Effects, Devices and Adventures

further. He has turned that arrogance and that violence inwards against those that criticize him, against immigrants, liberals, Mexicans, Muslims, women, in the name of America first and white supremacy.

I have no birthday card for you today Jed. Instead I can only thank you and the entire group at Caltech for inspiring me intellectually and politically, and for reassuring me that, in fact, a better world is possible. In the process, though, I have become like one of the cacti in the Huntington's desert garden: increasingly prickly as I adapt to an extraordinarily hostile environment in order to survive.

Elizabeth Cavicchi

Effects, Devices, and Adventures

Jed Buchwald had a profound effect on my research in teaching and learning science and its connection to history. At MIT in the fall of 1994, he opened a world of historical effects that arose in historical investigations to understand electricity for me and my classmates Diane Greco and Babak Ashrafi, in a course on *Science, Technology, and Society (STS) 150: Aspects of 19th Century Physics*. The following term I joined these classmates in further sessions in Prof. Buchwald's office on the scientific revolution. Philip Morrison, my longtime undergraduate physics professor at MIT, had recommended this course during our discussion about my doctoral studies. STS 150 was the first, and only, history of science course that I ever took, so that at its beginning I could not foresee how fascinating and revealing electrical effects and their historical analysis would prove to be.

In my doctoral studies at the Harvard Graduate School of Education I was seeking to change how physics is taught and absorbed by avoiding the abstractions and problem formalizations I had encountered during my undergraduate training (and graduate physics courses elsewhere), and from the textbook-answer emphasis of engineering programs. I had earlier encountered past science as a set of colorful human-interest anecdotes when working as a researcher for Morrison's

1987 public science TV series and book, *Ring of Truth*.* But in Buchwald's lectures and readings I became aware of relationships, confusions, learning processes, and interpretations that arise during observations, experiments, and collaborations. I became intrigued by the long trajectory that connects past to present learners. Multifaceted, critical, investigatory relationships of doing and expressing science, as they figured in Buchwald's discussions of science history, are what I now seek to evolve in the classroom.

As Buchwald's student, I had yet to trust and research the possibilities for exploratory and active learning. Conventional instruction had framed the contexts of my undergraduate physics teaching. The previous year I had begun to explore alternatives to such conventional instruction on motion. With my advisor Eleanor Duckworth I studied the work of Jean Piaget with a view to learning and teaching processes as development, as an ongoing and interactive nonlinear, spontaneous, engaging dialogue with the world and our thinking processes. It occurred to me that the history of science might illustrate developmental processes, such as the questioning and uncertainty that I was beginning to see at the heart of learning and teaching.

Evidence of such instances of development and dialogue were almost nowhere present in physics studies such as the year-long graduate physics course on electricity and magnetism based on the demanding textbook *Classical Electrodynamics*.† Looking to follow that austere text in detail, I had worked out all the derivations, including steps that were frequently omitted, a practice exemplified even more in that course by

*P. and P. Morrison. *The Ring of Truth: an inquiry into how we know what we know*. New York: Random House, 1987.

†J. D. Jackson. *Classical Electrodynamics*. New York: Wiley, 1962.

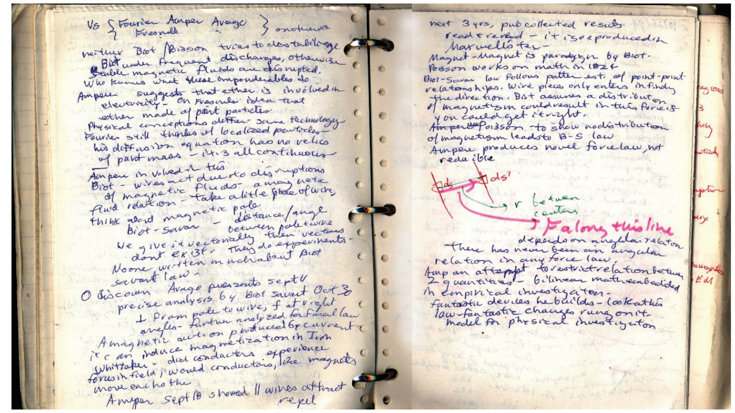
my professor Richard Milburn. There was both elegance, and stress to the student, in grasping and deriving these equations. These exercises were entirely mathematical, analogous to the mathematics education at Cambridge in the 19th century described by Buchwald. Equations that Buchwald presented in his lectures—Coulomb's law, Gauss's law, and Maxwell's equations—were familiar. But his lectures expressed an awareness, interest, and outlook that were unlike that of physics instruction. I therefore became increasingly drawn into the course, and my STS 150 lecture notes seem as thorough as those I recorded in physics courses.

Numerous interpretations, experiments, and phenomena of electricity figured in Buchwald's lectures. Describing the Cartesian universe as completely filled, the Newtonian as mostly void, Buchwald asked: "Is electricity 1) Cartesian; 2) Newtonian? Are there two fluids or one?" These genuine questions were respectful of the depth and potential of conflicting interpretations. Where physics treats the conservation of energy as foundational and universal, not to be questioned, and evidence of a student's error when absent, Buchwald invited us to consider scientists for whom energy had not yet been identified, let alone conserved. Buchwald's view that Franklin's explanations of electrical charge could be "clear and consistent" and yet simultaneously inconsistent as concerns the relationship of the atmosphere to bodies suggested a source of tensions among renowned past investigators. These tensions were analogous to what I was beginning to notice as generative among active learners—although suppressed in conventional instruction. I became intrigued by the potential for dialogue and exchange between historical and contemporary learning experiences.

Of Galvani's account of contractions in the frog's leg, Buchwald asked: "Is it a novel fact? Is it different? Is it a new class of phenomena?" And while some scholars had dismissed Galvani's findings, Buchwald noted the emergence of something new—the awareness of the character of a circuit: "discovery involves theory, not just observation; discovery is contextual." That attention to thinking and observation is what I was seeking to understand, learn, and facilitate among science learners.

I found a connection between Buchwald's responses to past efforts at understanding nature and Piaget's analyses of development which moves exploratively into new capacities and of limits and stasis where change does not come about. Buchwald described Ampére's work of suspending wires that act on each other as a challenge to electrostatic depictions of the voltaic pile that "produced current as a new category in nature." He emphasized how Franklin's principle of electricity, "What A loses, B gains, always an exchange," is analogous to the specific heats that J. Black measured with a calorimeter. While exchange is characteristic to a Newtonian outlook, Buchwald observed that Cartesian thinking left no opening for exchange.

It was also captivating to hear about the dynamic relation between thinking and experience. Oersted's sense of a unity in nature went beyond the realm of ideas. Buchwald said: "We must turn our attention to the world… where this truth will find its only corroboration; otherwise unity itself becomes a barren and empty thought leading to no insight." Oersted took risks when he performed his famous experiment for the first time during a lecture, placing a magnetic compass needle in various positions around a conducting wire. "Wouldn't you try it out first!?!," Buchwald asked of Oersted. He brought us to that day in 1820 when "Nature spoke loudly enough" in a classroom that its effect was "instantly reproducible" worldwide. While Oersted's finding posed "huge problems"



My notebook pages from STS 150, October 19, 1994.

for French theorists, reports of the wire's properties thrust Ampére into action. Initiating an "empirical investigation," Ampére suspended parallel wires that came together or pulled apart and produced a law describing a "novel" force due to its "angular relation." With awe, Buchwald identified the heart of Ampére's investigative work: "fantastic devices he builds—look at his law—fantastic changes rung on it. A model for physical investigation" (Figure 1). Investigation as taking risks and remaining open to 'the ringing of changes,' in Buchwald's frequent analogy, would become sustaining to the research, teaching, and learning I went on to do, and continue with.

In class, but without materials on hand, Buchwald encouraged us to try Oersted's experiment with a 1.5 volt battery, a paperclip, and a needle—"easy to make it happen." I had never before played with batteries—nor been invited to do so, or seen this effect, or observed other electromagnetic phenomena that our historical figures had observed. My entire training had been limited to theory. While we diagrammed electrical paths, oriented hands for the right hand rule, and calculated electrical outcomes, phenomena were seldom demonstrated.

Those who carried out the physical and intellectual developments discussed in Buchwald's class appeared only as names of units (oersted, farad, ampere, volt) or as carved inscriptions looming high over Killian Court at MIT, distant from the struggling learners below.

The magnetic effects of current-bearing wires became an experimental opening to the spatial character of magnetism in my dissertation project of redoing historical experiments, and later in my lab seminars for Harvard and MIT students, where we embarked on an extended exploration with batteries, bulbs, and wires. In long sessions, we developed an understanding of electrical relationships through creative and playful experimenting and discussion, while concurrently transforming our practice and vision of teaching and learning.[*]

Buchwald also introduced us to historical scientific instruments that are never mentioned in physics courses: the Leyden jar, the Volta pile, Ampére's wire devices, the telegraph, and the trans-Atlantic cable. On two occasions he ended class by bringing us downstairs to the gallery of the Dibner Library, where we could see an original Volta pile—as he pointed out, its metal end pieces being extraneous to the actual effect—and the amazing clear glass disc of an electrostatic friction machine standing on glass posts.

The possibility that past science might be experienced by any of us was not explicitly discussed. I was introduced to the work of historians involved in recreating scientific experiments, including the recent reconstruction of Coulomb's torsion balance by Peter Heering,[†] who would become my longtime colleague. Emphasizing the lack of standardization in instrumentation and practice of the 18th century in regard to the ambiguities surrounding Coulomb's experiment, Buchwald's remark "I've never done that" may have been a precursor for the lab course he would later teach at the MIT Edgerton Center (where I now teach), and for reconstructions he would go on to carry out with my Dibner cohort member A. Martinez.[‡] Uncertainty and complexity in such endeavors emerge as a theme across ongoing research into Coulomb's work,[§] and my work and that of my students.[¶] Buchwald's attention to instruments as inextricable from science resonated with insights gained from Phil Morrison, and became integral to my teaching. Historical science instruments, and my humbler renditions of instruments, are central in my paper

*E. Cavicchi. "Experimenting with Wires, Batteries, Bulbs and the Induction Coil: Narratives of Teaching and Learning Physics in the Electrical Investigations of Laura, David, Jamie, Myself and the Nineteenth Century Experimenters – Our Developments and Instruments." PhD dissertation, Harvard University, 1999.

†P. Heering. "On Coulomb's Inverse Square Law." *American Journal of Physics* 60 (1992): 988–994; "The Replication of the Torsion Balance Experiment: The Inverse Square Law and its Refutation by early 19th-Century German Physicists." In C. Blondel and M. Dörries (eds), *Restaging Coulomb: usages, controverses et réplications autour de la balance de torsion*. Firenze: L. S. Olschki, 1994, pp. 47–66.

‡A. A. Martinez. "Replication of Coulomb's Torsion Balance Experiment." *Arch. Hist. Exact Sci.* (2006) 60: 517–563.

§S. Heinicke & P. Heering. "Discovering Randomness, Recovering Expertise: The Different Approaches to the Quality in Measurement of Coulomb and Gauss and of Today's Students." *Science & Education* 22 (2013): 483–503.

¶ E. Cavicchi. "Learning science as explorers: Historical resonances, inventive instruments, evolving community." *Interchange* 45(2014): 185–204; "At Sea: Reversibility in Teaching and Learning." *Interchange* 49 (2018):25–68; Y. Yang. "A Learner's Voyage: My Moon Study in 2009." *Interchange* 49 (2018): 69–84.

for STS 150,* my Harvard dissertation, my research as a Dibner Institute Postdoctoral Fellow,† and my teaching.‡

Each experimenter discussed by Buchwald led me to further reading, and to envisaging them as future case-studies. But when it came to the figure that would sustain my fascination for years to come, my classmates and I fell behind in our reading. Starting a new topic on November 1, Buchwald's opening questions (which he presumably saw as easy, unthreatening, and obvious) "What is the Royal Institution? What was the training of Michael Faraday?" were met with dead silence. He rapidly recounted experiments whose startling effects and inferences "we know down to the hour." Faraday's writings and diary allow us to be at his side, moment by moment. In Faraday's work and records I found the connection to my aspirations for investigating and supporting active learning: they are a most vivid account, strikingly similar to Piaget's keen observing of infants in development.§

I thus became immersed in 19th century electromagnetic induction coils: I scouted for artifacts in collections, made my own drawings and interpretations of these coils, and examined experimental and therapeutic devices. Eventually I

*E. Cavicchi. "Ways of Learning Physics: Magnets, Needles, Fields." Qualifying Paper, Harvard University, 1995; "Experimenting with magnetism: Ways of learning of Joann and Faraday." *American Journal of Physics* 65 (1997): 867–882.

†E. Cavicchi. "Nineteenth century developments in coiled instruments and experiences with electromagnetic induction." *Annals of Science* (2006) 63:319–361; "Charles Grafton Page's Experiment with a Spiral Conductor." *Technology and Culture* 49 (2008): 884–907.

‡E. Cavicchi. "Historical Experiments in Students' Hands: Unfragmenting Science through Action and History." *Science and Education* 17(2008): 717–749 and note 5.

§E. Cavicchi. "Faraday and Piaget: Experimenting in Relation with the World." *Perspectives on Science* 14 (2006): 66–96.

was thrilled to undertake my own laborious winding of wire coils. For months I tinkered with the sometimes intermittent and always beautiful sparking devices I had struggled to build—always recording my observations and confusions, like Faraday, in an ever-expanding notebook. Had I not taken STS 150, my students, colleagues, and I would never have experienced these effects, devices, and adventures.

Buchwald's course, infused with his probing understanding of phenomena, of ways in which those phenomena manifested in past devices and experiments, and of the evolving process of past scientists' investigations, was transformational for me and the work I had yet to undertake. All of us—learners, teachers, instrument-makers, researchers, and ordinary folk—are investigators in the world. While living and learning together we come to create a community of mutual respect and development through our sharing in intrinsically exploratory experiences that extend beyond any of our lifetimes.

Thanks to Prof. Buchwald for extending that welcome to me as a student and for students yet to come.