students "recognize that they're seeing something they never saw before, and that they've learned something. Their eyes open up when they're so awed by what they see. That's a good educational shock." (Edgerton speaking in Sheldon, 1994).

Continuing Doc's commitment to open-ended student experimenting, the Edgerton Center is set up to support and encourage students' initiative, projects, and acting on their curiosity. It shares with the Cabinet of Curiosity in being an open workspace and resource for learner investigation. Learners tinker, observe, chat and invent in spaces ranging from virtually supported activity workshops to a classroom outfitted with work tables, to metal and wood working shops, to maker space, strobe lab, and areas for constructing large-scale projects including a solar-powered car! People of all ages, from children to experienced teachers and beyond are welcomed to meet each other and share in a fluid environment of exchange. Children and youth, largely from communities underrepresented in engineering, come for a hands-on lesson, drop-in lab, or summer program. Teachers do professional development workshops on maker space tools and molecular models. Undergraduates and alumni mentors undertake engineering and teamwork projects of personal interest. Undergraduate and graduate students take lab seminars and initiate projects for academic credit.

In this context of experiential learning, for almost 20 years, I have been teaching a lab seminar titled 'Recreate Historical Experiments: Inform the Future with the Past'.[2] This elective seminar has no prerequisites and is open to undergraduate and graduate students from any area. It is taken by students whose background ranges from first year, to those majoring in engineering or sciences, to graduate

[2] For an OpenCourseWare representation of one teaching of the seminar in a one-month format, having a theme of Galileo, see 'Recreate Experiments from History: Inform the Future from the Past: Galileo.' (Cavicchi, 2010).

students and teacher training candidates. Students observe, explore, do activities, readings, journal-keeping and a reflective paper.

In sessions of between two and four hours duration, the seminar meets in 'lab classrooms' that accommodate spontaneous experimental activity. The Edgerton Center spaces have worktables at standing height, sink, open floor space, shades for room darkening, blackboard, adjacent kitchen and projection facility. Chests and pegboards house saws, screwdrivers, chisels, glue guns, files, scissors, tape and other tools. Cabinet drawers hold various sized screws, washers, nails, soldering irons, wire, batteries and assorted electrical parts. Raw construction materials range from cardboard, plastic pipe and plywood to dowels of metal and wood, to Lego gears and parts, to colored feathers and felts, to candles and balloons. Among the chemicals on hand are paint, oil, vinegar, glycerin, salt, detergent, and varnish. Student-grade microscopes, telescopes, astrolabes and cameras are available. My stash of teaching materials specific for the seminar includes lenses, mirrors, rope, weights, pendulum frames, homemade balances, magnets, pins and needles, tuning forks, cork, plasticine clay and soda straws. All of these materials, and more, are accessible in the moment, whenever any experiment is underway. A drill press, band saw and laser cutter are available by arrangement, as is equipment for strobe and high speed video photography. Often the class walks into the hallway or outdoors, to observe and experiment. On most clear afternoons—and sometimes in the rain!—a session concludes with everyone going outdoors together to view the sky. Field trips to local museums, rare book library, and other sites, further augment these classroom sessions.

Together with learners, I encourage experiences where we come into relation with nature and others. Classes are intimate in size, with all interactively doing activities, discussing and developing our next explorations. Before any given class meeting, I have inklings of possibilities, originating in openness expressed among classmates along with other possibilities that I sense may be fruitful. Activities often arise in the moment, while growing out of prior class discussions and activities. Class readings, reflection activities, resources and links may originate in students' suggestions as well as my experience.

Unlike the physics courses of my previous experience, there is no preset list of experiments, readings, tasks or goals. There is no set of materials, experiments and activities that I expect to introduce, attempt or complete. Instead, I come to every class with a 'playbook', consisting of a set of possibilities for how discussion and experimentation may develop and how I will respond as an instructor to each potential development. 'Preparation' for a session consists of reflecting upon previously considered actions and questions, and organizing materials that might be germane to future developments, given what has arisen so far.

With this seminar, each session, and each term, is unique. Classmates' personal curiosity and expressive actions are generative of what we do- opening into collective fascinations and reflections that overflow what usually stands as boundaries. The usual academic guideposts are set aside. We are not alone; we find companionship and inspiration in the human, historical and natural worlds (Cavicchi, 2008, 2009, 2011, 2014, 2017, 2018, 2019, 2021, 2022).

Among our co-conspirators in curiosity, are: children; their teachers; a passerby on the bridge where we set up a telescope; Galileo; the engravers of 17th to 19th c book illustration plates; botanical specimen collectors; Leonardo da Vinci; and Doc Edgerton.

For myself as a visual artist and a science teacher, I experience Leonardo as living curiosity with immediacy in his every doing and in the world. Watching his notebook drawings is vicarious for me, in ways that I also invite for students. Mind, vision and action are of a whole, at play together to: be open in wonder; observe and investigate closely; and reflect and question. The jagged, stretching shadows of sunlight on stairs, how bodily organs connect, and the dynamics of birds in flight provoked Leonardo's curiosity into sustained observing, dissection, sketching, and visionary experiments with wings. Our typical education and practice places boundaries artificially yet firmly, as separators between thought and action, art and science, observing and understanding. Yet for Leonardo, any such divisions are not operative. The integrity is unbroken; he can bring his full capacities to whatever engages his curiosity.

Those capacities – available to any of us—are simultaneously unadulterated and unchildlike. Unadulterated—by being open to explore without constraints that are internally held and externally imposed. Unchildlike—by being present and active with insights, awareness and commitment of life experience. We resonate with Leonardo's quote:

> Observe how the beating of its wings against the air bears up the eagle…by adducing these things, you may be able to realize …great wings… to raise [your]self…. (Leonardo 1923a, p. 188)

Observing Leaves, Discovering Curiosity

In reporting here from this seminar of learning, teaching, and researching, I begin with the first session of the Fall 2018 semester, and trace threads and outgrowths that came about during two successive years. The make-up of the group changed, with some students continuing and others joining. Yet as the group explorations evolved, continuities emerged across those changes. Voices and curiosities came to be shared and developed in further ways, even when originators of those openings were not among us.

As the Fall 2018 first activity, three classmates and I went to the school's green courtyard at summer's end. I encouraged everyone to notice, sketch, observe. For Fan Xia, graduate student in education and research at Harvard, my open observing assignment in a strange place had her feeling unfamiliar, uncomfortable, and lacking about what to do. Then, sunlight on distant skyscrapers located across the river, caught her eye, afternoon reflections not evident for her before. Her sketches reveal her noticing and working out relationships among sun, a building's window, and her viewing position (Fig. 1a). While Akshay Agarwal, doctoral student in electrical engineering, had often been there, he realized: "I had never considered the kind of trees … I ran, found labels. Perhaps someone anticipated students would be curious

about trees!" (Agarwal, 2018) For everyone, both place and experience became new, by observing through curiosity.

Next time, Akshay shared his map (Fig. 1b) of the courtyard with each of its trees marked and identified, conceived on his own initiative. On the table before us, he laid out leaves (Fig. 1c), gathered from the ground. Those leaves were the first of many to be collected, compared, preserved and interpreted (Fig. 1d) as part of seminar activities.

Differing oak leaves amazed me! I had never before examined leaves as an opportunity for learning. Leaves began to instantiate character and consistency, provoking possibilities for me, and for our class. I began to imagine. Trees, leaves, observation, experiment and reflection, evolved freely into our seminar experience, which had typically gravitated around physical science phenomena, such as shadows, pendulums, or the sun and moon. Whatever the phenomena, whether physical, biological or social, what emerges in the explorations of learners surpasses my imagination. What Pappenheim noticed, in me as the teacher being in a world of the unexpected, came to be extended in yet further ways as we all responded to leaves.

As a class discussion, we shared inclinations to become open and curious together, along with awkwardness and uncertainty for bringing that about. Levity and insight came from the label "third grade" that one classmate's friend applied to our work, upon viewing our course assignments. In response to our reading from John Dewey, the reflections we shared were transformative for our understanding of childhood and of our personal experiences as children. Lila Wine, undergraduate in mechanical engineering, spoke about how, as a child, she strove to be independent of adults, to do everything herself without their aid or collaboration. Reacting to Lila's memory, Akshay found confusion in Dewey's statement that a child's dependence constitutes *power*.

Yet in Dewey's description of a child as having power to grow, to develop, to be *inter*dependent (Dewey, 1955, pp. 50–51), Akshay began considering interdependence among kids and adults in a new way. Instead of bringing about conformity to what one is told; interdependence could open from children's questions, encouraging their own growth and agency. Akshay's memory of one occasion where an adult supported him in that way, was revived by Dewey's quote from Emerson "Respect the child … keep his nature *and arm it with knowledge in the very direction in which it points*." (Emerson quoted in Dewey, 1955, p. 62) Akshay recalled:

> when I was young, I would tell people: I am going to study leaves. People laughed it off. I told an uncle. He looked at botany programs with me. At that moment, I felt empowered, wow! I study leaves! I ultimately changed, in the moment, I had a direction, what [Emerson] says here."[3]

A child's curious outlook often seems so distant—yet this arises from our very process of becoming. A direction originating in Akshay's childhood in India, yet put aside, was now active. Akin to Leonardo's fascination with flight, Akshay took up that direction with curiosity both unadulterated—full with wonder and enthusiasm,

[3] Quotes from EC.050 Transcript, September 18, 2018.

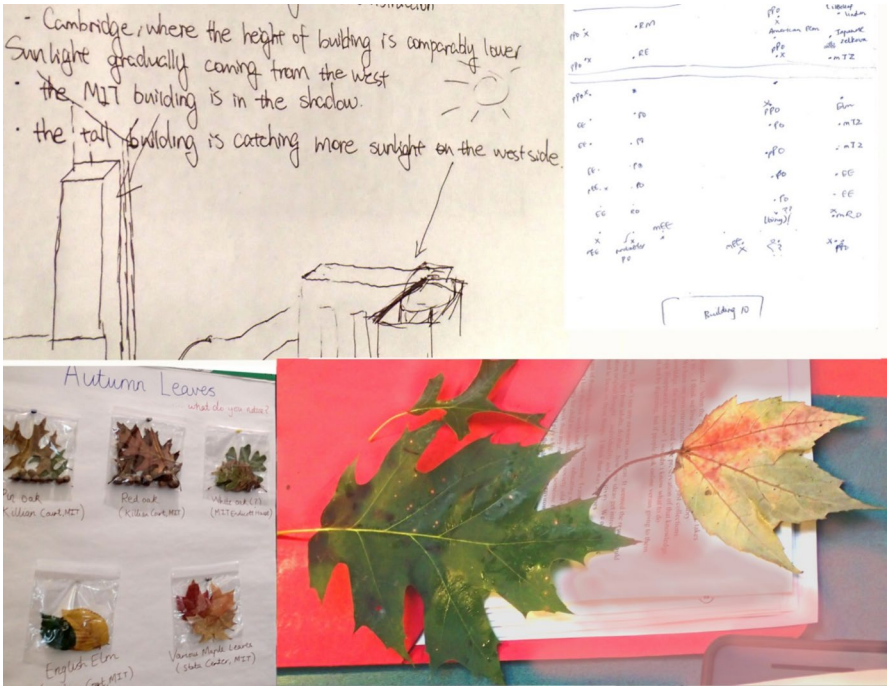

Fig. 1 [Clockwise, begin top left] **a** Fan's sketch showing the sun (top right) striking windows on only one side of the building. **b** Akshay's diagram of the grid placement of trees in the courtyard, with codes identifying each tree. **c** Leaves that Akshay picked up from the ground, on the classroom table. **d** Akshay's display poster of autumn leaves, with identifications

and unchildlike—being sustained and analytical. Marvelous transformations—in nature, in ourselves—were underway. New England's resplendent autumn was soon upon us. Akshay later reflected:

> The co-incidence of this re-emergence of my curiosity with fall [autumn] was wonderful, since I was able to observe the changing leaves and their myriad characters. (Agarwal, 2018)

Environment and Curiosity

As a class outing, we visited *Wonder of Learning*, the traveling exhibit of Reggio Emilia Preschools (Vecchi et al., 2011; Reggio Children, 2020), at the time installed in Boston. Young children's drawings, stories and interpretations of the alphabet letters are reproduced on wall-sized posters. Photo montages portray development in their sculptural response to paper, and in their experiments with light and shadow. Upon viewing these wonders, we discussed as one whole the children's works and the educational environment that made these possible:

> **Fan** I was inspired: kids go to park, collect and transform … with different colors, smells, materials.
> **Akshay** There aren't expected outcomes. I imagine as a kid, you don't feel pressure to produce a certain thing. Really cool.
> **Lila** I love how the kids describe materials: a material squished into a ball, that then goes right back to its original shape, he called it stubborn! Children are allowed to create and experiment
> **Elizabeth** Small child, with a napkin he has thrown … expression of wonder![4]

Given these joyous explorations, we all wondered how it was for these same children, undergoing education after completing Reggio Emilia preschools. Fan feared that traditional school would "smother the children's creativity" (Xia, 2018). Akshay later identified the critical role of the Reggio Emilia environment in facilitating children in learning and acting through curiosity:

> The children had ownership over the questions they asked, and the answers they tried. They had freedom to be as curious as they wanted to be, and explore and manipulate the objects … to understand their functioning better. (Agarwal, 2018)

In the next class, I invited sharing from whatever classmates observed over the weekend. The preschool children's candid curiosity—in everyday surroundings that adults routinely overlook—carried into experiences that seminar classmates opened for themselves and companions.

For Lila, swaying of trees viewed from a far shore evoked analogy to the rippled water below them. Along with her drawings interpreting water's patterns (Fig. 2), Lila offered as evidence the act of observing itself:

> My friend and I sat by the River... a really cool experience, that adults don't usually get to do. Sit and watch. Observe! (Wine 2018a)

Fan, too, went to the river with friends, on the evening of Chinese moon festival. At first disappointed not to see the full moon, when it appeared, its yellow color moved her thoughts.

In expanding his leaf collection, Akshay noticed oaks to be most common, and yet diverse in their leaves.

Being further drawn into his observations, including what is beneath trees, gave rise to a profound act of realization: "I discovered the acorn comes from the oak!".[5]

Each classmate: initiated personal experiences evolving from curiosity; reflected within those experiences; and expressed that learning to the others. An environment of openness, not impinged upon by preformed expectations, led to Lila's realization that adults seldom observe this way, and Akshay's exciting discovery that acorns fall from oaks. Curiosity expanded and interrelated, among each other, and with nature.

[4] Quotes from EC.050 Transcript, September 25, 2018.
[5] Quotes from EC.050 Transcript, September 27, 2018.

"Observe Trees", Akshay said, while looking at oaks with a fresh outlook, learning from the trees themselves. Others of us underwent change, in our relation to oaks and to learning. Wherever I went, I began noticing oak leaves in new ways, such as my surprise to find round-edged oak leaves (white oaks, I now learned from Akshay) in a forest, but not in city oaks. In previously ignored fallen leaves, I began to recognize characteristics, consider identities and wonder about being in dialogue with a part of the world new to me. Relating her riverbank experience to Dewey's advocacy of continuity between school and students' homes and personal lives, Lila affirmed education is happening where student take on "problems that have weight within their own lives".[6]

Arboretum Trees, Art, and Community

As trees emerged among our shared curiosities, each of us noticed trees in ways that were personally new. I responded with opportunities for our further engagement with leaves and others. I organized visits to the local arboretum on an autumn weekend and to Harvard's rare book library and herbarium. As extensions of our artistic and observing activities with leaves and liquids, I arranged sessions with the art studio's printing press and the Edgerton Center's high speed video camera.

As I imagined, in the arboretum environment committed to trees and their diversity, trees became our teachers. Even I was surprised as, by being there *with* our curiosity, trees entranced us. Hardly had we walked inside the park, when we were stopped by the stunning effect of water droplets appearing white on green fallen leaves. Picked up and turned over in their hands, classmates found spherical droplets resting on the undersides of tulip tree leaves, not the tops (Fig. 3a). Barren of leaves, the Amur cork tree yet stood out, drawing us over to feel its trunk (Fig. 3b). Too enormous for our arms to reach around, its bark was patterned in rough deep grooves. A contrasting sensation came from touching hands to the smoke tree's delicate filaments and the feathery fronds of narrow-leaved Japanese maple.

The tips of the divisions in a different Japanese maple's leaf were equally spaced as if on a circle's rim. Their botanic symmetry resembled the polygons that we had recently constructed in class using a divider compass and straightedge (Fig. 3c), in response to our readings of Euclid's geometry. Striking crimsons of sugar maples sparked our first consideration of maple sap—a flavor as yet unknown to some class members—which became a class springtime activity.

Even the ground offered much to notice. Colorful leaves lay like shadows beneath trees. Leaf "shadows" are not static, becoming mixed. We discovered confusion over discerning which tree any leaf came from! Fallen acorns were more diverse than what Akshay had collected on campus. Akshay picked up and held a burr oak acorn whose cap's pin-cushion-like spikes contrasted with the subtle texture of a different acorn (Fig. 3d). Acorns he found on campus were missing their caps; some at the park were complete. Lila envisioned a transition, saying "At what stage, I wonder,

[6] Quotes from EC.050 Transcript, October 11, 2018.

Fig. 2 **a** Lila's observational ink drawing of the river with calm water as white areas and waves as horizontal and wavy lines (Wine, 2018a, September 18). **b** Lila's interpretive ink drawing of the river's overlapping waves, with differing patterns filling the curved spaces between paired wavy lines (Wine, 2018a, September 22)

the cap falls off." So near winter's approach, some acorns were found sprouting (Fig. 3e), while others were not. Akshay observed: "The only acorns germinating were from white oaks. I wonder why. We find clumps near white oaks, in different stages of becoming a plant!" Fan and Lila concurred that the sprout itself was astonishing: "I have never seen an acorn sprout!".[7]

These experiences, questions and collections involving trees and leaves gave rise to further pursuits in later sessions. In the classroom, Akshay and Fan spread out leaves with both upper and undersides upward and applied to either side, water and oil from pipettes. Where we had happened upon waterdrops strikingly poised on leaves outdoors, they experimentally replicated the effect indoors. Finding that water drops beaded on a fresh leaf's upperside, and spread out over its reverse—whereas water beaded on both sides of a drier, microwaved leaf, Akshay said "I'm very curious to know" about that surface difference.[8] I supported this curiosity by providing other surfaces, liquids, and conditions—including paraffin wax, food dye, and a freezer.

These curiosities evolved into interweaving actions of observation, experiment and art. One afternoon, Lila released a drop of food dye into a glass of water. The experience and its beauty were transfixing. Recording the process again by video, she selected successive phases in it to freeze-frame. These she interpreted in a panel of four drawings on paper, charting the dye's expanding and diffusing tendrils (Fig. 4a). A drop of dye, meeting with her wonderment, became Lila's concurrent investigation and creation across the afternoon class session. I too observed with wonder, Lila's experience and agency melding with my hopes for what education can be. With leaves as well, Lila engaged art as means of observing, revealing and documenting transience. In her hands, autumn leaves' veined forms and vibrant colors were rendered directly in rubbings of crayon

[7] Quotes from EC.050 Transcript, October 30, 2018.
[8] Ibid.

Fig. 3 [Clockwise, begin top left] **a** Upper side of tulip tree leaf is uniformly wet (top left); underside has spherical drops of water. **b** Akshay and I are dwarfed by Amur cork tree trunk with its deeply fissured bark (Photo by Fan Xia). **c** Symmetrical Japanese maple leaf is overlaid on Fan's geometrical design, which it resembles. **d** Akshay holds two acorns, one with smooth cap, the other with spiky cap. **e** Capless sprouting acorns

on paper over leaves (Fig. 4c) and oppositely, by inking color onto leaves, then pressing them onto paper in the art studio's press.

Our visit to the art studio was part of my response to the class' expression of awe for microscopic imagery of Robert Hooke's intricate engraved illustrations (1665), that we viewed at Harvard's rare book library, and of Ramón y Cajal's neuron drawings that we viewed on exhibit (Newman et al., 2017). I was familiar with printmaking, but not engraving. Artist Thery Mislick trained us in using the press and encouraged our activity. With delicate marks that Lila cut by hand into a copper plate, she reinterpreted her own prior drawing of indoor and outdoor leaves in dialogue. Through bonding carefully cut and placed colored *chine collé* papers into the paper before applying the engraving plate to it, she introduced leaf color into the unique evocative print (Fig. 4b).

Fig. 4 [Clockwise, begin top left] **a** Lila's black on white graphite drawing, a 4-part sequence shows the expanding tendrils of food dye in water, as she observed them (Wine, 2018a, October 25). **b** Lila's engraving of interior and exterior plants, as viewed through a window, and printed over colored *chine collé* papers, emphasizing the contrast between interior (cool colors) and exterior (warm colors). **c** Lila's drawing of a maple leaf; she traced a black line around its perimeter, and crayoned the interior with reds blending into yellows

When placing the painstaking labor of engraving her small panel in the context of the immensity of historical book engravings, Lila reflected:

> the process itself was much more difficult than I expected, and the engraving tool kept slipping … making lines … which I would then have to buff out… As I continued to engrave, I realized that for a person to live a happy life and feel fulfilled by the work they do, they must be perfectly content with dedicating that much time to something that most other people would likely find extremely boring. (Wine, 2018b)

The impetus for our class engraving project originated with Lila's curiosity and sense of beauty arising in "childlike" immediacy. Completing the engraving had her acting with "unchildlike" commitment with the materials, an experience which expanded her curiosity into contexts of history and her own life.

During our subsequent visit to Harvard's Gray Herbarium, the curators displayed for us leaves, acorns, bark and wood from trees around the world, including India. Bearing analogy to our collections, these materials elicited questions and

curiosities that interrelated our observations with others and other places. Akshay was engrossed, keen to resemblances among the specimens with each other, and with his collections. Exquisite engravings, woodcuts and handbooks—and the Glass Flowers- introduced us to oaks and acorns wildly different from those local. We became aware of a larger community of people of diverse social status, identity, place and era, who shared with us in forming relationships with trees.

Meeting these works and collections through her personal experience as an engraver and observer of trees, Lila was moved to further reflection:

> The fact that one person found making sure others know how to accurately draw trees important enough to spend endless hours creating this book astonished me. On an even larger scale, the fact that our wonderful hosts spend their lives categorizing and documenting millions of specimens astounded me. I found it incredible (and extremely impressive) that a person could dedicate their life to doing such things. (Wine, 2018b)

This reflection deepens into Lila's questioning of herself, as she wonders about sustaining passion across the labor and ardor of whatever her life work may be:

> Hopefully, if I truly love whatever it is I end up doing, I will not feel the need to set goals and checkpoints for myself because I will be able to simply enjoy doing what I am doing, without fear of failure. (Wine, 2018b)

Lila's insights—about releasing from the control of goals and endpoints and being free to fail—figured in the class' collaboration in designing and presenting of a beautiful poster along with an activity, at a science education conference (Fig. 5; Wine et al., 2018). In representing the class exploratory process as cycling among observing, documenting and reflecting, the poster explicitly depicted "End Goal"- only to state that there is none. Some poster-viewers did not take in this understanding. Schooled to expect outcomes, they asked Akshay "what is the conclusion?".[9]

As relationships among classmates discovered and affirmed value in engaging the world with curiosity and open ignorance, I looked to support that awareness in our experiences together and with readings. Rejecting the goal-structured education of his day and ours, Dewey envisioned tentative experience in creative, original activity- as art and as education inseparably. Dewey described that experience as being productively sustained through "negative capability", the term by which poet John Keats characterized Shakespeare: "capable of being in uncertainties, mysteries, doubts, without any irritable reaching after fact and reason" (Dewey, 1934, pp. 39–40; Keats, 2021a/1817, 2021b/1819). Diving further into what "negative capability" might be for Dewey, Keats, and us, we read and discussed Keats' "Ode to a Grecian Urn" (2021b/1819), alongside Edna St. Vincent Millay's reading of "Euclid along has looked on Beauty bare"(2021/1923), and viewed Keats' original cross-written handwritten letter in Harvard's Houghton library(Keats, 1817).

[9] Ibid.

As a child, Akshay had resonated with the allure of holding mystery in life, upon reading the passage:

> one melodious sound, a sweet repeated trill, I have never traced to its source. … one small mystery, sweet, satisfying, entirely my own (Bond, 1993, p. 111)

Now as a researcher, Akshay finds himself "comfortable with the fact that there are uncertainties one doesn't know answers to", while simultaneously holding and acting on the "desire to know more". The nature of our exploratory process, with No End Goal, accommodates ever-continuing in uncertainty and in investigation, inseparably. For Keats, it was otherwise- he split mystery from investigation and prioritized mystery. I suggested to the class that Keats' exposure to academic learning was likely framed by goals and endpoints. Not having experienced the concurrent deepening in curiosity and mystery that investigation facilitates, in rejecting the goal-outcome orientation of its usual instantiation, perhaps Keats lost awareness of its fuller potential. Akshay discerned that Euclid—and Millay- saw beauty differently. Akshay observed, that the creation of geometrical proofs:

> requires you to address uncertainty through fact and reason… Euclid was patient, building this whole structure. Keats comes across as being passive.[10]

From wandering among trees, to releasing droplets of water, oil and dye, to making art, viewing historical specimens and pondering poetry, classmates and I shared in making experiences that opened through curiosity. Relationships evolve responsively: amazement and wonder in the park; concentration and analysis in the lab; vision and revision in the studio; contextual awareness in the historical collection; alternative interpreting with poems. Curiosity invites us into the unknown and has integrity across unbounded ways of knowing. And it goes on evolving with us.

Bubbling Sap from Trees and Leonardo's Bubbles

Our group met through shared curiosity, along with others, beyond that seminar's end. Yvonne Liu-Constant, professor of early childhood at Lesley University, joined us that winter. As a local organizer of the Boston Reggio Emilia *Wonder of Learning* exhibit (BARIN, 2018; see above for my class' visit to that exhibit), she had arranged and presented at programs and gatherings introducing preschool teachers to pedagogies by which children and teachers construct knowledge together. With the emphasis on building evocative environments for preschool children to act on their curiosity, Yvonne found herself lacking in the opportunity to be curious herself! By participating in our class, she sought to renew personal curiosity. Regarding Leonardo as an exemplar of curiosity in life, she was intent to understand his work through recreating it. At her instigation we read the recent biography of Leonardo by Isaacson (2017), relating how, through "unstoppable curiosity" (20) and a social

[10] Quotes from EC.050 Transcript, November 11, 2018.

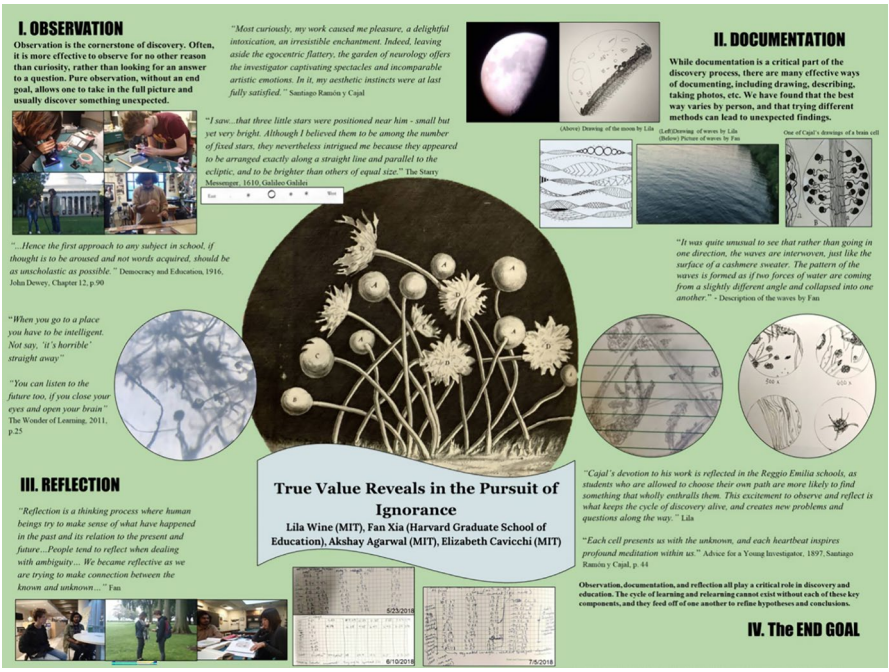

Fig. 5 Poster created by the class, titled 'True Value Reveals in the Pursuit of Ignorance' (Wine et al., 2018) Its 4 sections describe and illustrate the class exploratory cycle: Observation, Documentation, Reflection, The End Goal (i.e. no end). The center circle, showing Robert Hooke's microscopic drawing of mold, is flanked by the students' own microscopic images

position that put him outside academic structures, Leonardo lived in exploratory, passionate dialogue with nature. Science and art flow mutually integral across his being.

The fascination of trees was at first at a remove from Yvonne. She had not met Akshay, who was now in India. Fan and I raised the question of whether we could do anything with the sap that was then beginning to rise in trees. Having never observed or collected sap before, and doubtful of its feasibility for us novices, I was anxious. The immense labor and logistics described in readings about historical and commercial maple sap production (Lange, 2017; Nearing, 1970) nearly dissuaded me from trying.

Yvonne became drawn into our questions. Familiar with sugar cane from childhood in Taiwan, the prospect of sugar from trees intrigued Yvonne. Already a longtime friend with Mable, the Norway Maple in her yard, Yvonne drilled a hole in her trunk. Mable's sap flowed and flowed! Observing at the tap, she counted 300 drops a minute! Yvonne found herself borrowing a multi-gallon container to deal with rates of up to a gallon a day![11]

[11] Later we read Kimmerer's account of using trash barrels to contain collected sap, then boiling down great quantities of sap in a vat suspended over a wood fire outdoors, overnight (Kimmerer 2013, 65–7).

New experiments built on our methods with autumn leaf surfaces, yet now as our effort to understand indigenous practices of concentrating the sugars in maple sap by partially freezing sap and then boiling it (Nearing, 1970). Yvonne observantly controlled experiments with sap, sugar, honey and water, in an array of beakers, and beautifully documented everything in her notebook and in her accompanying article (Liu-Constant, 2024). What happens when sugar water, sap, syrup, or cream is frozen? Separating frozen chunks from the yet-unfrozen liquid that often pooled within, we compared color and taste of frozen and liquid parts.

Investigating tree saps attuned us to multiple senses and sensations, evoking curious response. Intensified in sweetness, we put the frozen part into hotplates to boil. Intent over sap bubbling in our hotplate, we observed changes in sounds, bubble patterns, stickiness and flow. Pursuing these activities at home with her greater volumes, Yvonne found that leaving the pot unwatched on a stovetop could yield trouble! She discovered an advance warning:

> When the sap is boiling, the smell changes, when you get to the syrup part! Even my dog reacted! Sweet in the air!![12]

Where our professor advised us that Norway maple sap is "horrible" and her husband characterized its flavor as "tree", Yvonne persevered with further boiling. Its remarkable sweetness, revealed through her extended efforts, we compared to commercial syrup and preferred it.

In the midst of steamy pots on the stove, and jars of different sap concentrations on the counter, Yvonne's husband asked: "What are you doing this for?" When she could not respond with a tangible outcome or goal, Yvonne realized, she had rediscovered her curiosity!

Sap season waned. Responding to Yvonne's interest in Leonardo and his flight inventions, I arranged our visit to view a facsimile of his notebook on the flight of birds (1893), and a historical printing of his studies of water (1828), in MIT's Distinctive Collections. Frustrated in her own attempts to make out how birds fly while observing, Yvonne marveled at Leonardo's evocative sketches. Yet it was the other book, on water, that left us awestruck. Although we could not follow the Italian, and the illustrations were another artist's more stilted interpretation, Leonardo's analyses of water flow outshone those barriers. We came upon a puzzling passage that appeared to depict an experiment—could we try it?

Another time, I brought to class a later Italian printing (Leonardo, 1923b, p. 41), and the online facsimile (Leonardo, 1986, MS C 26v) for that passage. Giving credence to Leonardo's drawing (Fig. 6a) and expressing her own imagination in its interpretation, Yvonne put herself into its paradox of underwater balance between water and air. The historical context itself was inscrutable. What was going on with an animal skin bag near the bottom of a well? Excitement rose with Yvonne's synthesis: "the bag becomes a new bottom [for the well], it pushes water out. He wants a way to get the water out of the well! He is pumping air [to move water]!!"[13]

[12] Quotes from EC.050 Transcript, March 14, 2019.

[13] Quotes from EC.050 Transcript, April 18, 2019.

And there was more. Upon following a reference to another passage, we came upon Leonardo noticing a spiral character in how bubbles move while rising to the surface in a body of water (Fig. 6b; Leonardo, 1988, MS F 37v; 1923b, p. 40).

With lab-sized materials that I gathered, Yvonne experimented with releasing air bubbles at the bottom of a column of water (emulating the well). Using a hand-squeeze air pump in place of Leonardo's leather bellows, she pumped air into a flexible narrow tube whose end we held at the bottom of a clear graduated cylinder (Fig. 6c; not quite half a meter in height). Upon squeezing the pump, she released an air bubble so large that its perimeter coincided with the cylinder's walls, water level in the cylinder rose—just as Leonardo portrayed for the well. The cylinder's water level dropped when the bubble reached the surface. (We didn't try doing this with the water level at the cylinder's top; the overflowing of that experiment would test Leonardo's claim of lifting water from the well by means of air in the skin bag (Fig. 6a).)

When she released less air from the pump, small air bubbles took spiral paths in rising to the water column's surface, as in Leonardo's drawing (Fig. 6b). There was so much going on to engage her curiosity—and relate to Leonardo. The experiment comes to life in her successive exclamations as she releases bubbles, by syringe, at the cylinder's bottom, and observes bubbles rising and spiraling upward within the cylinder, to the water's top surface:

> I see what he means by swirly thing, each bubble spins as it goes up. See the bubble spin! Ah!! ...They all do that spinny thing he drew! What a curious mind [Leonardo] to look at bubbles and discover! … It is really fun to watch [bubbles rise by putting your head at] the top [of cylinder]. Really fun!! … But that makes it more amazing that Leonardo! Where he was looking??! It [bubble] goes up so fast you can't see it![14]

I substituted a blown up balloon for the syringe, as the source of air. What ensued, astounded us! Furious bubbling—ensued, then stopped. Yvonne positioned the tube's open end nearer the water's surface (Fig. 6d)—and bubbling resumed! We re-inflated the balloon. The interactive phenomena escalated Yvonne's curiosity. Her questions and experiments interleaved fluidly. At her direction, I raised and lowered the balloon. She raised and lowered the tube's open end (Fig. 6e). The graduated cylinder's markings provided a reference for where bubbling appeared. Yvonne exclaimed with her emerging ideas.

> Wow!! Fascinating! It matters how much air is in the balloon, but when balloon gets smaller, then it [bubbling level] changes!... now it is limp balloon, the [bubbling] level is at the surface! Wow! Ha! Mind boggling! .. Wow! I got to think on that.[15]

Awareness of bubbles, flow, and states of water, that we collectively formed with maple sap experiments, became integral to Yvonne's experimenting in response

[14] Quotes from EC.050 Transcript, April 30, 2019.
[15] Ibid.

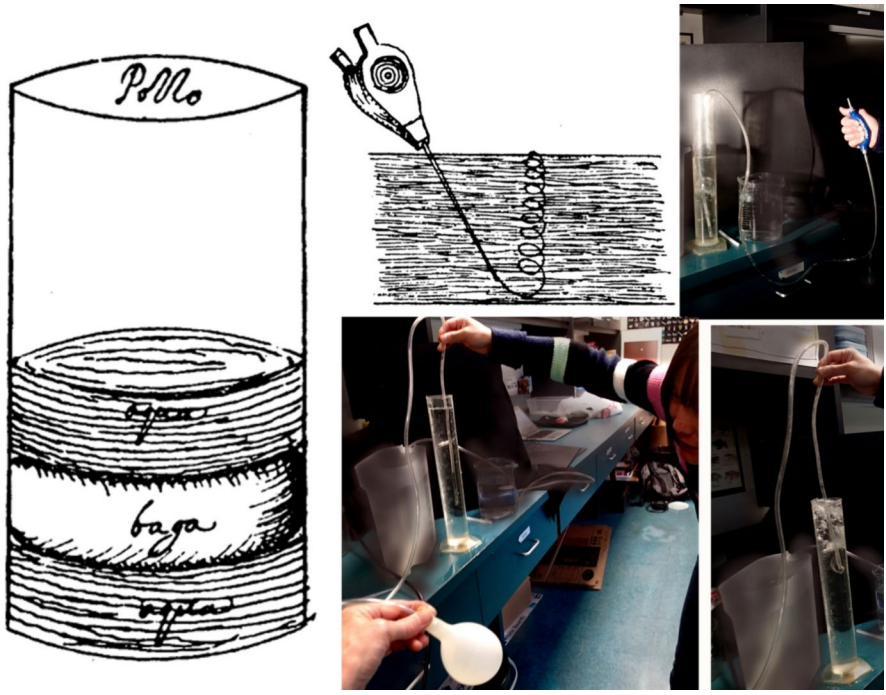

Fig. 6 [Clockwise, begin left] **a** Based on Leonardo's original, diagram depicts clear cylinder having lower layer water; mid layer bag filled with air; next layer water with air above (Leonardo 1923b, p. 41). **b** Based on Leonardo's original, diagram depicts a bellows pumping air through a tube, whose end is under water. A rising spiral represents the bubbles rising to the water's surface (Leonardo 1923b, p. 40). **c** Photo of graduated cylinder containing water. A clear tube, connected to a squeeze air pump at Yvonne's hand, runs to the bottom of the cylinder. When she squeezes the pump, a large bubble rises through the water to the surface. **d** When Yvonne raises the tube so its submerged end is nearer the surface of the water in the cylinder, bubbling is intense. **e** when Yvonne lowers the tube, bubbling ceases. In this experiment, instead of a pump, a balloon (white circle) provides air to the tube

to Leonardo. Without that experience, we may have passed by Leonardo's cryptic sketch, without dwelling in curiosity on its significance. Leonardo's keen observations of water and air opened us to extend that experience in ways that resourcefully re-interpreted Leonardo and what he described. Yvonne and I were collaborators with Leonardo and with the balloon, bubbles, water cylinder, and all that happened so immediately. That experience of living curiosity was as effervescent as the actual bubbles: spontaneity, wonder and methodical responsiveness all at once.

Relationships with others, the world, and understanding are active and emergent across the explorations that Yvonne developed together with me. Yvonne's relationship with Mable the Maple moved from initial admiration to active dialogue and exchange through her sap projects, and to grief and continuity of spirit, in later experiences related in her accompanying paper (Liu-Constant, 2024). Akshay introduced us to trees as teachers and companions. Yvonne—becoming infused with Akshay's passion before meeting him—engaged with the living active being

of a particular tree. Relating to something of the tree, from the inside with its changing flow, brought about for her, the mutuality and respect that courses through indigenous relationships with trees and ancestors, as described by Kimmerer:

> a bond physical, emotional, and spiritual. I have no way to pay them back… Perhaps all I can do is love them… in reciprocity for their gift. (Kimmerer, 2013, pp. 70–17).

Leonardo's legendary curiosity and works were an inimitable exemplar for Yvonne, that reading about him only exacerbated – until a particular drawing ensnared her own personal curiosity. In thought, experiment and spontaneity, she lived curiosity with Leonardo in re-creations unbounded by time and heedless of disparity in circumstance.

Collaborating with Children

On re-commencing the next fall, we were joined by Second Grader Giulia! Giulia was among the participants at the activity table that accompanied the class poster at the educational conference the previous year (as described above; Wine et al., 2018). Having enjoyed floating acorns and pine needles, and making a small boat there, Guilia asked me to participate in our class.

That fall, Akshay was taking Eleanor Duckworth's course on teaching and learning, then taught by Lisa Schneier.[16] One class assignment asks each student to engage someone else in working out all the permutations of 4 objects, by making their own arrangements with actual objects to represent friends sitting in a movie theater row (Duckworth, 2006a), based on an activity that Jean Piaget and Bärbel Inhelder did with children (1975). Having done this assignment with an adult, Akshay wondered what it would be like, doing it with a child.

He brought 4 items: cotton squares, pasta, stick, and binder clip. Giulia immediately appropriated the cotton squares, to represent the actual seats. I added paper clips, as the fourth object. She commenced each next arrangement by laying out 4 cotton seats, and then placing a different item in each seat (Fig. 7a). Looking for whether an object already had a turn in that seat, she created arrangements, checked them against the others, with excitement for each next one. "Cool! I found all these ways! Actually! I have a new idea! This is really fun!" Giulia found herself making "A miniauditorium!" Having reached 15 arrangements, she diverged to have fun in a new way: sprinkling glitter sparkles over the arrangements! (Fig. 7b) When Akshay invited her to make more, she deferred, "these are enough, there's no more space." (Fig. 7c).[17]

We offered another whole table surface. Giulia reengaged, amazed to have found "so many!" Checking for repeats between the two tables added complexity. In her

[16] This is the Harvard Graduate School of Education course, T440 Teaching and Learning, that I took, in which I did the floating and sinking activity with Yvonne Pappenheim as learner, as discussed above.
[17] Quotes from EC.050 Transcript, October 1, 2019.

search for untried arrangements, Giulia closed her eyes, mixed pieces up, sought out randomness as a path to new order. Near the end of our time, Giulia created a new question for herself. One by one, she counted: 19 rows, 19 ways, 19 sets of seats. One by one she counted up all the white seats: 76. Next, she asked – how many sticks? Her count of 19 surprised her, and was confirming, at the same time: "Wait! 19? That means I did the same number of all those materials!".[18]

Excited by her experience, Giulia voluntarily wrote a report for Akshay (Fig. 7d):

> Best time ever!! YOU HAVE TO TRY!!!!! IT IS AWESOME!!! Imagine you are in a auditorium and you keep switching seats. Fuuun!!!" (Stevens, 2019)

Giulia regularly participates in seminar sessions (Stevens, 2024). Between sessions, Akshay, Yvonne, Fan and I discuss ideas. The Auditorium Activity evolved into the differing orders of: three friends together in a car, three colors of beads for a necklace, and a tune made of three notes. As another activity, Akshay engaged Giulia in finding his image, while viewing through a small mirror, taped to the wall. Tossing a clay ball across the visual barrier we'd made, Giulia elaborated the game in ways we'd never imagined. In online sessions during the pandemic, Giulia, Fan and I made birds' nests, drew, played a shape cancel game of her invention, made cat's cradles in yarn, danced (Stevens et al., 2021).

With Trees and Children, Curiosity Abounds

Another year later, when pandemic conditions allowed for doing activities outdoors while masked, we met at the park. Yvonne proposed a Piaget-inspired activity for Giulia and 3 year-old brother Giorgio: collecting autumn leaves and sorting them (Inhelder & Piaget, 1969). In the process of sorting leaves, the younger child's reasoning and classification methods would differ from that of the older child.

At the park, my students met me, each other, and the children, for the first time in person. We began by reading the MIT Land Acknowledgement (n.d.) relating to original peoples of the place where we stood. Giulia offered that it means "understanding this land is of Wampanoag". Graduate student Dana Gretton reflected on injustices done here and making "sure we don't forget"; graduate student Vira Dhaliwal shared sadness for what was done to those whose "peaceful life" was here.[19]

My colleague (and skilled rockclimber) Cheetiri Smith and I opened the activity for the children: first find leaves to put in their baskets. When Dana asked about getting the most leaves, Vira clarified "getting different types and shades", and I added, "collect whatever you want".

Giorgio expressed an immediate curiosity "I want only big leaves! I like big ones!" With leaves a-plenty on the ground, Giorgio soon found one that Chee described as larger than his face. Observing the ground ever more closely, Giorgio

[18] Ibid.

[19] Quotes from EC.090 Transcript, October 22, 2020.

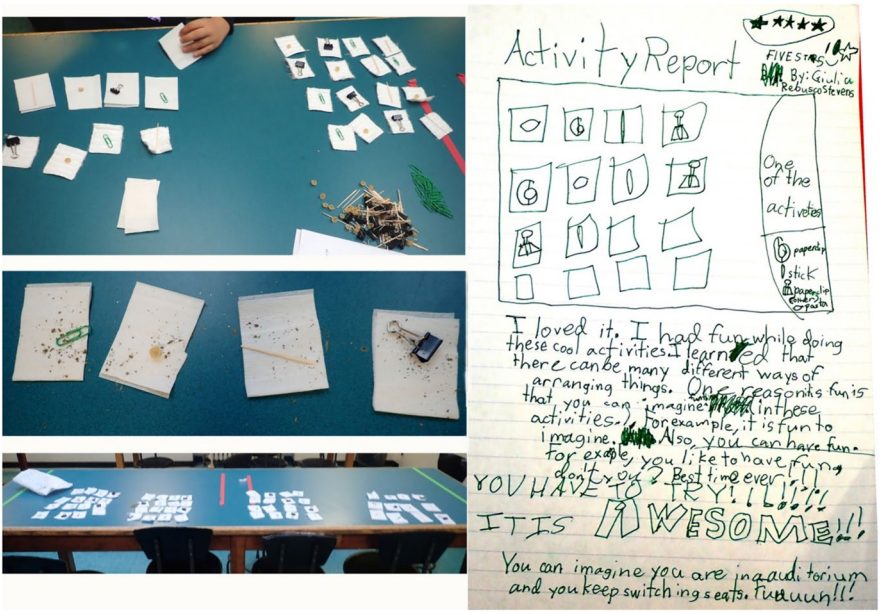

Fig. 7 (counterclockwise, begin top left) **a** Photo of table where Giulia is arranging permutations of 4 objects: paperclip, pasta, binder clip, toothpick. Each object rests on a white cotton square. 6 rows, having 4 white squares each, are complete, as Giulia begins to add the next white square. **b** Photo of one row of 4 squares – decorated with glitter sprinkles- paper clip, pasta, toothpick, binder clip. **c** Photo of table, filled with 16 completed rows of 4 objects. **d** Giulia's handwritten Activity report, with drawing showing 2 completed rows, and exclamation: "YOU HAVE TO TRY!!!!! IT IS **AWESOME**!!!"

became absorbed with its caterpillars, ants and holes, a fascination he shared with new companion Dana.

Meanwhile Giulia's response was: "climb the trees to get leaves!"[20] (In preparing for that session, neither I, nor my students, had envisioned tree-climbing). Into a crabapple whose low branches spread out invitingly, Giulia went, picking green leaves and crabapples while climbing (Fig. 8a). Climbing yet higher in a neighboring tree, Vira experienced the freeing of his own curiosity, vibrant in his childhood in Norway, yet too often "stifled" since (Dhaliwal 2020, p. 4).

Back on the ground, Giulia excited shared her basket's contents. Keeping in mind the sorting activity we planned next, Vira questioned the uniformity of leaf color, saying "Green is not that cool. What about red? Yellow? Look around where we can find some." Across the field, sugar maple trees were resplendent in reds; not having noticed these, Giulia stayed within the grove of green. When Chee proposed climbing those distant trees, Giulia ran off together with her.

Starting higher from the ground, the maple's great limbs spiraled upward. Chee climbed up, picking and dropping red leaves for Giulia. On her own and inspired by her new friends, Giulia jumped to reach its lowest branch, pulling herself into it

[20] Ibid.

Fig. 8 [Clockwise, begin top left] **a** Giulia climbs into the wide low branches of the crabapple tree; her basket is perched on the branch below her. **b** Koala-style, hanging upsidedown, Giulia mounts the lowest maple branch. **c** "People trees": Chee's shoe is visible at the nearer tree's branch (top right); Vira climbs up the farther maple. **d** From branches above, Chee encourages Giulia's climbing. **e** Giulia tosses another leaf onto her blanket; Vira releases one from further back. f. Giorgio (back view) shares his basket of leaves and sticks with Dana; his blanket (behind) has one big leaf

upsidedown at first –in what Chee described as "koala" style (Fig. 8b).[21] Seeing Vira scale the heights of a taller maple (Fig. 8c), Giulia marveled:

It's a people tree!!! [Crab]apple tree, maple tree, now there is also people trees![22]

Getting to the next limb looked daunting to Giulia; Chee encouraged her, demonstrating alternative routes (Fig. 8d). Standing upright, Giulia mounted into its sequence of crotches, with excitement for her heightened perspective, being much taller than her dad: "it's so fun to climb trees!".[23]

With red leaves added to her basket—and a purple wildflower she spied amid the grass—Giulia rejoined her brother. Along with leaves, his basket included sticks—"pieces of tree". We laid out blankets on the grass, one for each child to spread out their findings. We asked them to make an arrangement. Vira clarified, "put leaves together that go together".[24]

[21] Ibid.
[22] Ibid.
[23] Ibid.
[24] Ibid.

Giulia recreated the activity—by throwing each leaf into the air while dancing, seeing where it fell on the blanket (Fig. 8e). Interactively, Vira responded to her curiosity, such as suggesting ways of adapting to the wind. A more directive mode of leaf transit in air emerged as they folded leaves into "leaf paper airplanes" and tossed them. Meanwhile, having put just one leaf—the very largest—onto his blanket (Fig. 8f), Giorgio searched for rocks.

Vira later reflected:

> We told the children they can organize leaves exactly how they want, and were excited to consider their organization in light of our readings of Piaget. Giulia, however, … just wanted to throw them…! Although I was a bit frustrated at first, I quickly realized that there was much to be learnt from throwing the leaves onto the blanket too. We then proceeded to …throw leaves up in the air and let the wind carry them onto the blanket. Instead of telling students what to do, the role of the educator can be to give them hints and ideas that allow them to make discoveries on their own. (Dhaliwal, 2020)

Curiosity is mutually extended among children and adults. Where Giulia thrilled to climbing to gather leaves, mounting the low crabapple's limbs, the adults joined—some of whom may have long since given up climbing trees—joined. Sharing Giulia's passion for climbing, Chee extended Giulia's curiosity, inviting her to the maple tree and demonstrating its access. Renewing the process of experiencing and acting on curiosity through tree-climbing and with the children, Vira responded to Giulia's leaf-arranging dance in ways that extended with wind and flight.

The mutual curiosity extends to those not with us. Where Akshay initiated learning from trees, and collaborating with Giulia, among me and my students, he was not along when the trees became "people trees". Similarly, Yvonne's investigations brought her into dialogue with indigenous practices of maple sap and with Leonardo's well. Collaborating together among and in trees, children and adults raise each other up, metaphorically on Leonardo's wings!

Discussion

The narratives above carry the research developments of learning and teaching through centering and encouraging learners' curiosity and extending it through investigation. I summarize some overall findings here.

Conventional academic structures obstructed me from realizing, valuing and creating space for the relational understandings and experiences that learners build through curiosity and acting on curiosity. My questioning of those conventional practices did not in itself provide me with means of enacting the transformative education that I began to consider. When I first arranged class sessions outside what is academically normal, my students responded with fascination. Concurrently I found myself uncertain about what teaching involved. A shadow framework of prescribed teaching and learning followed me and my students into the experimental classroom. By listening to my teachers and students, my

learning responded relationally with the stirrings of curiosity among us. The shadow framework receded.

My evolution in teaching and learning with exploration is ongoing, uncertain, developing through interactive and narrative research. In that process, I began to appreciate that engaging with relationships in the subject matter and among participants, is core to teaching, learning and research. My ways of understanding the subject matter, and of enacting the role of teacher, changed along with my realizations of relationships and how learners' curiosity inferred and probed them. In a related account, elementary school teacher Chryssanthi Pikouli (2024) finds curiosity changing her and the students as she responded to children's delight for archaic science devices perched on the windowsill.

The environment of the MIT Edgerton Center, where I currently teach, explicitly supports student initiatives and the spontaneity of evolving experiences, such as are conveyed in the narratives above. As a curiosity or effect arises through student involvement, in the moment, I am free to act to follow it, such as by bringing over tools and supplies, and adapting that session (or later ones) to support it. Students and I together create and enact curriculum relationally; we are not compelled by an external template. This setting is unusual in academic studies.

For students, as for me, there is a process of becoming open to be curious and act with curiosity together. Fan was initially inhibited in the courtyard; Yvonne started our seminar with an expectation that did not include maple trees. In their own uncertain process of embracing curiosity, students are encouraged by others in their lives: Akshay's uncle; Lila's friend at the river; the Reggio children exhibit (Vecchi et al., 2011; BARIN, 2018; Reggio Children, 2020); and historical works of Leonardo and Dewey. Taking the historical figure Galileo as mentor and confident, Yan Yang, my student in another semester, describes curiosity, perplexity and confusion emerging through her questioning investigations with geometry, learning and social justice (2024).

Inviting children as full coparticipants in the class encourages adult students to rediscover curiosity and collaborate in the child's learning. In doing the auditorium problem together, Akshay saw Giulia building patterns, making comparisons, counting rows, marveling at, and challenging, her own thinking. Taking up the children's enthusiasm for climbing trees, Vira went higher yet, and experienced joy and liberation. Giulia herself reflects on these experiences, as fun and education, in her essay (Stevens, 2024).

The natural world, opened by curiosity, embodies ever-emerging relationships that accommodate concurrent widening and deepening of learners' involvement and realizations. Whereas conventional units of subject matter are disjoint, not essential for starting the next one, curriculum opened through curiosity is interdependent, calling upon and expanding from the shared web of activities, discussions, experiments, reflections and materials. Yvonne's engrossing experiments with maple sap liquid, ice and vapors (Liu-Constant, 2024) attuned her wonder for Leonardo's pump drawing, curiosity for trying it herself, and excitement for the rising and spiraling bubbles. Yvonne's realizations that curiosity brings about self-sustaining investigation corroborates with a study where Israeli teens did open-ended biology

experiments: "curious students seek the challenge and enjoy modifying their inquiry as they progress throughout the inquiry progress" (Zion & Sadeh, 2007, p. 166).

Learning experiences happening through relationships are infused with emotion, aesthetic qualities, and social connections and concerns. Perceiving Euclid's geometry in the Japanese maple leaf and Millay's poem moves Akshay to infer limitation in Keat's account of beauty. Whereas conventional education typically separates such works from each other, curiosity interrelates these as Akshay discerns relationships and understandings not previously exposed. Years after taking my seminar, while Ronald Heisser (2023) was viewing the moon near sunset, its beauty and form provoked curiosity that he acted upon, building more coherent understanding of the moon and personal commitment to lifelong learning.

Not an End, But a Beginning

Curiosity grows and travels via relationships inhering in and among materials and experiences ranging from personal, to shared, to those at further removes, such as Leonardo and history. These relational ways are not accessed under the predesigned routes of formal instruction. Narratives developed from experiences mediated by curiosity, such as those related here, demonstrate education happening. Relation, imagination and openness, along with listening, documenting and responding, constitute work of teaching that is not emphasized under the traditional teacher role.

Curiosity relies on staying with uncertainty and the unexpected—with "negative capacity" of Keats. Though being in that unknown, and, as Akshay discerned with Euclid, through taking action, curiosity moves us into new constructive understandings and wonderment. The interrelating of actions and befuddlement facilitates flow in what we do and realize in thought. For example, Pappenheim's freedom to propose to cut the potato and float it on the spot was alongside my freedom to be openly surprised when it sank. Reflecting on how curiosity—not compliance—is germinal for historical scientists, Vira identified its concurrence with the children's curiosity.

> … instead of following a certain set of "correct" guidelines for a scientist (as is sometimes taught), their state of mind was more like that of Giulia and Giorgio exploring the leaves at Magazine Beach. (Dhaliwal, 2020)

Curiosity is living together unbounded—with 'No End Goal' imposed from without, as Lila, Fan and Akshay express it. In formal instruction, grades frame an end goal while preset boundaries limit and direct students and teacher in getting there. Those grades and boundaries impact students inequitably, stopping and inhibiting some while advancing others having advantaged access and means for dealing with academia. Curiosity, by originating with learners, offers potential for learning that is contingent upon, and builds through relations of equity.

Yet formal instruction suppresses curiosity, casting a shadow that even extends into alternative settings, as I realized as a beginning teacher. In class and in writing, my students similarly describe educational lack of support for their curiosity. In an explicit example, everyone but Akshay's uncle reacted by dismissing his childhood curiosity for plants. By contrast, suppression is often applied subtly, circumventing

learners' notice. That restraint can be exposed and undone, as Akshay encountered with trees in autumn; Yvonne with maple sap and bubbles; Vira with climbing trees and Giulia; and as I continue to experience in activities co-created among adults and children.

On being released into the world, curiosity sustains our potential for living and learning. These narratives from my students and me doing teaching, learning and researching together, provide examples for doing education differently, as ongoing processes opening through students' curiosity in environments that educators create with commitment to interaction and inclusion. We inspire readers to reflect on their teaching practices, watch and listen for curiosity, and promote lifelong learning to encourage exploration among participants in community.

Acknowledgements I am happy to thank the learners in these narratives: Akshay Agarwal, Yvonne Liu-Constant, Lila Wine, Fan Xia, Giulia and Giorgio Rebusco Stevens, Vira Dhaliwal, Dana Gretton, and Cheetiri Smith. These activities are supported by MIT Edgerton Center, with participation by Jim Bales, Thery Mislick, Sandi Lipnoski, Ed Moriarty, Amy Fitzgerald, Diane Brancuzio, and Chris Mayer. Class museum and library visits were facilitated by Debbie Douglas, Elizabeth Neswald, John Overholt, and Harvard University Herbaria. The reviewers' responses improved this manuscript. My development in exploratory teaching and learning is inspired by Eleanor Duckworth, Chris Lowry, and Alva Couch. This work honors the memory of: Alanna Connors, Phil Morrison, Yvonne Pappenheim, Sukant Tripathy, Yan Yang, and my parents.

Funding Open Access funding provided by the MIT Libraries.

Declarations

Competing Interests The author has no competing interests to declare that are relevant to the content of this article. Informed consent practices were used in this study.

References

Agarwal, A. (2018). *Intersections of science and humanity*. Final reflective paper, EC.090. MIT, Cambridge MA.

BARIN (2018). Boston area Reggio inspired network (BARIN). The wonder of learning Boston 2018. Retrieved January 27, 2024, from https://bostonreggionetwork.org/event/the-wonder-of-learning-boston-2018/

Bond, R. (1993). *Rain in the Mountains: Notes from the Himalayas*. Penguin Books Ltd.

Cavicchi, R. H., & English, R. E. (1953). *A rapid method for use in design of turbines within specified aerodynamic limits* (No. NACA-TN-2905).

Cavicchi, R. H. (1959). *Design analysis of a subsonic nuclear-powered logistic airplane with helium-cooled reactor*. National Aeronautics and Space Administration.

Cavicchi, R. H. (1967). *Mapping a tungsten-reactor rocket engine as a guide to operation and control* (No. NASA-TN-D-3840).
Cavicchi, E. (1992a). *Test 2 Physics 2 99,132 April 2, 1992*. University of Massachusetts.
Cavicchi, E. (1992b). Science from Our Lives Course Reader 1992, University of Massachusetts, Lowell, MA
Cavicchi, E. (1993a). Final Fieldwork I, December 5, 1993, T440 HGSE unpublished manuscript, Cambridge
Cavicchi, E. (1993b) Final Fieldwork II, December 16, 1993, T440 HGSE unpublished manuscript, Cambridge MA.
Cavicchi, E. (1994). Final Paper, January 1994, T440 HGSE unpublished manuscript, Cambridge MA
Cavicchi, E. (1995). Tales of Physics, Authority and Hope, May 1995, MIT STS, unpublished manuscript, Cambridge
Cavicchi, R. H. (2004). *Probing within the boundary layer of an airfoil by using the wind numerical code* (No. NASA/TM-2004-213221).
Cavicchi, E. (2008). Opening possibilities in experimental science and its history: Critical explorations with pendulums and singing tubes. *Interchange, 39*, 415–442. https://doi.org/10.1007/s10780-008-9073-0
Cavicchi, E. (2009). Exploring mirrors, recreating science and history, becoming a class community. *New Educator, 5*(3), 249–273. https://doi.org/10.1080/1547688X.2009.10399577
Cavicchi, E. (2010). Recreate Experiments from History: Inform the Future with the Past: Galileo. MIT OpenCourseWare. Retrieved June 6, 2024 from https://ocw.mit.edu/courses/ec-050-recreate-experiments-from-history-inform-the-future-from-the-past-galileo-january-iap-2010/
Cavicchi, E. (2011). Classroom explorations: Pendulums, Mirrors and Galileo's Drama. *Interchange, 42*(1), 21–50. https://doi.org/10.1007/s10780-011-9144-5
Cavicchi, E. (2014). Learning Science as explorers: Historical resonances, inventive instruments, evolving community. *Interchange, 45*(3), 185–204. https://doi.org/10.1007/s10780-015-9235-9
Cavicchi, E, (2017). Shaping and being shaped by environments for learning science: Continuities with the space and democratic vision of a century ago. *Science and Education, 26*, 529–556. https://doi.org/10.1007/s11191-017-9910-6
Cavicchi, E. (2018). "At sea": Reversibility in teaching and learning. *Interchange, 49*, 25–68. https://doi.org/10.1007/s10780-018-9314-9
Cavicchi, E. (2019). Becoming curious science investigators through recreating with history and philosophy. In A. P. B. da Silva & B. A. Moura (Eds.), *Objetivos Humanísticos, Conteúdos Científicos: Contribuções da História e da Filosofia da Sciência para o Ensino de Ciências* (pp. 265–284). Edupb.
Cavicchi, E. (2021). Observing, Exploring and Learning in Science and its History. In M. K. Delaney & S. J. Mayer (Eds.), *Looking and Listening for Learning* (pp. 129–145). Berlin: Teachers College Press.
Cavicchi, E. (2022). Historical science instruments in exploratory teaching and learning. In E. Cavicchi & P. Heering (Eds.), *Historical scientific instruments in contemporary education* (pp. 158–180). Brill.
Reggio Children (2020). The wonder of learning : the hundred languages of children. Traveling exhibit. Retrieved January 27, 2024, from https://www.reggiochildren.it/en/rc/exhibitions/the-wonder-of-learning-the-hundred-languages-of-children/
Chiu, S.-M. (2009). The ancient master painted like me. *The New Educator, 5*(3), 229–248.
Delaney, M. K., & Mayer, S. J. (Eds.). (2021). *In search of wonderful Ideas: Critical exploration in teacher education*. Teachers College Press.
Dewey, J. (1955). *Democracy and education: an introduction to the philosophy of education*. Macmillan. (Original work published in 1916) Retrieved January 27, 2024, from https://archive.org/details/in.ernet.dli.2015.274992
Dewey, J. (1934). *Art as experience*. Minton, Balch & Company.
Dhaliwal, V. (2020). Letting the world in: Final reflective paper, EC.090, MIT, Cambridge MA.
Di Stefano, R. (1996). The IUPP evaluation: What we were trying to learn and how we were trying to learn it. *American Journal of Physics, 64*, 49–57. https://doi.org/10.1119/1.18292
Duckworth, E. (2001). Inventing density. In E. Duckworth (Ed.), *Tell me more: Listening to learners explain* (pp. 1–41). Teachers College Press.
Duckworth, E. (2006a). Twenty-four, forty-two and I love you: Keeping it complex. In E. Duckworth (Ed.), *The having of wonderful ideas" and other essays on teaching and learning* (3rd ed., pp. 125–155). Teacher's 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). 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). Teachers College Press.
Edgerton, H. E. & Killian, jr. J. R. (1979). *Moments of Vision*. MIT Press.
Edgerton, H. E. (1987). *Stopping time: A collection of photographs*. H. N. Abrams.
Edgerton, H. E., & Killian, J. R., Jr. (1954). *Flash!: Seeing the unseen by ultra high-speed photography*. Hale, Cushman & Flint.
Elementary Science Study, (1970). *The ESS Reader*. Educational Development Center.
Elementary Science Study. (1965). *Elementary science study*. McGraw-Hill.
Engel, S. (2011). Children's need to know: Curiosity in schools. *Harvard Educational Review, 81*(4), 625–645.
Engel, S. (2015). *The hungry mind: The origins of curiosity in childhood*. Harvard University Press.
Hawkins, D. (2002). I, Thou and It. In D. Hawkins (Ed.), *The informed vision: Essays on learning and human nature* (2nd ed., pp. 51–64). Algora.
Heisser, R. (2023). Open up to curiosity. *Interchange, 54*(4), 459–464.
Hooke, R. (1665). *Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses : with observations and inquiries thereupon*. Jo. Martyn and Ja. Allestry.
Hughes-McDonnell, F. J. (2000). *Circuits and pathways of understanding: "I can't believe we're actually figuring out some of this stuff*." Unpublished Doctoral Dissertation: Harvard University.
Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence* (A. Parsons and S. Milgram, Trans.). Basic Books.
Inhelder, B. and Piaget, J. (1969). *The early growth of logic in the child: classification and seriation* (E. A. Lunzer and D. Papert, Trans.). Norton
Inhelder, B., Sinclair, H., & Bovet, M. (1974). *Learning and the development of cognition* (Susan Wedgwood, Trans.). Harvard University Press.
Isaacson, W. (2017). *Leonardo da Vinci*. Simon & Schuster.
Keats, J. (1817) Letter November 22, 1817. John Keats Collection, 1814–1891; MS Keats 1, Letters by John Keats. Houghton Library, Harvard University, Cambridge, Mass. [1817 November 22], to Benjamin Bailey. MS Keats 1.16. Page (seq. 53) Houghton Library, Harvard University, Cambridge MA. Retrieved January 27, 2024, from https://nrs.harvard.edu/urn-3:FHCL.Hough:10385405?n=53
Keats, J. (2021a/1817). Letter to George and Tom Keats, 21,27 December 1817. Retrieved January 27, 2024, from https://www.poetryfoundation.org/articles/69384/selections-from-keatss-letters
Keats, J. (2021b/1819). Ode on a Grecian Urn. Retrieved January 27, 2024, from https://www.poetryfoundation.org/articles/145240/john-keats-ode-on-a-grecian-urn
Kibga, E. S., Gakuba, E., & Sentongo, J. (2021). Developing students' curiosity through chemistry hands-on activities: a case of selected community secondary schools in Dar es Salaam, Tanzania. *Eurasia Journal of Mathematics Science and Technology Education, 17*(5), em1962.
Kimmerer, R. W. (2013). *Braiding Sweetgrass: Indigenous wisdom, scientific knowledge and the teachings of plants*. Milkweed Editions.
Labella, M. (2009). Encouraging Exploration: The effects of Teacher Behavior on Student Expressions of Curiosity. BA. Thesis, Williams College. Retrieved January 27, 2024 from https://librarysearch.williams.edu/discovery/delivery/01WIL_INST:01WIL_SPECIAL/12288877180002786
Lamnina, M., & Chase, C. C. (2021). Uncertain instruction: Effects on curiosity, learning, and transfer. *Instructional Science, 49*, 661–685.
MIT Land Acknowledgement Statement (n.d.) Retrieved January 27, 2024, from https://iceo.mit.edu/land-acknowledgement/
Lange, M. A. (2017). *Meanings of maple: An ethnography of sugaring*. The University of Arkansas Press.
Leonardo, da Vinci (1828). *Del moto e misura dell'acqua*. F. Cardinali.
Leonardo, da Vinci (1893). *I manoscritti di Leonardo da Vinci : Codice sul volo degli uccelli e varie altre materie*. Facsimile. Edoardo Rouveyre.
Leonardo, da Vinci (1986). Manuscripts of the Institut de France, Manuscript C: Facsimile Florence: Giunti Barbèra. eLeo Retrieved January 27, 2024, from https://www.leonardodigitale.com/
Leonardo, da Vinci (1988). Manuscripts of the Institut de France, Manuscript F: Facsimile Florence: Giunti Barbèra. eLeo, Retrieved January 27, 2024, from https://www.leonardodigitale.com/
Leonardo, da Vinci (1923a). In E. McCurdy (Ed.), *Leonardo da Vinci's note-books.* Empire State Book Company.

Leonardo, da Vinci (1923b). *Del moto e misura dell'acqua, libri nove ordinati da f. Luigi Maria Arconati.* In L. M. Arconati, E. Carusi, & A. Favaro (Eds.). Gardinali.
Lindholm, M. (2018). Promoting curiosity? Possibilities and pitfalls in science education. *Science & Education, 27*, 987–1002.
Liu-Constant, Y. (2024). What is Curiosity For? An Early Childhood Teacher Educator's Reflection on Curiosity. Manuscript submitted.
Low, S., Peck, A., & Rockefeller, T. K. (1987). *The Ring of Truth*. With Philip Morrison. Public Broadcasting Associates, Inc.
Magau, N. (2001). Looking at learning to understand teaching: A South African study. In E. Duckworth (Ed.), *"Tell me more": Listening to learners explain* (pp. 166–180). Teachers College Press.
Millay, E. St. V. (2021/1923) Euclid alone has looked on Beauty bare. Retrieved January 27, 2024, from https://www.poetryfoundation.org/poems/148566/euclid-alone-has-looked-on-beauty-bare
MIT Edgerton Center (2021). Retrieved January 27, 2024, from https://edgerton.mit.edu/
Morrison, P. and P. (1987). *The Ring of Truth: An inquiry into how we know what we know*. Random House.
Morrison, P. (1995a). The full and open classroom. In P. Morrison (Ed.), *Nothing is too wonderful to be true* (pp. 258–269). American Institute of Physics.
Morrison, P. (1995b). Knowing where you are. In P. Morrison (Ed.), *Nothing is too wonderful to be true* (pp. 4–7). American Institute of Physics.
Morrison, P. (1995c). Engineers in kindergarten? In P. Morrison (Ed.), *Nothing is too wonderful to be true* (pp. 282–290). American Institute of Physics.
Nearing, H., & S. (1970). *The maple sugar book*. Chelsea Pub Co.
Newman, E., Araque, A., & Dubinsky, J. (Eds.). (2017). *Beautiful Brain: Drawings of Santiago Ramón y Cajal*. Abrams.
Piaget, J. and Inhelder, B. (1975). *Origin of the Idea of Chance in Children* (L. Leake, Jr., P. Burrell, H. D. Fishbein, Trans.). Norton.
Piaget, J., & Inhelder, B. (1956). *The child's conception of space*. Routlege.
Pikoula, C. and Lazos, P. (2024). How curiosity becomes a question: Creating a school community that insists on asking questions. Manuscript submitted.
Plantevin, F., & Milici, P. (2022). Historical instruments, education, and do-it-yourself in the cabinet of curiosity of Brest, France: University experiences in mathematics. In E. Cavicchi & P. Heering (Eds.), *Historical scientific instruments in contemporary education* (pp. 209–225). Brill.
Recording of Millay reciting the poem; Retrieved January 27, 2024, from https://www.youtube.com/watch?v=7Q0W0VUcuCQ
Sheldon, J. (Executive Producer). (1994). How Fast is Fast? [Film]. MIT Video Productions, Harold and Esther Edgerton Family Foundation. January 27, 2024, from https://infinitehistory.mit.edu/video/how-fast-fast-1994
Sidney, G. (Director). (1940) "Quicker 'n a Wink [Film]. P. Smith Producer. Retrieved January 27, 2024, from https://infinitehistory.mit.edu/video/quicker-n-wink-1940
Stevens, G. R. (2019). Activity Report. October 29, 2019, unpublished manuscript, Cambridge MA.
Stevens, G.R., Agarwal, A., Liu-Constant, Y., Xia, F., Wine, L., Dhaliwal, V., Gretton, D., Smith, C., Cavicchi, E. (2021). "I Love Activities – Child collaborating with adults in exploratory activities", Jean Piaget Society (JPS) Conference, Virtual, June 3.
Stevens, G.R. (2024). Curiosity and Me. *Interchange*.
Sulistiani, E., & Waluya, S. B. (2018). The analysis of student's critical thinking ability on discovery learning by using hand on activity based on the curiosity. In *Journal of Physics: Conference Series* (Vol. 983, No. 1, p. 012134). IOP Publishing.
Vandiver, J. K. & Kennedy, P. (2005). "Harold Eugene Edgerton 1903–1990", *Biographical Memoirs*, *86*, National Academies Press. Retrieved January 27, 2024, from http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/edgerton-harold.pdf
Vecchi, V., McCall, J., Bendotti, M., & Children, R. (2011). *The wonder of learning: the hundred languages of children*. Berlin: Reggio Children.
Wine, L. (2018a). Journal. EC.090, MIT Cambridge MA.
Wine, L. (2018b). The Importance of Not Needing Goals. Final Paper. EC.090, MIT, Cambridge MA.
Wine, L., Xia, F., Agarwal, A., Cavicchi, E. (2018, October 26). *True Value Reveals in the Pursuit of Ignorance*. The Undiscovered Conference. Harvard Radcliffe Institute, Cambridge MA. Retrieved January 27, 2024, from https://www.radcliffe.harvard.edu/event/2018-undiscovered-symposium
Xia, F. (2018). A Letter to My Future Child. Final Paper. EC.090, MIT, Cambridge MA.

Yang, Y. (2024). An Open Letter to Galileo: Unrelenting Curiosity. Interchange.
Zion, M. I., & Sadeh, I. (2007). Curiosity and open inquiry learning. *Journal of Biological Education, 41*(4), 162–169.

Authors and Affiliations

Elizabeth Cavicchi[1]

✉ Elizabeth Cavicchi
ecavicch@mit.edu

[1] Massachusetts Institute of Technology, Edgerton Center, 77 Massachusetts Avenue, Cambridge, MA 02139, USA