Toward Effective Algorithm Visualization Artifacts: Designing for Participation and Negotiation in an Undergraduate Algorithms Course

Christopher D. Hundhausen
Department of Computer and Information Science
University of Oregon
Eugene, OR 97403–1202
chundhau@cs.uoregon.edu

ABSTRACT
Despite their intuitive appeal, computer-based algorithm visualization (AV) artifacts have failed to enter mainstream computer science education. I argue that past research into the design, evaluation, and pedagogical use of AV artifacts has been guided by an underlying theory of effectiveness that is fundamentally deficient. Inspired by an alternative pedagogy in which students construct their own AVs, and by recent research into the situated nature of communication and learning, my dissertation develops an alternative theory that stresses the value of AV artifacts both in facilitating students' participation in the Community of Algorithmaticians, and in providing students and instructors with resources for negotiating a shared understanding of algorithms.

KEYWORDS: Algorithm visualization, Situated Action Theory, Situated Learning Theory

PROBLEMS
Computer algorithms are notoriously difficult to learn. In an effort to enhance algorithms curricula, computer science educators have explored the potential for computer-based algorithm visualization (AV) artifacts, which enable instructors and students to create and explore graphical representations (AVs) of algorithms under study.

Despite the enthusiasm and high expectations of their developers, however, computer-based AV artifacts have failed to enter mainstream computer science instruction (see, e.g., [4]). AV researchers have speculated three main obstacles to AV technology's widespread adoption:

O1. The technological infrastructure required to deploy AV systems may not be readily available.

O2. Preparing visualizations requires substantial time and effort.

O3. Past efforts to validate AV technology's pedagogical benefits empirically have been unconvincing.

THE THESIS
I argue that past efforts to overcome these obstacles have been guided by an underlying theory of effectiveness that is fundamentally deficient. Thus, if we are to avoid perpetuating that theory's deficiencies, we need to work toward an alternative theory . Below, I outline the argument—first, by elaborating on the deficient theory, which I call *Epistemic Fidelity* (EF) Theory (following Roschelle [3]); second, by critiquing the theory; and finally, by sketching out both the alternative theory that I am presently developing, and my methods for building an empirical case in support of it.

Epistemic Fidelity Theory
The foundation of EF Theory is a set of assumptions about what knowledge is, how it is transferred, and the efficacy of graphical representations in facilitating that transfer. EF Theory holds that an algorithm expert's knowledge is encoded in an AV, and decoded by a viewer. Knowledge is thus seen to flow from expert to viewer through the "conduit" of the visual medium. The value of AV, according to the theory, lies in its ability to provide a faithful account (i.e., one with *high epistemic fidelity*) of an algorithm's execution in terms of an algorithm expert's mental model.

According to the *strong* version of the theory, high epistemic fidelity alone leads to robust, efficient acquisition of target knowledge by AV viewers. Three *weak* versions of the theory, however, ascribe importance to other factors as well: (1) *individual differences* in human cognitive abilities; (2) *dual-coding*, by which knowledge is encoded in both verbal and non-verbal modes; and (3) *viewer involvement*—that is, having viewers *actively* explore AVs by, for example, creating their own input data or making explicit predictions regarding future AV states.

A Critique of EF Theory
To date, nine controlled experiments have explicitly evaluated the efficacy of various AV technology-based pedagogical exercises. Based on their independent variables, all of these experiments aim to substantiate a particular version of EF Theory. A review the experimental results in support of each version of EF Theory indicates that the *viewer involvement* version of Weak EF Theory has by far the most consistent experimental support. Indeed, all four of the experiments that put *viewer involvement* to the test yielded significant results. That the most significant factor appears to be not what AV viewers *see*, but what they *do*, seriously

calls into question EF Theory's assumption that epistemic fidelity matters.

Toward an Alternative Theory

Given the significance of viewer involvement, it is reasonable to explore pedagogical approaches that get viewers even more involved. To that end, a few computer science educators (see esp. [4]) have advocated "AV assignments" in which students actually construct their own AVs. Notice that, because this pedagogical approach shifts the responsibility of AV creation from expert to learner, EF Theory can no longer account for its benefits; knowledge cannot flow from expert to learner through an AV. The approach is thus a promising point of departure on the search for an alternative theory.

Preliminary Ethnographic Fieldwork

In the interest of understanding the benefits of student-constructed AVs, and of developing a theory that might account for those benefits, I conducted a six-month ethnographic study of a third-year undergraduate algorithms course that included student-constructed AV assignments. Participant observation (as both a student observer and assistant to the instructor), semi-structured interviews, and videotaping constituted my primary field methods; I also collected student diaries and administered e-mail surveys.

Observations made during the study suggest that the benefits of student-constructed AVs have less to do with their ability to *transfer* knowledge than with their ability to facilitate *participation* in the Community of Algorithmaticians. Two forms of participation afforded by AV artifacts appear particularly significant in successful learning episodes. First, the process of constructing AVs vests students in the activities of algorithmaticians; through their AV-building activities, students become keenly interested in producing AVs that resemble those of experienced algorithmaticians. Second, conversations about those AVs with experts enable students gradually to develop an algorithmatician's understanding of *what* is important about algorithms (e.g., correctness, efficiency), and of *how* to communicate it. In such conversations, students' AVs bridge the gap between student and expert perspectives, allowing mutually meaningful conversations to take place.

Recent anthropological and sociological research into the situated nature of communication (see esp. [5]) and learning (see esp. [2]) provides a theoretical framework within which the above observations start to make sense. At the level of the community of practice, AV artifacts are beneficial insofar as they provide *access* to increasingly central participation in the Community of Algorithmaticians. At the level of conversations, AV artifacts are beneficial insofar as they serve as powerful *communicative resources*.

Refining and Building an Empirical Case for the Theory

The remainder of my dissertation research aims both to refine this emerging theory, which I have labeled PAVE (Participatory AV Environments) Theory, and to compare it to the *viewer involvement* version of Weak EF Theory. Two key research questions driving this research include:

1. What are the implications of PAVE Theory for AV artifact design?
2. What are the theoretical and practical advantages of PAVE Theory, as compared to EF Theory?

To address (1), I am using extensive footage of student-instructor AV discussion sessions recorded during my ethnographic study as a basis for designing an AV artifact rooted in PAVE Theory. Because of its emphasis on communication and participation, the PAVE artifact will support rough sketches of algorithm concepts and behavior, as well as "quick and dirty" animation. In stark contrast to present AV artifacts, the PAVE artifact will *not* support the generation of (high epistemic fidelity) AVs as a by-product of algorithm execution.

To address (2), I shall conduct a controlled experiment in which PAVE Theory is pitted against the *viewer involvement* version of EF Theory. The between-subjects design will include (a) a PAVE condition in which students use my computer-based PAVE artifact to facilitate discussions with an instructor; (b) a PAVE condition in which students use low-tech, low-cost materials (pen, paper, scissors) to do the same; and (c) an EF condition in which students interact with a pre-defined AV using their own input data. Dependent measures will include post-test performance and learning session time. All participants will work in pairs; this will facilitate post-hoc Interaction Analysis [1], which will be used to evaluate the experimental sessions with respect to, and in order to refine, the evolving PAVE Theory.

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