

Creating Mechanical Toys: Steps Toward a CAD Tool for Educational Automata

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Abstract

This paper describes our work on a computational tool for the design of mechanical elements suitable for use in automata (mechanical toys and sculpture). The purpose of the tool is to permit students to create customized mechanical components (such as cams); to combine and simulate sets of components; and to "print out" the components on devices such as laser cutters that realize the designs in wood. We discuss the educational rationale behind our work; describe the current (still early) state of our system; and explore the relationship between our work and larger issues highlighted by work in "computational crafting."

Introduction

Artistic mechanical objects—"automata", in the pre-computer-age interpretation of the word—are fun. The workings of physical machines (gears, cams, linkages, levers, springs, rods, strings, and their various combinations) when embedded in animated sculpture are an endless source of wonder to both children and adults. This has been true for centuries, as illustrated [Hillier 1988] by the hydraulic-powered inventions of Hero of Alexandria in the first century A.D.; the European tradition of clockwork figures of the late Middle Ages; the gorgeous eighteenth-century devices created by showmen such as Vaucanson and Jacquet-Droz; and the modern-day artwork of England's Cabaret Mechanical Theatre.[Onn and Alexander 1998] What, precisely, is the source of this ancient fascination is still a bit mysterious. The way in which automata perform lifelike movements (e.g., of animals or humans), the manner in which behavioral complexity arises from individually simple and understandable parts, the sheer visual pleasure of well-designed machinery in operation, all seem to play a role; but to go much further in this vein would be a venture into psychological speculation.

In any event, there is an educational side to this human fascination with mechanical devices as well. Seymour Papert, in his well-known book *Mindstorms*, offers an eloquent discussion of his early childhood fascination with gears; he points out that these objects served for him not only as an entry into mathematical and physical reflection, but also as a source of positive affective experiences in education:

I believe that working with differentials did more for my mathematical development than anything I was taught in elementary school. Gears, serving as models, carried many otherwise abstract ideas into my head.... Assimilating equations to gears certainly is a powerful way to bring old knowledge to bear on a new subject. But it does more as well. I am certain that such assimilations helped to endow mathematics, for me, with a positive affective tone that can be traced back to my infantile experiences with cars. [Papert 1980, pp. xviii-xix]

Papert's experience is beautifully described, but he is only one of numerous mathematicians and scientists who have drawn inspiration from mechanical devices. Contemporaries of both Isaac Newton and James Clerk Maxwell (just to mention two illustrious examples) report those scientists' early fascination with machines; Charles Babbage's autobiography describes the author's powerful memories of an automaton

exhibition; and—just to give another twentieth-century example—Claude Shannon, the founder of information theory, has described in interviews a similar lifelong attachment to playful mechanical construction.

Granted, then, that mechanical design is a venerable, intellectually rich, and potentially emotionally powerful educational experience for budding scientists and engineers; still, there seems to be an unfortunate divergence between the rich worlds of educational computing and educational automata. It is odd that this should be so, since the activity of computer programming bears a compelling similarity with that of mechanical design (e.g., in their parallel attention to the aesthetic values of skilled engineering); indeed, this is a larger point of Papert's book. Nonetheless, educational computing by and large focuses its attention on the intangible side of computational media—on virtual laboratories, notebooks, museums, on animations and simulations—to the exclusion of physical construction, which is often viewed as quaint and limited by comparison.

To some degree, this harsh judgment is mitigated by the refreshing presence of newer commercial systems such as Lego's *Mindstorms*, through which children may create physical constructions that include programmed behaviors. While these systems are undoubtedly marvelous, they represent a very small region of a much larger, and richer, design space in which mechanical creation and computational media may be woven together. In particular, they are still largely based on a notion of mechanical creation through predesigned and presupplied kits of basic elements (in this case, plastic bricks). Such kits are useful, but they are also limiting in a variety of ways—aesthetically, stylistically, materially. By way of contrast, the Cabaret Mechanical Theatre devices reveal a profusion of artistic styles, basic materials, and subject matter; they hint at the treasures available to the mechanical practitioner who moves beyond the realm of predesigned construction kits.

We believe that computational media can be effectively integrated into a much broader region of educational mechanical construction than is currently the case; and the remainder of this paper describes our current work on a software system to support and enhance the work of children (and adults) in the creation of customized automata. The second section describes the foundations of our current system; in the third section we discuss the way in which this work plays into larger themes of "computational crafting"; and in the fourth and final section we describe related work, as well as our own ongoing and future efforts.

A Tool for the Design of Educational Automata

Our current system for automaton design is still at a very early stage of development, and is emphatically a work-in-progress. The system as planned will include a suite of tools for the creation of mechanical elements such as cams, gears, and cranks; tools for the animation of behavior of pieces and (at least small) combinations; a browsable database of components; and tools for fabricating components in paper or wood.

To date, we are furthest along in the cam-development tool, shown in Figure 1 below. The user chooses a cam with the desired number of lobes from the Cam Parameters panel of the window. She then selects a starting diameter for the lobes from the drop down menu and clicks the Create button; the profile of the default cam is then drawn in the Cam Profile panel and a graphical representation of the motion of a cam follower is displayed in the Motion Graph panel. This enables the user to connect visually the shape of the cam with the type of motion that it would produce in a physically-constructed follower.

It will be rare that the lift (height) and dwell (duration) of the lobes of this cam are precisely what the user wants so the handles in the graphical representation can be moved about to vary these parameters. This allows a great variety of cams to be designed whose lobes have different dwells, lifts and minimum and maximum locations.

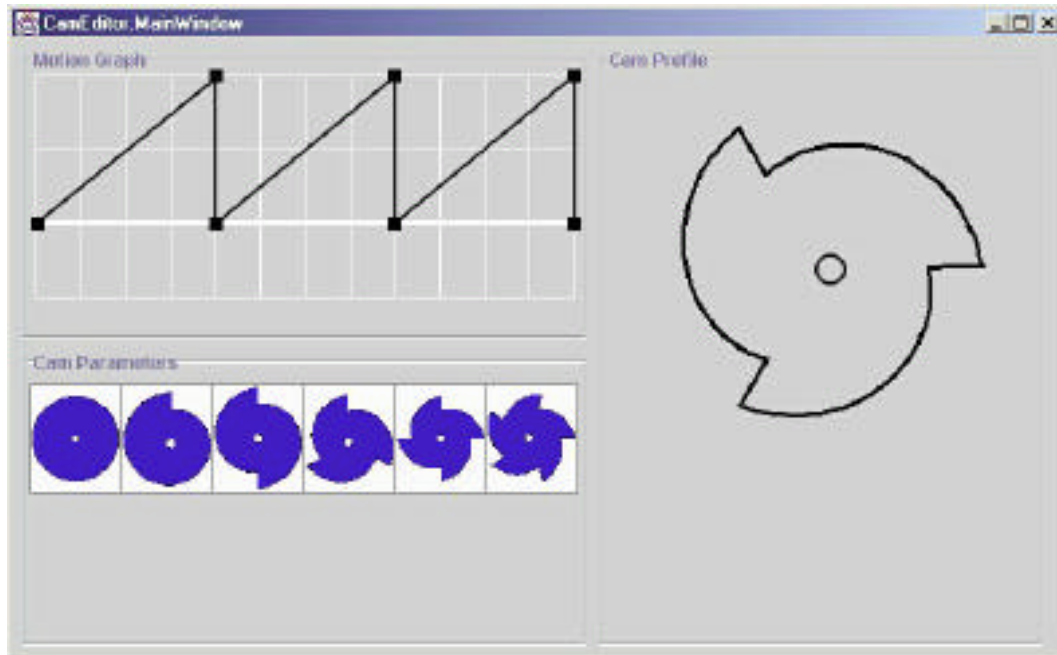


Figure 1. A screenshot of the cam-design tool.

Importantly, once the cam is designed to the user's taste it may be represented in a form suitable for printing out in basswood on an inexpensive laser cutter. Thus, the cam-design system should not be viewed as primarily a tool for simulation, but rather as a tool for customized design and fabrication.

Educational Automata and the World of Computational Crafting

Even in its current, still-embryonic version, the automaton CAD tool described in the previous section touches upon a variety of themes that we believe are important in the larger realm of computationally-enriched handicrafts—i.e., the realm in which computational media and personalized physical construction (in classrooms, home workshops, and amateur laboratories) intersect. In this section, we draw out several of these themes.

• *Output Devices*

One of the more powerful themes of computational crafting is the understanding that terms such as "educational technology" need not be synonymous only with "computers" as narrowly construed. In particular, the burgeoning variety of computational output devices and materials deserves close attention among educational technologists. Without exorbitant expense, for instance, it is now possible to use laser cutters to "print out" flat objects in materials such as wood, cardboard, foam core, and plastic. The near future may see a still more expressive range of materials in the form of affordable three-dimensional printers that output complex shapes in plastic or paper. (See Gershenfeld [1999] for a highly readable discussion.) Pragmatically, the expanding space of output materials and specifications

implies a parallel expansion of the types of constructions available to students and hobbyists. Construction kits—of plastic bricks, architectural blocks, mechanical parts, chemical models, polygonal geometric pieces, and so forth—may increasingly be viewed as objects that can be created, customized, and "printed out" by users, rather than as sets that must be purchased whole. This in turn implies that various educationally-oriented construction domains (of architectural, chemical, or geometric modelling, for example) may be greatly enriched by tools much like that described in the previous section—i.e., tools that permit customized design on a computer screen followed by output in physical form.

- *Expanding the Expressive Range of Craft Artifacts*

Computational design tools for crafting—such as the system described above—offer users (and especially children or beginners) a means by which they can create more expressive artifacts than would generally be possible without the computer. In the case of the automaton system, a student may play with a variety of sophisticated cams and complex motions before actually creating a physical object. We have seen this same principle play out in earlier projects in which we have participated: both the HyperGami system (for mathematical papercrafting) and the HyperSpider system (for creating mathematical string sculptures) permit users to experiment with design possibilities on the computer screen before taking the plunge into real-world materials. (Much more detail may be found in [Blauvelt, Wrensch, and Eisenberg 1999] and [Eisenberg, Rubin, and Chen 1998].) Such systems do not deprive the student of the real-world activity, but they do tend to lower the barrier to early experimentation, allowing the student to see "what might work" and to reject failed designs with considerably less frustration. There is of course a delicate question lurking here—namely, just how much "real-world failure" is of pedagogical value, and how much of that value is lost by the activity of design on the computer screen. Still, it may be argued that for many students, the barrier to participation in educational crafts lies precisely in this tradition of early, time-consuming hands-on failure; and for these students in particular, computational design tools can tip the affective balance toward enjoying the activity of crafting.

- *Integrating Craft Design Tools with Other Systems*

One of the more unexpected and powerful features of doing certain portions of craft design on the computer is that it affords the user the benefits of the existing landscape of computational media. A novel cam shape (with an animation of its related motion) could be displayed on the World Wide Web and traded with another student; the cam might be rendered in three dimensions by a sophisticated CAD system; or the surface of the cam might be treated as a two-dimensional template for decoration in a painting program (after which, a multicolor decoration might be printed out in paper on a standard color printer and glued to the surface of the separately-printed-out wooden cam). The larger point here is that the world of existing computer applications permits a certain degree of integration, though perhaps less than we would like; and by exploiting this integration, we can discover inventive new ways of expanding our craft activities.

- *Languages and Notations as Artifacts*

In our view, the most important theme that emerges from computational crafting is the idea of design notations or languages as creative artifacts in their own right. Traditionally, crafts such as origami and knitting are associated with design notations; these notations have typically grown over long periods of time and are occasionally obscure or unwieldy. By creating computational tools for (both traditional and novel) crafts, we are compelled as designers to reconsider the notations that accompany those crafts. For instance, a cam design tool might describe or customize cams not only according to the geometry of the object itself, but according to properties of the time-series that describes the periodic up-and-down motion of the cam follower. Or alternatively, one might create sets of operations

or procedures that modify cams in a systematic way (e.g., altering a cam by incrementing the number of lobes, or randomly varying the lifts of successive lobes). Thinking in this way reflects something of a productively "computational mindset" in which languages are conceived as imaginative products to be critiqued and reworked. Rather, for example, than treating existing origami notation as something necessarily perfect and immutable, the designer of a computational crafting tool might well explore the possibility of (e.g.) including dynamic or animated elements in origami instructions; or showing the position of the folder's hand as a complex fold is performed; or defining certain classes of folds in terms of parameterized procedures. This is not to say that the existing or traditional notations are wrong—merely to say that (like the crafts themselves) they are human creations, and thus worthy of study, critique, and re-examination in their own right.

Related Work; Ongoing and Future Work

Many of our design ideas have been influenced by the work of Resnick and his colleagues at the MIT Media Lab in integrating physical objects with computational media.[Resnick et al. 1998] In particular, Resnick's group has devoted tremendous attention to the ways in which new computational media (such as programmable Lego bricks) enable children to encounter educational themes (e.g., emergent complex systems, or artificial life) that would otherwise have been considered too advanced or unapproachable for students. Our belief is that creative mechanical design is likewise rich in potentially advanced content (e.g., the geometric patterns of linkages), but that the construction tools currently available to children are either limited by being purely "virtual" in nature (so that only computerized versions of components are created or used) or else are limited by the constraints of kits of physical pieces.

Our automaton design system, as noted above, is still in a very early stage of development. We plan to include a variety of mechanical component design tools (including gears and cranks, as well as additional forms of cams); tools that permit virtual assembly and operation of small combinations of pieces (e.g., animations that allow the user to see whether two proposed gears mesh correctly and are in the desired ratio); and a repository of components, mechanisms, and sample automata that users can browse.

Still another possible direction is to reconsider the types of components that may be employed in student-constructed automata—that is, to move beyond the standard set of "traditional" mechanical components. For several years now, we have been designing prototypes of *computationally-enhanced craft items*—i.e., craft items such as hinges, tiles, and tacks that include embedded computational elements.[Wrensch and Eisenberg 1998] The notion behind such small items is that they are user-programmable to perform such operations as repetitive open-and-close movements (in the case of the hinge) or rotational patterns (in the case of the tack). Computationally-enhanced craft items may ultimately permit a far wider and more complex range of potential behaviors than their non-programmable equivalents; and they could greatly expand the range and expressiveness of student projects. By creating design tools that not only encompass traditional mechanical components but programmable components as well, we could conceivably introduce children in a technological age to the appreciation of Vaucanson and Hero's art.

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